The Nautilus Institute
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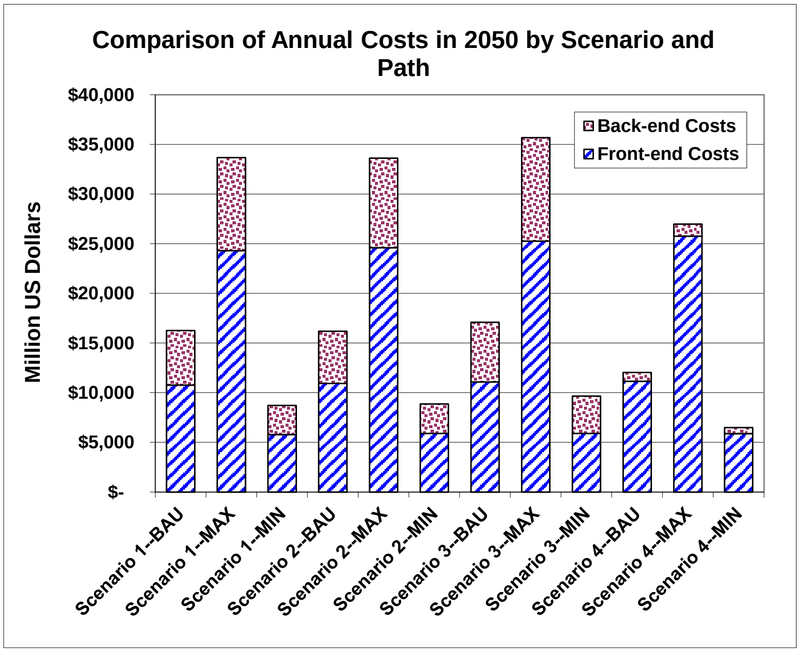
NAPSNET SPECIAL REPORT

AFTER FUKUSHIMA: RADIOLOGICAL RISK FROM NON-STATE DIVERSION OF OR ATTACK ON SPENT FUEL—SUMMARY REPORT



Banner image: Cost comparison of nuclear cooperation scenarios and nuclear power development paths for East Asia (result from "After Fukushima…" project)

David F. von Hippel and Project Working Team Members

February 22, 2018 (originally completed August 15, 2016)

Nautilus Institute for Security and Sustainability

Summary Report of the AFTER FUKUSHIMA: RADIOLOGICAL RISK FROM NON-STATE DIVERSION OF OR ATTACK ON SPENT FUEL Project, organized by Nautilus Institute with funding from the John D. and Catherine T. MacArthur Foundation

Recommended Citation: David F. von Hippel and Peter Hayes, "AFTER FUKUSHIMA: RADIOLOGICAL RISK FROM NON-STATE DIVERSION OF OR ATTACK ON SPENT FUEL—SUMMARY REPORT", NAPSNet Special Reports, February 22, 2018.

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AFTER FUKUSHIMA: RADIOLOGICAL RISK FROM NON-STATE DIVERSION OF OR ATTACK ON SPENT FUEL

August 15, 2016

PROJECT SUMMARY REPORT

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Overview

This Project Summary Report describes work done by Nautilus Institute and collaborating colleagues in exploring the connections between nuclear fuel cycle management and nuclear safety/security by analyzing the risk of radiological releases resulting from an attack on or accident at nuclear facilities, identifying the factors that increase or decrease this risk, and making realistic recommendations for changes in the storage, management, and disposal of spent fuel to reduce this threat. The project drew upon a network of experts on energy futures, energy security, and nuclear fuel cycle development, safety and security in East Asia and the United States.

Country Teams from the Republic of Korea, Japan, and China, working with Nautilus staff, and nuclear spent fuel management/modeling experts from the United States worked together to:

- Update the energy sector scenario and nuclear spent fuel management work undertaken by the country teams;
- Complete and apply a methodology and associated Excel workbook tool for assessing radiological risks associated with accidents or attacks at nuclear facilities;
- Integrate national regional results of energy and spent-fuel management modeling through the updating of Nautilus' analysis of scenarios for nuclear fuel cycle cooperation;
- Test the radiological risk assessment methodology both by applications in each of the participating nations, and by application to the light water reactor (LWR) currently under construction by the Democratic People's Republic of Korea (DPRK); and
- Explore the prospects for deep borehole disposal of nuclear spent fuel and other radioactive wastes in the countries of Northeast Asia.

The key findings of the collaborative research include the following:

- The Fukushima accident has had profound but different impacts on the nuclear sector in each of the three countries included in this Project. Japan has shut down its reactors for extensive safety checks and retrofits related to back-up and other systems that were implicated in the Fukushima accident. In the ROK, reactors were also checked for safety, and a recent scandal regarding falsification of certifications for reactor parts has added to concerns raised by Fukushima. In China, the Fukushima incident has caused authorities to revisit ambitious reactor construction plans, and to somewhat slow the pace of nuclear plant construction, including reconsideration of some plants, notably those to be located inland.
- The results of the Fukushima accident have shown, and findings of this project have underlined, the need for key power and cooling water provision systems at reactors and in spent fuel pools to be both multiply backed-up and also sufficiently separate that an accident

in one element (such as a reactor) does not cascade to pose a threat to another unit (another reactor or a spent fuel pool).

- The project has shown that some modes of management of spent fuel—non-dense racking in spent fuel pools vs. dense racking, and dry cask storage of cooled spent fuel, including centralized, below-ground storage—are superior to current methods of spent fuel management. Some of these alternative methods are under investigation in the region, but the pace of adopting these methods of risk reduction is slow, in part due to a combination of a lack of independence between the authorities regulating nuclear power in each nation from those planning and implementing nuclear power facilities, and in part because of existing laws regarding the siting of nuclear facilities, particularly in Japan and the ROK, that make it difficult for reactor operators to store spent fuel on site in dry casks, but do not affect the storage of spent fuel in pools.

- Dry-cask storage of spent fuel appears much less vulnerable to release of radiation through accident or attack than storage in spent fuel pools. Zircaloy-clad fuel assemblies in dense-racked spent fuel pools, on the other hand, can ignite if water from the pool is lost, as dense-racked pools lack the ability to passively release sufficient heat through the air when coolant is lost, leading to rising temperatures and, eventually, ignition of fuel cladding, resulting in releases of radioactivity.

- Each of the nations involved in the project has at least a general interest in international collaboration on spent fuel issues, but because of asymmetries between the nations, collaboration has been difficult to start. These asymmetries include China being a nuclear weapons state, while Japan and the ROK are not, and Japan having a reprocessing program and uranium enrichment capability, while the ROK does not, although some ROK nuclear researchers and official wish to pursue "pyroprocessing", a lightly-modified form of reprocessing.

- Deep borehole disposal of nuclear spent fuel and high-level waste seems likely to be an attractive possibility, and there are areas within the countries of the region that would make good hosts for deep borehole facilities from a geological point of view. Deep borehole disposal facilities may well even have cost advantages over other forms of disposal (such as mined repositories), but will require both technological advances to assure the reliability of key operational elements, as well as domestic and possibly international policy agreements to allow the siting of deep borehole facilities. Despite their potential simplicity and low cost relative to mined repositories deep borehole disposal of nuclear materials is probably 30 years from full-scale implementation, about the same as other disposal options, and the closed nuclear fuel cycle options also under consideration in the region. What this means is that it is inevitable that intermediate spent fuel storage, and most likely dry cask storage, must be employed by all three nations in advance of any final disposal option.

- Our preliminary calculations have indicated that the costs of spent fuel management in general are very modest when compared to the full cost of nuclear generation, and particularly when compared with the cost of electricity in Japan, the ROK, and China (Japan especially). Costs of nuclear cooperation (or non-cooperation) scenarios that include reprocessing are higher than those without reprocessing, and costs for dry-cask storage are likely to be a tiny part of overall nuclear fuel cycle costs. This means that there is no reason for cost to play a significant role in decisions to modify spent fuel management planning, rather, that radiological risk and attendant political, social, and legal concerns should drive decisions regarding spent fuel management.

Key follow-on activities related to the work described in this Report include:

- Convene a diverse group of regional and international experts to further investigate options for spent fuel management, focusing on ways to mitigate the different hazard events (natural disasters, aerial bombardment, non-state attack), and in particular, to clarify whether reducing spent fuel pool density is justified to reduce the possible risk of inadvertent or malevolent radiological release from spent fuel pools and reactor sites. In addition to expert meetings, synthesis, analysis, and summarizing of findings for policy input would be carried out.
- Work with colleagues and civil society groups in the region to better understand the challenges to siting at-reactor or away-from-reactor dry cask storage options that would reduce risks associated with spent fuel pools.
- Move forward the consideration of deep borehole disposal (DBD) by the countries of Northeast Asia by convening a regional meeting, attended by researchers and officials responsible for designing and managing nuclear waste disposal in the countries of the region, at which DBD concepts are described, and discussions are held on the specific barriers, especially institutional barriers, to DBD in the countries of Northeast Asia.
- Building on previous work on the topic and Nautilus' existing quantitative analysis, further investigate the potential for nuclear fuel cycle cooperation in the region using a combination of expert analysis and input, development of possible organizational structures and activities for nuclear fuel cycle cooperation institutions in the region, and one or more workshops to discuss the political, organizational, institutional, and economic challenges that might be faced in developing nuclear cooperation.
- The underpinnings of Nautilus' work on nuclear fuel cycle cooperation in general, and spent fuel management in particular, has been our work since 2000 with Country Teams on energy sector status, policy, and futures in the countries of the region. Continuing and deepening this work, including advanced full energy-sector and national/regional energy futures modeling, will continue to provide the full economic, environmental, political and social context for nuclear energy, and thus, nuclear spent fuel management and nuclear cooperation scenarios. Broadening the group of participating nations to include those in the East Asia and Pacific region with nascent or proposed nuclear energy programs offers significant opportunities for sharing of knowledge and perspectives, and for uncovering both challenges to and opportunities for cooperation in nuclear fuel cycle management.

Please note that although this Project Summary Report is a synthesis of work by the individuals of the Project Team, the opinions and conclusions described in this report are not intended to reflect the opinions of all individual Project Team members in all cases.

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List of Acronyms and Abbreviations

AFR:	Away from Reactor (spent fuel storage)
BAU:	Business as Usual
Bq:	Becquerel
BWR:	Boiling Water Reactor
CAEA:	China Atomic Energy Agency
CANDU:	CANada Deuterium Uranium reactor
CO_2:	Carbon Dioxide
Cs-137:	Cesium 137 isotope
DBD:	Deep Borehole Disposal
DPRK:	Democratic People's Republic of Korea
FYP:	Five-year Plan (China)
GHG:	Greenhouse gases
GW:	Gigawatts
GWe:	Gigawatts of electric power
GWh:	Gigawatt-hour
GWP:	Global Warming Potential
HLW:	High Level Wastes
IAEA:	International Atomic Energy Agency
KHNP:	Korea Hydro & Nuclear Power Co., Ltd
LEAP:	Long-range Energy Alternatives Planning (software system)
LILW:	Low and Intermediate Level Radioactive Waste
LWR:	Light Water Reactor
MOx:	Mixed Oxide Fuel
mSv:	Millisieverts
MW:	Megawatts
MWe:	Megawatts of electric power
MWth:	Megawatts of thermal power
NNSA:	National Nuclear Safety Administration (China)
NPP:	Nuclear Power Plants

NRA:	Japan's Nuclear Regulation Authority
NUMO:	Nuclear Waste Management Organization of Japan
pBq:	Petabecquerel (10^{15} Becquerel)
PM2.5:	Particulate Matter, less than or equal to 2.5 micrometers in diameter
Pu:	Plutonium
PWR:	Pressurized Water Reactor
R&D:	Research and Development
RFE:	Russian Far East
ROK:	Republic of Korea
Sv:	Sieverts
SNF:	Spent Nuclear Fuel
SWU:	Separative Work Units
tHM:	Tonnes of Heavy Metal (Uranium/Plutonium)
TWh:	Terawatt-hour
U:	Uranium
UOx	Uranium Oxide (fuel)

1 Project Background and Summary

1.1 Background and Goals of Project

The Fukushima disaster highlighted the relationship between nuclear power and the risk of radiological exposure, whether such exposure results from radiation released as a result of an accident—caused by technical or human error, or, as in Fukushima, by an overwhelming natural disaster, or through attack on nuclear facilities by state or non-state actors. The earthquake, tsunami, and nuclear meltdowns in Japan made the location, configuration, and physical security of nuclear plants and spent fuel storage facilities priority areas for policies aimed at concurrently minimizing the potential for diversion of fissile material, and the consequences of an attack on spent fuel facilities or the impacts of an accident initiated by a natural disaster or technical systems failure.

Since the Fukushima accident, Japan, China, and the Republic of Korea (ROK) have each taken steps toward improving reactor safety. These steps include improving "defense in depth", adding layers of back-up facilities in the event that power to cooling systems have been lost, and improving reactor safety protocols, among others. Not yet included to a significant extent, however, have been change in the structure of some of the most vulnerable elements of some nuclear plants and spent fuel management systems.

The Seoul Nuclear Security Summit in March 2012 called for coordination to make this connection between nuclear fuel cycle management, safety and security, noting, "We affirm that nuclear security and nuclear safety measures should be designed, implemented and managed in nuclear facilities in a coherent and synergistic manner… Noting that the security of nuclear and other radioactive materials also includes spent nuclear fuel and radioactive waste, we encourage States to consider establishing appropriate plans for the management of these materials[1]."

Although it called for action to address risks related to the management of spent fuel and wastes, the Summit focused on control of fissile material, did not have a panel on nuclear safety and security, and failed to offer any concrete recommendations for how nuclear facilities should be designed or secured so as to reduce the risk of accident or attack and the attendant radiological consequences of such events.

Since the Fukushima accident, the countries of Northeast Asia have each stepped back, to varying degrees, to examine the lessons of Fukushima for their own nuclear programs. In Japan, this has resulted in the closing for extensive safety assessments of all of its reactors, with only a few units having been brought back on line on an interim basis, and no plants on line as of this writing. Japan also undertook a comprehensive, multi-stakeholder review of its plans for a nuclear future, resulting, at least temporarily, in a plan to phase out nuclear power in the long term, though those plans, assembled under the Yoshihiko Noda administration are being revised, and probably reversed, by the more pro-nuclear power Shinzo Abe administration. Perhaps more importantly, in the longer-term, the Fukushima accident seems to have galvanized a grassroots response that has spurred the implementation of energy efficiency and renewable energy sources,

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[1] "Seoul Communiqué at 2012 Nuclear Security Summit" at: http://www.cfr.org/proliferation/seoulcommuniqu-2012-nuclear-security-summit/p27735.

as well as other changes, in a way that could not have been foreseen. Independent of what is decided by the government regarding the nuclear sector, these grassroots changes may in fact be the most important and enduring legacy of Fukushima. In the Republic of Korea (ROK), the Fukushima accident caused authorities to undertake safety checks at the ROK's nuclear plants. More recently, a scandal involving falsified information about reactor parts has forced many reactors off-line, resulting in projected power shortages for the summer of 2013. It remains unclear what the lasting effects of Fukushima will be for the ROK, but it is clear that nuclear safety is of greater concern in Korean society than it was before the accident, perhaps reflected in what appears to be scaled-down plans for nuclear capacity expansion recently announced by the ROK government as a part of its new Energy Plan.[2] In China, the reaction to the Fukushima accident was a review of both at-plant safety arrangements and of China's ambitious plan for building additional nuclear capacity. These reviews resulted in a modest scale-back of plans for new reactors, and though China's construction of new plants continues, certain planned reactors, including most or all of those planned for inland locations, have been placed on hold for the time being.

The "After Fukushima: Radiological Risk from Non-State Diversion of or Attack on Spent Fuel" Project has directly addressed the nexus between nuclear fuel cycle security and nuclear safety by analyzing the risk of radiological releases resulting from an attack on or accident at nuclear facilities, identifying the factors that increase or decrease this risk, and making realistic recommendations for changes in the storage, management, and disposal of spent fuel to reduce this threat. The project drew upon a network of experts on energy futures, energy security, and nuclear fuel cycle development, safety and security in East Asia and the United States. Country teams from China, Japan, and South Korea examined how alternative spent fuel storage locations, management strategies, and storage technologies can minimize the risk of radioactive releases caused by nuclear terrorism or by accidents, as well as the impacts of different scenarios of energy and nuclear power development on the risk of radioactive releases.

Participants from the three country teams, Nautilus staff, and nuclear spent fuel management/modeling experts from the United States worked toward the project's goals throughout the project by:

- Updating of the energy sector scenario and nuclear spent fuel management work undertaken by the country teams;
- Completing and applying a methodology and associated Excel workbook tool for assessing radiological risk of accident or attack at nuclear facilities;[3]
- Integrating national and regional results of energy and spent-fuel management modeling through the updating of our analysis of scenarios for nuclear fuel cycle cooperation;[4]

[2] See, for example, Simon Mundy (2014), "South Korea cuts target for nuclear power", *FT.com*, dated January 14, 2014, and available as http://www.ft.com/cms/s/0/4e8c1872-7cf7-11e3-81dd-00144feabdc0.html#axzz2zpxtBbWu.

[3] The radiological risk methodology and related tools were prepared for Nautilus by Dr, Gordon D. Thompson, and is available as *Handbook to Support Assessment of Radiological Risk Arising From Management of Spent Nuclear Fuel*, Nautilus Institute Special Report dated May 14, 2013, http://nautilus.org/napsnet/napsnet-special-reports/handbook-to-support-assessment-of-radiological-risk-arising-from-management-of-spent-nuclear-fuel/.

- Testing applications of the radiological risk assessment methodology for nuclear plants in China, Japan, and North Korea, the latter using as its subject the Light Water Reactor (LWR) currently under construction by the Democratic People's Republic of Korea (DPRK).[5]

1.2 Project Meetings

The organization and realization of project meetings were key elements of work on the project. Two meetings, the 2012 "Resilience and Security of Spent Fuel in East Asia", Working Group meeting, held from April 12 to 15 in Seoul, and the 2013 "Spent Fuel and Reduction of Radiological Risk after Fukushima and Deep Borehole and Spent Fuel in East Asia" Working Group Meeting, held from May 28 to 30, 2013, held in Beijing, included presentations providing updates on energy sector activities and energy policies, nuclear energy sector developments including developments related to nuclear spent fuel management, and, with support from the Carnegie Corporation of New York, on the prospects for deep borehole disposal for nuclear spent fuel and other nuclear wastes in each nation. Agendas, presentations, and other materials from these meetings are available on the Nautilus website..[6]

Nautilus is also continuing its analytical work to examine the relative risk, and relative cost, of undertaking modifications to the way that nuclear spent fuel is managed in Northeast Asia to minimize the potential for radiological risk associated with accidents at or non-state attacks on nuclear facilities. This work, in the context of the ongoing MacArthur-funded "Vulnerability to Terrorism in Nuclear Spent Fuel Management" project, focusing on the situation and possibilities in Japan, and carried out with the active participation of Japanese and other colleagues, examines the tradeoff between modifying spent fuel management systems so as to minimize exposure to non-state attacks (or Fukushima-type accidents) that could lead to significant release of radioactivity from reactors and spent fuel facilities, often, given population densities in the area, implying significant human health and environmental implications, as well as billions or trillions of dollars in economic damage. This tradeoff, assuming that the costs of modifying systems are

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[4] An earlier version of a summary of the analysis of scenarios for nuclear fuel cycle cooperation is available as David F. von Hippel and Peter Hayes (2013), *Potential Regional Nuclear Energy Sector Cooperation on Enrichment and Reprocessing: Scenarios, Issues, and Energy Security Implications*, NAPSNet Special Reports, November 19, 2013, at http://nautilus.org/napsnet/napsnet-special-reports/potential-regional-nuclear-energy-sector-cooperation-on-enrichment-and-reprocessing-scenarios-issues-and-energy-security-implications-2/.

[5] The results of the application of the radiological risk assessment methodology to the DPRK's Experimental LWR is presented in David F. von Hippel and Peter Hayes (2014),*"Illustrative Assessment of the Risk of Radiological Release from an Accident at the DPRK LWR at Yongbyon*, NAPSNet Special Report, May 06, 2014, and available as http://nautilus.org/napsnet/napsnet-special-reports/illustrative-assessment-of-the-risk-of-radiological-release-from-an-accident-at-the-dprk-lwr-at-yongbyon-2/.

[6] Materials from these meetings are available at http://nautilus.org/projects/by-name/security-of-spent-nuclear-fuel/2012-working-group-meeting/#axzz32wD2Vsdb and http://nautilus.org/projects/by-name/security-of-spent-nuclear-fuel/2013-working-group-meeting/.

shown to be affordable (the indications that we have seen thus far suggest that costs of modification will be modest, relative to the cost of electricity from nuclear plants—see below), suggests that these modifications (including possible retrofit of existing reactors) are desirable from a cost and societal risk management perspective.

1.3 Summary of Key Project Findings

Key findings from the project to date include:

- The Fukushima accident has had a profound impact on the nuclear sector in each of the three countries included in this Project, but the response to the accident has been different in each country with respect to both the modes of response and the degree of response. Japan has shut down its reactors for extensive safety checks and retrofits related to back-up and other systems that were implicated in the Fukushima accident. In the ROK, reactors were also checked for safety, although a more recent scandal that has come to light regarding falsification of certifications for reactor parts has added to concerns raised by Fukushima. In China, the Fukushima incident has caused authorities to revisit ambitious reactor construction plans, and to somewhat slow the pace of nuclear plant construction, including reconsideration of some plants, notably those to be located inland (on rivers where reactor cooling, at times, may be problematic).
- The project has shown that some modes of management of spent fuel—non-dense racking in spent fuel pools vs. dense racking, and dry cask storage of cooled spent fuel, including centralized, below-ground storage—are superior to current methods of spent fuel management with regard to radiological risk. Some of these alternative methods are under investigation in the region, but the pace of adopting these methods of risk reduction is slow, in part due to a combination of a lack of independence between the authorities regulating nuclear power in each nation from those planning and implementing nuclear power facilities, and in part because of existing laws regarding the siting of nuclear facilities, particularly in Japan and the ROK, that make it difficult for reactor operators to store spent fuel on site in dry casks, but do not affect the storage of spent fuel in pools.
- Each of the nations involved in the project has at least a general interest in international collaboration on spent fuel issues, but because of asymmetries between the nations, collaboration has been difficult to start. These asymmetries include China being a nuclear weapons state, while Japan and the ROK are not, and Japan having a reprocessing program and uranium enrichment capability, while the ROK does not (although it wishes to pursue a lightly-modified form of reprocessing called "pyroprocessing"). In addition, longstanding regional rivalries likely impede the potential for cooperation on this sensitive issue.
- Dry-cask storage of spent fuel appears much less vulnerable to release of radiation through accident or attack than storage in spent fuel pools. Release of radiation from fuel stored in dry casks essentially requires a concerted effort targeted specifically at the dry cask to not only break it open—requiring high explosives detonate essentially on each

individual cask or physically drilling into the cask, requiring proximity of attackers—but to ignite the spent fuel assemblies stored in the cask. Dense racked spent fuel pools, on the other hand, can ignite if water from the pool is lost, as dense-racked pools lack the ability to passively release sufficient heat through the air when coolant is lost, leading to rising temperatures and, eventually, ignition of fuel cladding, resulting in releases of radioactivity.

- Deep borehole disposal of nuclear spent fuel and high-level waste seems likely to be an attractive possibility, and there are areas within the Korean peninsula and China, as well as in other countries of the region, though possibly not in Japan, that would make good hosts for deep borehole facilities from a geological point of view. Deep borehole disposal facilities may well even have cost advantages over other forms of disposal (such as mined repositories). Deep borehole disposal, however, will require both technological advances to assure that key operational elements, such as emplacement of wastes, can be done safely and in a reliable manner, as well as domestic and possibly international policy agreements to allow the siting of deep borehole facilities. In addition, materials stored in deep boreholes should likely be considered essentially irretrievable, as a huge effort will be required to remove emplaced materials from boreholes. This can well be considered a significant advantage, from a risk-of-diversion-of-nuclear materials point of view, but it brings up significant design considerations, and is of concern to those who see spent fuel as a potential future resource for energy production. The status of readiness of deep borehole technologies, despite their potential simplicity and low cost relative to mined repositories is probably 30 or so years from full-scale implementation, or about the same as other disposal options (or, for that matter, the closed nuclear fuel cycle options involving the use of fast reactors that are under consideration in all three of the nations involved in this project). What this means is that it is inevitable that intermediate spent fuel storage, and most likely dry cask storage, must be employed by all three nations in advance of any final disposal option.
- Our preliminary calculations have indicated that the costs of spent fuel management in general are modest when compared to the full cost of nuclear generation, and particularly when compared with the cost of electricity in the three countries (Japan especially). Costs of nuclear cooperation (or non-cooperation) scenarios that include reprocessing are higher than those without reprocessing if any reasonable estimates of future uranium prices are assumed, and costs for dry-cask storage are likely to be a tiny part of overall nuclear fuel cycle costs.

1.4 <u>Road Map of this Report</u>

This Final Report to the MacArthur Foundation provides a summary of the key topics covered under the three years of the Project. As such, the remainder of this Final Report is organized as follows:

- **Chapter 2** covers the activities and results of project elements focused on Radiological Risk from Accident/Attack on Nuclear Energy Facilities in East Asia, including a summary of illustrative analyses prepared by Nautilus for reactors in China and Japan, as well as a summary of a an analysis completed by Nautilus for the Experimental Light Water Reactor (LWR) being built in the Democratic People's Republic of Korea (DPRK).
- **Chapter 3** focuses on nuclear energy and nuclear spent fuel management in East Asia, summarizing, country by country, the current status and future plans for the sector in each of the participating nations.
- A possible alternative for long-term spent fuel management is deep borehole disposal, the prospects for which, both in technological and political terms, are discussed in **Chapter 4**.
- The need for nuclear power, and thus for nuclear spent fuel management, is a function of trends in energy supply and demand and in energy policy. Energy-sector trends and policies for each of the nations participating in the project, as well as in the DPRK, are discussed in **Chapter 5**.
- **Chapter 6** discusses the inputs to and results of Nautilus' cooperation scenarios on spent fuel management in East Asia
- In **Chapter 7**, we discuss the overall conclusions of the research and collaboration efforts under this project, and provide ideas as to possible next steps building on this research.

Throughout this Project Summary Report, text from papers prepared both by Nautilus authors and by members of the Project Team, including Country Team members and other experts, has been summarized and adapted. As such, this Summary Report is in effect the work of multiple authors, so passages from individual papers, when used, do not explicitly quote the authors of those papers. The original papers from which the summaries have been drawn are referenced in this Summary Report.

2 Radiological Risk from Accident/Attack on Nuclear Energy Facilities in East Asia

2.1 Summary of Activities under this Project

The Fukushima accident, perhaps even more dramatically than those at Three Mile Island and Chernobyl before it, brought home to the world the lesson that the even events considered highly improbable can, in fact, happen, and when they do, the fragilities of technologies can be exposed in unexpected ways. Further, the failure of some technologies can put humans and the ecosystems they live in at significant risk. In the case of Fukushima, a combination of the failure of the Fukushima Daiichi plant to withstand a powerful earthquake and tsunami, coupled with common-mode failures (failures in shared electrical, road access, and other systems) between the Fukushima reactors and the associated pools where spent nuclear fuel, with a radioactive inventory much higher than the cores of the reactors themselves, resulted in significant and ongoing releases of radiation to the atmosphere and ocean. Even more compelling, however, were the risks of events that could, but for a combination of luck and intervention, *have happened*, including the release of a substantial fraction of the inventory of the cesium-137 (Cs-137) in the spent fuel pools, a prospect which had then-Prime-Minister Naoto Kan agonizing about how to possibly evacuate 50 million people from the Tokyo area.[7]

A key problem, however, with the concept of radiological risks associated with rare and severe incidents at nuclear reactors—whether accidents initiated by some combination of human error, technological failure, and/or natural disaster, or by attack on a nuclear facility by state or, more likely, non-state actors—is understanding the extent of such risks. In order to provide an objective and systematic assessment of the radiological risk of emissions from a reactor and/or spent fuel storage facilities compromised in an accident or attack, Nautilus commissioned Dr. Gordon Thompson of the Institute for Resource and Security Studies (IRSS) to create a Handbook and analytical methodology to describe the key issues related to non-routine radiological releases from nuclear energy facilities and to enable users to perform a rapid assessment of the radiological releases from an accident at or attack on nuclear energy facilities, and potential human radiation exposure resulting from such releases.

The Handbook commissioned by Nautilus as a part of this project, and subsequently prepared by Dr. Thompson, is entitled *Handbook to Support Assessment of Radiological Risk Arising From Management of Spent Nuclear Fuel*,[8] and has been made available on the Nautilus website. Dr. Thompson also prepared an Excel workbook tool to allow users to estimate the radiological consequences of an incident at a nuclear facility using data describing a particular facility, but with sufficient generic data and general estimates to make the overall exercise tractable. A User's Guide was also prepared to aid in the application of the Excel Workbook template. The first draft of Dr. Thompson's Handbook was made available for the April, 2012 Working Group meeting on the project, and was informally reviewed by Working Group participants. Subsequent to the Working Group meeting, expert review of the Handbook was solicited, and the Handbook was revised taking into account the review comments.

Nautilus project staff used the Handbook prepared by Dr. Thompson to carry out approximate estimates of the radiological for illustrative nuclear facilities in China and Japan. The results of these estimates are provided below.

Nautilus authors also undertook, as a part of the project, an assessment of estimated radiological releases from an accident at or attack on the experimental LWR now under construction by the DPRK at the Yongbyon nuclear complex in North Pyongan Province in the DPRK's northwest. A first draft of this assessment was reviewed by a number of US and European nuclear experts; their comments were taken into account in the final version of the paper, which has been

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[7] See http://www.democracynow.org/2014/3/11/ex_japanese_pm_on_how_fukushima for the text of an interview on the topic with Prime Minister Kan.

[8] Gordon R. Thompson (2013), *Handbook to Support Assessment of Radiological Risk Arising From Management of Spent Nuclear Fuel*, NAPSNet Special Reports, May 14, 2013, http://nautilus.org/napsnet/napsnet-special-reports/handbook-to-support-assessment-of-radiological-risk-arising-from-management-of-spent-nuclear-fuel/

published on the Nautilus website as *Illustrative Assessment of the Risk of Radiological Release from an Accident at the DPRK LWR at Yongbyon*,[9] and is summarized later in this Chapter.

2.2 Summary of Key Issues in Radiological Risk Related to Nuclear Energy Facilities

Harnessing nuclear fission creates various types of risk. This project, and the *Handbook* prepared for the project by Dr. Thompson, focused on a particular type of risk with two major features. First, the risk is associated with spent nuclear fuel (SNF) discharged from the fission reactors at NPPs. Although the fuel is "spent", it contains some fissionable material – uranium and plutonium – and a large amount of radioactive material. Second, the risk is "radiological" referring to the potential for harm to humans as a result of their exposure to ionizing radiation due to an unplanned release of radioactive material.

Although the danger of a nuclear accident at any given power plant may be relatively low—experience suggests a rate of one major accident in 1500 reactor-years of operation—Japan in March 2011 is the place and time where risk became reality.

Storage of spent fuel at many reactors that have been in operation for a decade or more involves, as described below, dense packing of spent fuel assemblies in wet storage facilities. These dense-packed pools are particularly vulnerable to incidents leading to significant radiological releases in the event of an accident or attack.

Risks Associated with Spent Nuclear Fuel Storage

The radiological risk posed by SNF has existed since fission reactors first began operating in the 1940s.[10] The radiological risk posed by SNF has existed since that time. Over the intervening decades, the risk has increased due to: (i) growth in SNF inventories; (ii) changed properties of nuclear fuel; and (iii) design choices regarding modes of SNF storage.

Through 2010, some 226,000 fuel assemblies representing 65,200 tonnes of initial uranium constituted the inventory of SNF discharged from commercial reactors in the USA through 2010.[11] The average age of the spent fuel (time since discharge) was on the order of 15 years. About three-quarters of that inventory is stored in spent-fuel pools adjacent to operating reactors, the remainder being stored in dry casks. Other countries have accumulated smaller inventories of SNF, determined in each instance by the size, type, and history of operation of the country's fleet

[9] David F. von Hippel and Peter Hayes (2014), *Illustrative Assessment of the Risk of Radiological Release from an Accident at the DPRK LWR at Yongbyon*, Nautilus Institute Special Report, dated April 29, 2014, and available as http://nautilus.org/napsnet/napsnet-special-reports/illustrative-assessment-of-the-risk-of-radiological-release-from-an-accident-at-the-dprk-lwr-at-yongbyon-2/#axzz32x7Ok64x.

[10] Natural, geological fission reactors are known to have operated in uranium deposits at Oklo, in Gabon, Africa.

[11] For an overview of practices and regulations regarding SNF storage in the USA, see: Electric Power Research Institute, *Industry Spent Fuel Storage Handbook* (Palo Alto, California: EPRI, July 2010).

of NPPs. The International Panel on Fissile Materials has published a useful review of worldwide experience in managing SNF.[12]

The growth in SNF inventories around the world reflects a long-term trend away from the reprocessing of spent fuel. When the nuclear fission industry was launched in the 1950s and 1960s, the industry's managers assumed that SNF would be reprocessed. One outcome of that assumption is that the spent-fuel pools at NPPs were originally designed to hold only a few years' discharge of spent fuel from the reactors. Over time, countries have turned away from reprocessing. For example, commercial SNF in the USA has not been reprocessed since 1972.

Growth in SNF inventories would, other factors remaining equal, have yielded a proportional increase in SNF radiological risk. The risk has actually grown at a faster, disproportionate rate, as a result of design decisions by the nuclear industry. One set of these decisions relates to the properties of nuclear fuel, and the other to choices regarding modes of SNF storage.

One of the risks associated with nuclear fuel is related to the materials used in the fuel assemblies. The active portion of the assemblies consists of uranium oxide pellets – or, in some instances, mixed plutonium and uranium oxide (MOX) pellets – inside thin-walled metal tubes. When the fuel is fresh, the uranium is low-enriched (up to 5% U-235). The tubes are typically known as "cladding". In contemporary NPPs the cladding is made of zircaloy, whose primary ingredient is zirconium.

Zircaloy is not the only material that can be used for fuel cladding. Stainless steel is an alternative cladding material, and was used in a number of water-cooled reactors during the early years of development of this type of reactor. As of mid-1979, about 7% (about 1,500 fuel assemblies) of the commercial SNF inventory in the USA was fuel with stainless steel cladding. Generally, this fuel performed well. In illustration, a thorough examination was made of a stainless-steel-clad PWR fuel assembly that was driven to a burnup of 32 GWth-days per Mg U in the Connecticut Yankee reactor and then stored for 5 years in a spent-fuel pool. No degradation was observed. Other tests and analyses have indicated that "it is technically feasible to use either stainless steel or zirconium or one of its alloys as structural material, fuel cladding or fuel diluent"[13] Zircaloy is, however, used in the vast majority of modern LWRs because it allows uranium of lower enrichment to be used, and thus reduces fuel costs.

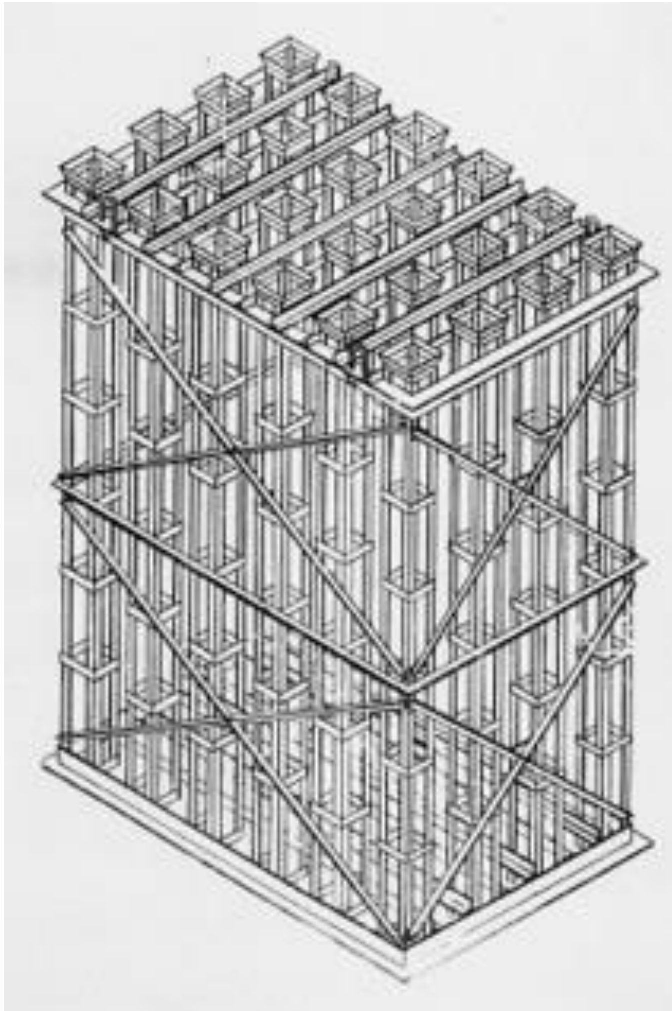
Although the economic advantage of zircaloy cladding during routine operation of an NPP is clear, there is a price to be paid in terms of radiological risk. Zircaloy, like zirconium, is a chemically reactive material that will react vigorously and exothermically with either air or steam if its temperature reaches the ignition point – about 1,000 deg. C. This temperature is well above the operating temperature of a water-cooled reactor, where zircaloy exhibits good corrosion resistance. The potential for ignition of zircaloy is well known in the field of reactor risk, and has been observed in practice on a number of occasions. For example, during the Three

[12] International Panel on Fissile Materials, *Managing Spent Fuel from Nuclear Power Reactors: Experience and Lessons from Around the World* (Princeton, New Jersey: Program on Science and Global Security, Princeton University, September 2011).
[13] Manson Benedict, Summary Report: *Economic Comparison of Zircaloy and Stainless Steel in Nuclear Power Reactors* (Cambridge, Massachusetts: Columbia-National Corporation, 6 February 1958).

Mile Island (TMI) reactor accident of 1979, steam-zirconium reaction occurred in the reactor vessel, generating a substantial amount of hydrogen. Some of that hydrogen escaped into the reactor containment, mixed with air, and exploded. Fortunately, the resulting pressure pulse did not rupture the containment. Similar explosions during the Fukushima #1 accident of 2011 caused severe damage to the reactor buildings of Units 1, 3, and 4. Measures to reduce risks associated with zircaloy cladding could involve substituting stainless steel cladding for zircaloy, although, stainless steel can react exothermically with air or steam, albeit with a lower heat of reaction than is exhibited by zircaloy, or by substituting ceramic cladding options that are now under development, although ceramic claddings may not be available for deployment until 2030 or so.

At every NPP with a water-cooled reactor, a spent-fuel pool is located adjacent to the reactor. Fresh fuel enters the reactor via the pool, and spent fuel is discharged into the pool. The pools were originally designed to hold only a few years' discharge of spent fuel from the reactors. As part of that design, the pools were equipped with low-density, open-frame racks into which fuel assemblies were placed, as shown in Figure 2-1. Similar racks were used for BWR fuel.

Figure 2-1: Typical Low-Density, Open-Frame Rack for Pool Storage of PWR Spent Fuel[14]



If water were lost from a pool equipped with low-density racks, there would be vigorous, natural convection of air and steam throughout the racks, providing cooling to the SNF. Thus, in most situations, the temperature of the zircaloy cladding of SNF in the racks would not rise to the ignition point. Exceptional circumstances that could lead to ignition include the presence of SNF very recently discharged from a reactor, and deformation of the racks. Even then, propagation of combustion to other fuel assemblies would be comparatively ineffective, and the total release of radioactive material would be limited to the comparatively small inventory in the pool.

Faced with the problem of growing inventories of SNF, the nuclear industry could have continued using low-density racks in the pools while placing excess fuel in dry casks. That

[14] Adapted from Figure B.2 of: Anthony Nero, *A Guidebook to Nuclear Reactors* (Berkeley, California: University of California Press, 1979).

approach would have limited SNF radiological risk. Instead, most nuclear plant operators adopted a cheaper option. Beginning in the 1970s, the industry re-equipped its pools with higher density racks. In the high-density racks that are now routinely used around the world, the center-center spacing of fuel assemblies approaches the spacing in a reactor. To suppress criticality, the assemblies are separated by plates containing neutron-absorbing material such as boral (boron carbide particles in an aluminum matrix). The neutron-absorbing plates divide the racks into long, narrow, vertical cells, open only at the top and bottom. If water were lost from a pool, this arrangement would suppress heat transfer by convection and radiation. The presence of residual water in the lower portion of the pool, which would occur in many water-loss situations, would limit heat transfer to only one effective mechanism – convective cooling by steam rising from the residual water. Over a range of water-loss scenarios, radioactive decay heating in the SNF would cause cladding temperature to rise toward the ignition point.

The preceding discussion sets the scene for considering the attributes of a "pool fire". This incident would involve the following sequence of events:

(i) loss of water from a spent-fuel pool due to leakage, boiling away, siphoning, or

other mechanism;

(ii) failure to provide water makeup or cooling;

(iii) uncovering of SNF assemblies;

(iv) heat-up of some SNF assemblies to the ignition point of zircaloy, followed by combustion of these assemblies in steam and/or air;

(v) a hydrogen explosion (not inevitable, but likely) that damages the building surrounding the pool;

(vi) release of radioactive material from affected SNF assemblies to the atmosphere; and

(vii) propagation of combustion to other SNF assemblies.

A pool-fire event sequence would unfold over a timeframe ranging from a few hours to a number of days. During this timeframe, there would be opportunities for personnel to halt or mitigate the event sequence through actions such as plugging holes in a pool, or adding water. However, addition of water after zircaloy ignites could be counterproductive, because the water could feed combustion. Circumstances accompanying the pool-fire event sequence, such as a core-damage event sequence at an adjacent reactor, could preclude mitigating actions.

At NPPs, a spent-fuel pool is located adjacent to each reactor. In BWRs, spent fuel pools are often located adjacent to and above the reactor vessel. At PWR plants, the pool is typically located in a separate building that is outside the reactor containment but immediately adjacent to it. There may, however, be open spaces (e.g., rooms, corridors) below the pool floor, into which water could drain.

Systems to cool the water in the pool, and to provide makeup water, are integrated with similar systems that support reactor operation. Thus, cooling and water makeup to the pool would be interrupted during many of the potential event sequences that could lead to reactor core damage.

This interruption could initiate – or contribute to – a sequence of events that lead to a pool fire. As mentioned above, that sequence would unfold over a timeframe ranging from a few hours to a number of days. There would be opportunities during this period for personnel to halt or mitigate the event sequence. In some cases, simply adding water to the pool would be sufficient to prevent a pool fire. However, accompanying circumstances could prevent personnel from taking the necessary actions. For example, the site could be contaminated by radioactive material released from one or more reactors, and structures and equipment could be damaged by hydrogen explosion and/or the influence (e.g., an earthquake) that initiated the event sequence. Indeed, these circumstances arose during the Fukushima #1 accident, and substantially impeded mitigating actions by onsite personnel.

A reactor and its adjacent pool (if filled with SNF at high density) can be thought of as a coupled risk system. The reactor and the pool can affect each other in ways that increase the total risk posed by the system. To illustrate, consider the following hypothetical sequence of events. First, a reactor experiences core damage and a breach of containment. These events lead to severe contamination of the site by short-lived radioisotopes that are released from the reactor. Intense radiation fields from this contamination, together with damage from a hydrogen explosion, preclude onsite mitigating actions by personnel. The pool then boils dry, or drains due to a related influence. That outcome initiates a pool fire that leads to another hydrogen explosion and a large release of longer-lived radio-isotopes (especially Cesium-137) from the pool. Those phenomena further preclude onsite mitigating actions by personnel, thus prolonging the reactor release and, potentially, initiating releases from other reactors and pools on the site.

This hypothetical sequence of events is not far-fetched. The Fukushima #1 accident could have followed a similar course, given a few changes in site preconditions, in the initiating earthquake/tsunami, and/or in site management during the accident. In that case, the accident would have involved a much larger release of radioactive material than was actually experienced.

The potential for a linked sequence of reactor and pool events is especially ominous when one considers the possibility that a malevolent group of people would deliberately trigger the sequence. A technically knowledgeable and operationally capable group could focus and time an attack in such a manner that both a reactor release and a pool fire would be likely outcomes. The group's investment of resources would be small by comparison with the damage inflicted on the attacked country. Thus, from a military-strategic perspective, a reactor and an adjacent pool filled with SNF at high density are, taken together, a large, pre-emplaced radiological weapon awaiting activation by an enemy.

Public awareness of SNF radiological risk was low before the 2011 accident at the Fukushima Dai-ichi (#1) nuclear site in Japan. Awareness grew during that accident, as citizens learned that SNF was stored in pools adjacent to the affected reactors, and that there was a potential for a large release of radioactive material from this SNF to the atmosphere.

The present level of SNF radiological risk is not inevitable. Instead, it reflects choices made by the nuclear industry and accepted by regulatory organizations. Options are available whereby the risk could be substantially reduced. Some options would affect the operation of NPPs, while others would not.

Handbook and Methodology for Simplified Radiological Risk Assessment

The Handbook prepared for this Project by Dr. Thompson addresses a range of technical issues. As can be seen from the summary above, each issue is complex, and is associated with a substantial technical literature and body of practical experience. By contrast, the Handbook avoids much of the complexity, and sets forth a comparatively simple approach to assessing SNF radiological risk is set forth, involving various assumptions and simplifications. With this approach, analysts can assess the risk using a sequence of hand calculations and judgments that is easy to follow. The findings could be used for a variety of public policy purposes. The findings from application of the Handbook methodology should not, however, be used in situations where a more detailed analysis is required.

Under this project, the risk of radiological release following accident at or attack on nuclear facilities has been assessed by compiling qualitative and quantitative information regarding the radiological consequences of accidents at or attacks on key facilities under different scenarios of nuclear fuel cycle development. The Handbook developed by Dr. Thompson identifies major factors that determine the potential for an unplanned release of radioactive material, and the impacts of such a release, including "internal" and "external" initiators that are examined in a typical risk assessment of a release caused by forces of nature, deliberate, malevolent acts of various types, and/or gross errors on the part of plant operators. The analytical steps for determining radiological risk as identified by Dr. Thompson are as follows:

Step 1: Specify the system

Step 2: Characterize SNF in the system

Step 3: Assess the potential for atmospheric release of radioactive material

Step 4: Estimate the behavior of a radioactive plume

Step 5: Characterize downwind assets

Step 6: Assess harm to downwind assets

Step 7: Assess collateral implications of SNF radiological risk

For some of these steps, Thompson has provided quantitative tools for estimating key parameters and results, while for other steps—including steps 5 and 7 above—more qualitative approaches or other quantitative tools are likely to be needed.

As noted above, the Handbook has been used by the Project Team, together with an array of nuclear fuel cycle and nuclear energy development scenarios from each of the participating nations, as well as other data, to produce illustrative assessments of the radiological risk at key nuclear facilities in Japan, South Korea, and China under different scenarios.

A guidance document entitled *Instructions for Workbook to Calculate Aspects of SNF Radiological Risk* was prepared by Thompson to complement the Handbook, and incorporates portions of the seven-step process described above into a workbook consisting of a Microsoft Excel file. Instructions for use of the workbook are set out in the guidance document. The workbook calculates aspects of SNF radiological risk that are amenable to numerical calculation using a spreadsheet. Substantial portions of the Handbook's seven-step process are amenable to this approach, as will be seen below. Other portions of the seven-step process require a user to exercise informed judgment or obtain information from other sources. Thus, the workbook is a useful aid in assessing SNF radiological risk, but Thompson stresses (as do the authors of this Summary Report) that it does not substitute for judgment and knowledge.

2.3 Radiological Risk Attitudes and Estimate in China

A pair of illustrative calculations of radiological risk were carried out for Chinese reactors by Nautilus project staff, and are described below. The first of these was for the oldest large plant in China, the Daya Bay plant near Hong Kong and Guangzhou. The Daya Bay plant is a BWR facility, but does not use dense packing in its spent fuel pools, sending cooled fuel to an off-site facility instead. The second calculation was for the Ling'Ao nuclear plant, a newer facility adjacent to the Daya Bay plant, and thus near to the same major cities. The Ling'Ao reactors use dense-packed spent fuel pools.

Some nuclear experts in China (and elsewhere) take the overall attitude, that while radiological risks are admittedly substantial in extreme events, those events are improbable, and the risks of more probable nuclear release events (with more limited impacts) are fairly manageable, particularly in relation to other risks (climate change, energy supply security, and local air pollution among them) that China chronically faces. Although we are mindful of and understand this point of view, we feel that an exploration of the potential consequences of accident at or attack on nuclear facilities is worthwhile, even if the underlying event is improbable, as one (of many) inputs to policymaking.

Interestingly, though not unexpectedly, the topic of radiological risk assessment in the event of accident or attack is not new to China, as in 2005 a Chinese team prepared and published in a Chinese scientific journal an assessment of the potential implications of a terrorist attack on a Chinese nuclear power plant, and specifically, on a spent fuel pool.[15] Investigating three scenarios in which the spent fuel in the pool was subject to different degrees of damage, the authors of the paper found radiuses in which the effective dose was greater than 50 mSv were about 80, 34, and 9 km, respectively.

[15] Zheng Qiyan, Shi Zhongqi, and Wang Xingyu (2005), "Consequence Assessment of Attacking Nuclear Spent Fuel Pool by Terrorists", *Radiation Protection*, Volume 25, No. 1, January 2005 (in Chinese). Available as http://www.cnki.net/kcms/detail/detail.aspx?dbcode=CJFQ&dbName=CJFQ2005&FileName=FSFH200501007&v=MTY4MjdSvMkjPs1msbge1Myuj0VjhH4PfT67H2eYTHtMduOrETQWsJREvp9j52cWKOc=&uid= and .http://caod.oriprobe.com/articles/575372/CONSEQUENCE_ASSESSMENT_OF_ATTACKING_NUCLEAR_SPENT_FUEL_POOL_BY_TERRORI.htm. A rough, partial translation is available from Nautilus upon request.

2.3.1 Radiological Risk Estimate for Daya Bay Nuclear Power Station

Reactor and Spent Fuel Pool Operational Parameters

The Daya Bay Nuclear Power Station is located on a coastal site in Guangdong province, close to Hong Kong (see **Error! Reference source not found.**). The Daya Bay units use the French -310 PWR design, and each unit has a gross generation capacity of 984 MWe and thermal capacities of 2905 MWth. Historically, capacity factors at the plants have averaged about 85 percent since their first operation in 1994. Spent fuel in the Daya Bay plants is stored in at-reactor spent fuel pools. Based on data from the World Nuclear Organization, "A standard 18-month fuel cycle is the normal routine for Daya Bay, Ling'Ao, and early M310 to CPR-1000 reactors. This has average burn-up of 43 GWd/t, with maximum of 50 GWd/t".[16] For this analysis, we assume an average burn-up of 43 GWd/tHM. The reactor core in each unit contains 72.4 tHM.[17] We assume that 40% of the fuel in each of the Daya Bay reactors is replaced every 18 months, which implies that the fuel that is removed during refueling has been in the reactor for about 45 months, that the burnup in the fuel removed from the cores is about 1,342 GWth-days, and that there is about 2,282 total GWth-days of burnup in the core at the time of refueling, under routine loading/discharge conditions.

The spent fuel pools at the two Daya Bay units are reported to contain 282 and 284 tHM of spent reactor fuel, respectively, which is consistent with the pools, being essentially full.[18] As a result, cooled spent fuel is removed from the spent fuel pools and sent to away-from-reactor storage at Lanzhou or another storage location. We assume that the transport casks used for Daya Bay spent fuel transport to Lanzhou or another location are of the NAC-STC type.[19] These casks hold 26 assemblies each, meaning that they hold about 12 tHM each, and thus to hold a refuelings' worth of cooled spent fuel from the spent fuel pool for 2 reactors will require just under 5 casks. This is roughly consistent with the 104 assemblies per year (apparently) reported by Zhou.[20]

The combination of the assumptions regarding reactor loading/unloading and spent fuel management listed above yields the Cesium-137 (Cs-137) inventories shown in Figure 2-3. Here, radioactivity in the reactor core builds up after refueling until the next refueling cycle (the area shown in red), while the radioactivity in the spent fuel pool, as well as in the combined reactor and spent fuel pool, varies by a few hundred PBq (petabecquerel) over the load/unload

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[16] World Nuclear Organization (2015), "China--Nuclear Fuel Cycle, available as http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China--Nuclear-Fuel-Cycle/.

[17] Nuclear Division of The Hong Kong Institution of Engineers (HKIE) (2008), "Guangdong Nuclear Power Base", available as http://home.pacific.net.hk/~nuclear/info0211.htm.

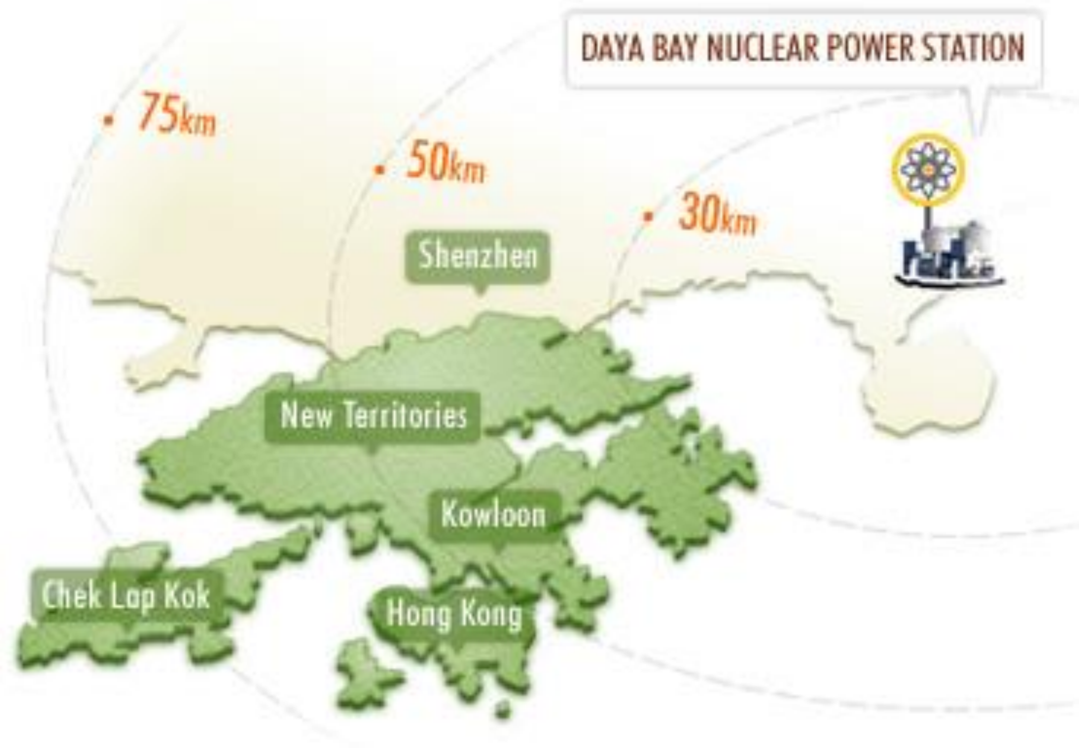
[18] See, for example, "Daya Bay Nuclear Power Plant Unit 2 Reactor" at http://nuclear-power-plants.findthedata.com/l/599/Daya-Bay-Nuclear-Power-Plant-Unit-2.

[19] See Liu Xuegang (2012), *China's Nuclear Energy Development and Spent Fuel Management Plans*, Nautilus Special Report available as http://nautilus.org/napsnet/napsnet-special-reports/chinas-nuclear-energy-development-and-spent-fuel-management-plans/.

[20] Yun Zhou (2011), "China's Spent Nuclear Fuel Management: Current Practices and Future Strategies", Working Paper, Center for International and Security Studies at Maryland, dated March 2011, includes "Since then [2003], the plant has transported 104 assemblies of spent fuel twice a year to the interim storage pool.".

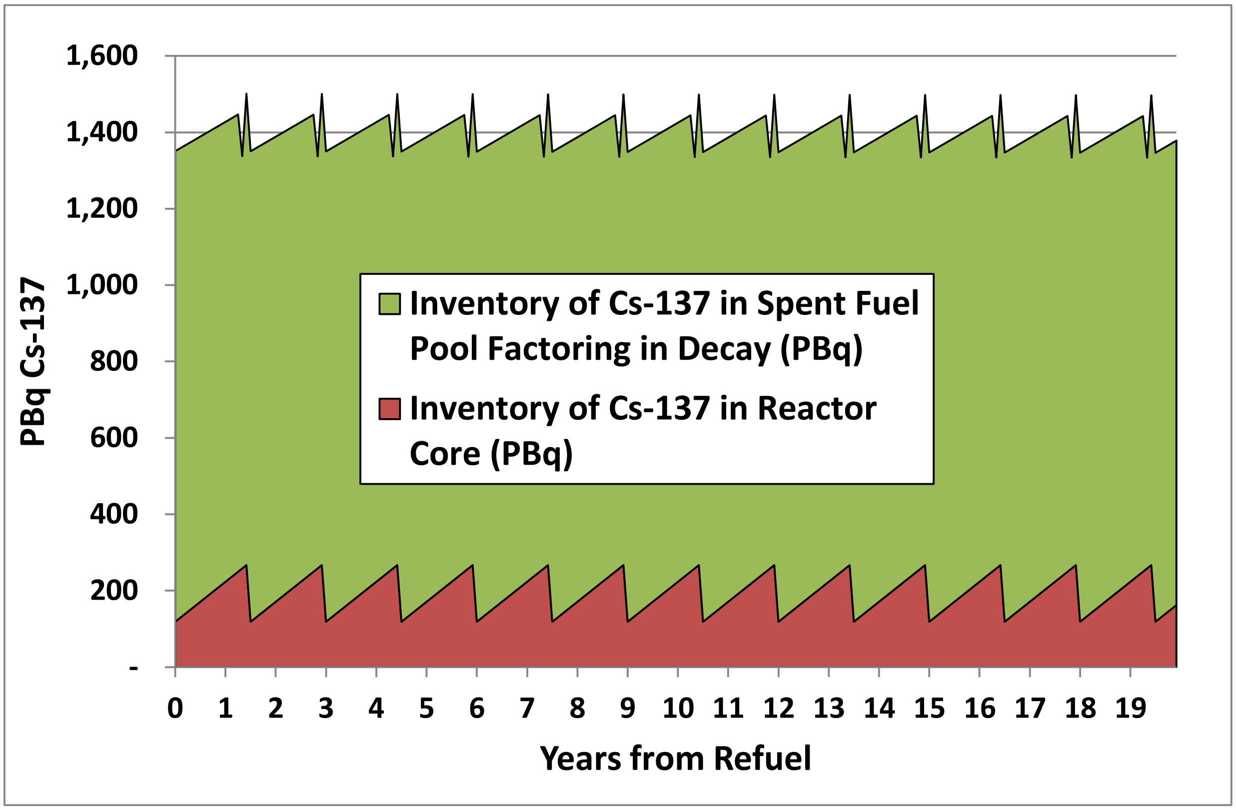
cycle, with an average of around 1400 PBq. See Annexes 1A and 1C to this Report for additional details of input data and assumptions beyond those presented here.

Figure 2-2: Location of Daya Bay (and Ling'Ao) Nuclear Power Stations[21]



[21] Figure from https://www.hknuclear.com/dayabay/location/pages/locationsiteselection.aspx.

Figure 2-3: Cs-137 Inventory in Daya Bay Reactor Core and Spent Fuel Pool as Modeled (Unit #2 shown, Unit #1 would be similar)



Incident Modeling Assumptions

We consider two main scenarios for incidents involving the Daya Bay reactors and spent fuel pool. For the first scenario, which we call "Worst-case Reactor Incident" (or "S1"), one of the reactors is assumed to suffer a core breach and subsequent loss of coolant due to an extreme seismic event or attack. In this case, the spent fuel pool may or may not suffer a loss of coolant, either through being breached by the same event or by losing cooling capacity when utilities (power and/or water) are lost as a result of the incident, but because the spent fuel pool is not dense-packed, the spent fuel in the pool is able to cool in air and a zirconium cladding fire does NOT ensue. We assume, in scenario 1, since the two Daya Bay units are physically separated, that the second reactor core remains intact, and standard or emergency cooling can be maintained, even if there is damage to the second reactor. This scenario therefore does not include common mode failures--such as the interruption of pumping and water utilities affecting both units, coupled with radiation or other conditions that prevent emergency cooling measures from being undertaken.

For the second scenario, which we call "Worst-case Spent Fuel Pool Incident" (or "S2"), we assume that as a result of a seismic event, catastrophic operational accident (such as dropping a transport cask into the pool), or terrorist attack, the pool suffers a coolant loss and cooling cannot be restored before cooling water mostly or completely evaporates. Further, those regions of the stored spent fuel that have been most recently (within the past few months) off-loaded from the two reactors are assumed to reach temperatures high enough for cladding failure and ignition, resulting in a zirconium fire that engulfs an amount of spent fuel equal to the most recent off-loading. The "Participation Fraction" (The variable "PART FRAC", in the analytical Handbook and workbook prepared by Gordon Thompson) of the material in the spent fuel pool is assumed to be a function of the density of racking in the pool. We assume that the racking continues to be low-density in both scenarios.

In S1 we assume that even if the incident focused on a reactor does cause a loss of coolant in a spent fuel pool, passive cooling in air is sufficient that the cladding does not reach ignition temperature, and thus the Participation Fraction for each of the spent fuel pools in S1 is zero, and the release fraction (fraction of radioactive material in the spent fuel pool released to the atmosphere) is similarly zero. In S2, however, we assume that the most recently off-loaded spent fuel, a total of 28.96 tHM, does participate in a pool fire. The Participation Fraction for the spent fuel pool (assumed to be unit 2) in scenario 2 would therefore be 0.10. In this scenario involving cladding failure and significant Cs-137 emissions (S2), a release fraction of 0.3 is assumed. We assume that in this scenario only the spent fuel pool for the first unit is affected, and thus the participation and release fractions for the spent fuel pool for the first unit are both zero.

For one of the reactors, for S1, we assume that it experiences a core melt, and thus its participation fraction is 1, though the participation fraction for the second reactor is assumed to be zero, and the release fraction is similarly zero.

Based on consideration of Table II.3-7 in the Handbook, as well as estimates of fraction of the Cs-137 inventory in the Fukushima reactor cores that were released to the atmosphere,[22] we assume a release fraction of 0.05 for one of the reactors for S1, which assume an incident that would breach containment and the reactor vessel, and severely damage the reactor and the fuel within. For the both of the reactors, for S2, we assume that the incident involving one of the spent fuel pools does not affect the reactors enough to cause a core melt (or emergency procedures are sufficient to prevent a core melt if the reactors is damaged), and thus the participation fraction for both reactors is by definition zero. The release fraction ("REL FRAC") for S2 for the reactors is assumed to be zero, since neither reactor is assumed to undergo a core melt.

In either scenario, though dry casks or transport casks are present at the time of the incident (and transport casks, at least, may well be), we assume that the casks will be sufficiently distant from the reactor and spent fuel pool and/or sufficiently robust that their participation and release fractions are all zero. A possible exceptional case might be if the incident (accident or attack) occurs the period when transport casks are being loaded, in which case, depending on where they are physically located near the spent fuel pool and how much fuel is in them at the time of the incident, there could be additional complications. The spent fuel placed in transport casks,

[22] See, for example, Stohl et al, 2012 (http://www.fukushimaishere.info/AtmosphereRprt_mar12.pdf), and Koo et al, 2014 (abstract at http://www.sciencedirect.com/science/article/pii/S0149197014000444).

however, has been cooled for several years, and is thus likely to be passively cooled if coolant is lost. The spent fuel in a not-yet-closed transport cask might be vulnerable to terrorist attack with an incendiary device that would ignite the cladding in the spent fuel in the cask, but this eventuality is not explicitly considered in our scenarios.

We assume an average wind speed of 3.4 meters/second, based very roughly on considerations of recent annual windspeed values for the spring and fall (when prevailing winds are mostly East to West for Shanwei, which is east along the coast from Daya Bay, and for Hong Kong, which is West and South from Daya Bay.[23] An older document entitled *Environmental Radiation Monitoring in Hong Kong, Technical Report No. 3, Surface Meteorological Conditions in Daya Bay, 1984-1988,*[24] suggests that average wind speeds in Daya Bay are more likely to be similar to those in Shanwei than in Hong Kong. This wind speed is equivalent to 12.07 km/hour. We use a deposition velocity ("DEP VEL") of 1 cm/second, or 0.01 meter/second, which is a typical value used with the wedge model.

Nearby Populations

The Daya Bay (and Ling'Ao) nuclear stations are located in heavily populated Guangdong Province. We assume a prevailing wind at the time of the incident from the east or northeast, which is common in the area for most times of year except the summer (June through August), when winds from the southwest prevail. There are some smaller population centers—with tens of thousands of residents—within about 30 km of the plans, and major population centers—multi-million-resident Shenzhen and Zhongshan to the West, and Hong Kong to the Southwest—starting at about 40 km from the plants. Figure 2-4 shows a satellite view of the near-plant area and the nearest nearby community, about 6 km away. Figure 2-5 shows a map of the area overlaid with trajectories for emissions clouds traveling in two potential directions, assuming wedge angles of about 0.25 radians. Note that the impacts associated with these two trajectories are not additive—they represent different trajectory scenarios, but each is associated with winds that are not uncommon in the area.

[23] Data from http://www.windfinder.com/windstatistics/.
[24] B.Y. Lee, M.C. Wong and W.Y. Chan of the Royal Observatory, Hong Kong, dated July, 1991, and available as http://www.hko.gov.hk/publica/rm/rm003.pdf.

Figure 2-4: Google Earth Image of the Daya Bay/Ling'Ao Complex (Yellow Oval) and Nearby Community (Red Circle)

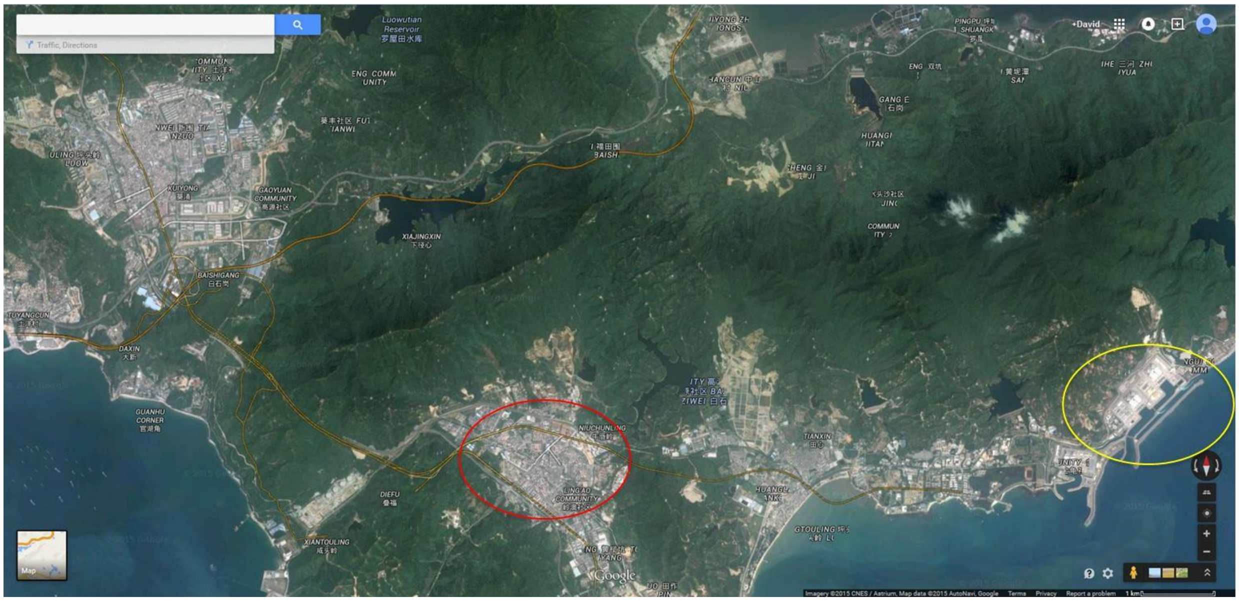
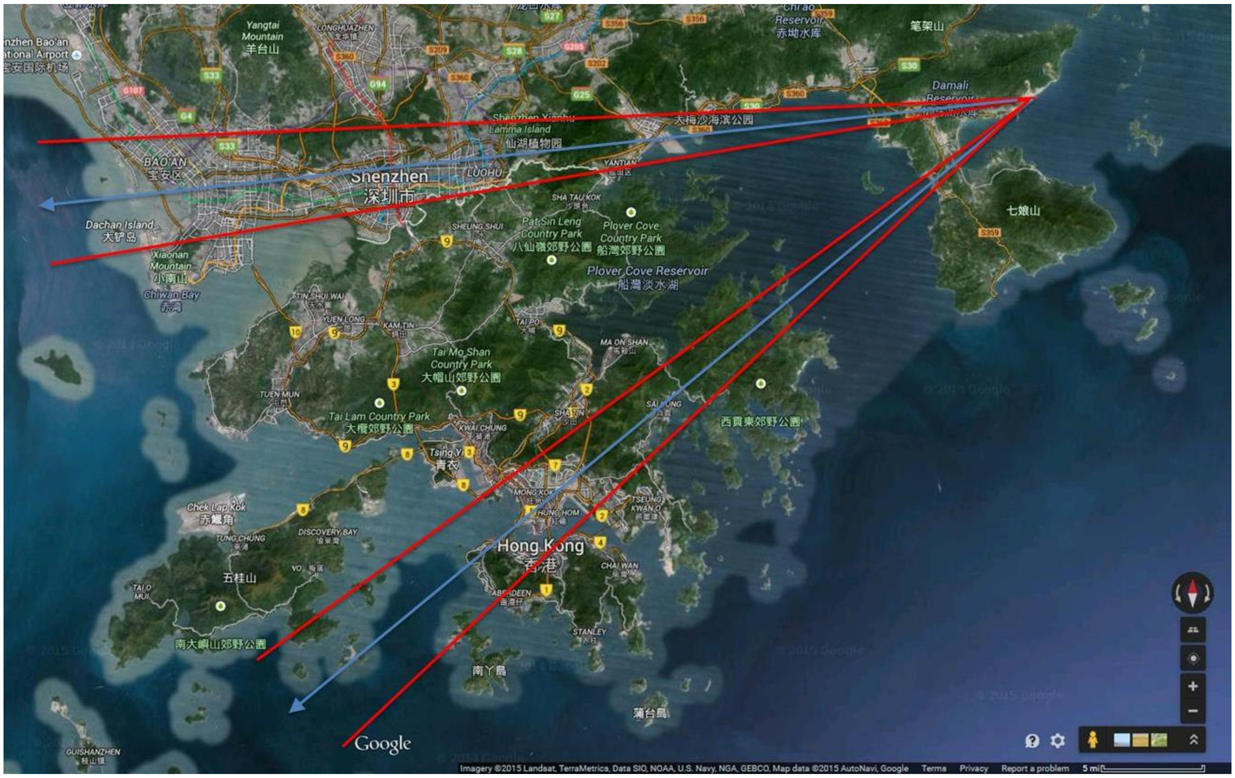


Figure 2-5: Google Earth Image of the Daya Bay/Ling'Ao/South Guangdong/Hong Kong Area with Assumed Directions of Emissions Clouds



Modeling Results

Table 2-1 summarizes the atmospheric releases of Cs-137 in each of the two scenarios evaluated for incidents occurring at various time intervals after the first refueling modeled. Because the inventory of radioactivity in the Daya Bay reactor cores vary significantly over the refueling cycle, the total release in Scenario 1, which affects the reactor core, can change depending on when the incident occurs. The spent fuel pool inventory of Cs-137 varies relatively little over the refueling cycle, because cooled fuel is removed whenever new spent fuel is added to the pool, so the variation of emissions of Cs-137 depending on when the release occurs is relatively small for Scenario 2.

Table 2-1: Summary of Cs-137 Emissions Results from Both Scenarios Based on Timing of Incident

	Atmospheric Emissions of Cs-137 (PBq) for an Incident Occuring				
Scenario	1 year after refueling	3 years after refueling	5 years after refueling	10 years after refueling	20 years after refueling
S1: Worst-case Reactor Incident	10.7	13.3	8.1	10.7	8.1
S2: Worst-case Spent Fuel Pool Incident	36.9	37.7	37.3	36.8	37.2

Figure 2-6 and Figure 2-7 show the estimated ground contamination from a radiological release incident at one of the Daya Bay reactors for Scenario 1 (reactor incident) and Scenario 2 (spent fuel pool incident), respectively. In both cases, an incident 20 years after the first refueling modeled would produce similar results to those shown.

Figure 2-6: Estimated Ground Contamination from a Radiological Release Incident at One of the Daya Bay Reactors Involving the Reactor Core (Scenario 1)

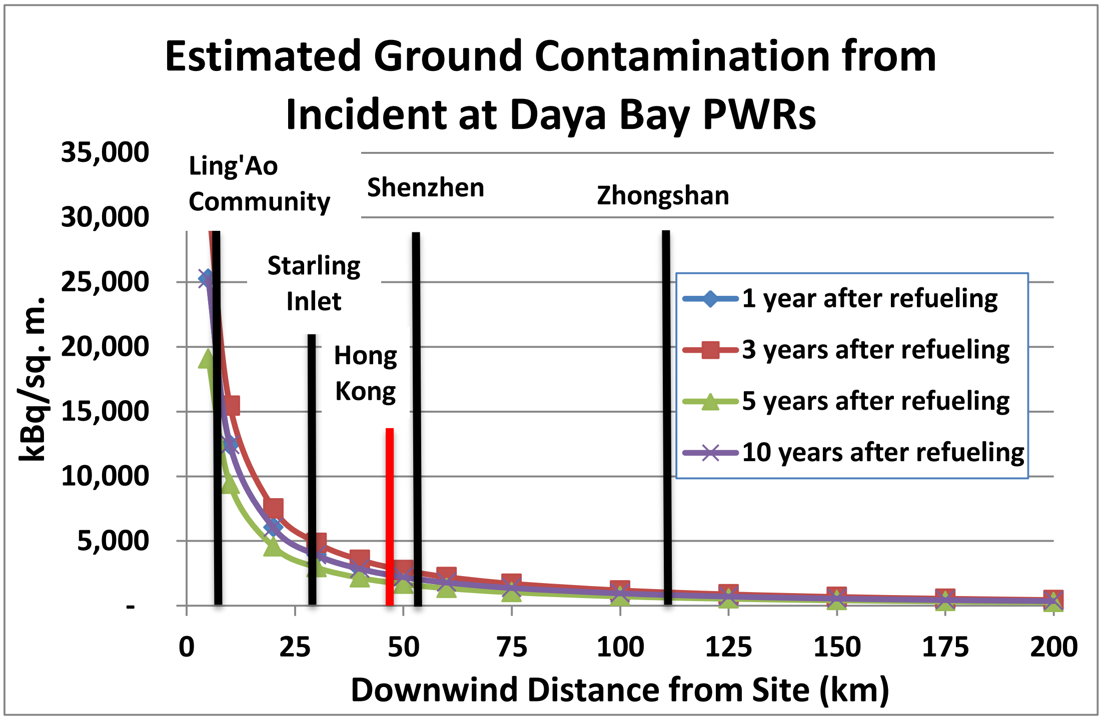


Figure 2-7: Estimated Ground Contamination from a Radiological Release Incident at One of the Daya Bay Reactors Involving the Spent Fuel Pool (Scenario 2)

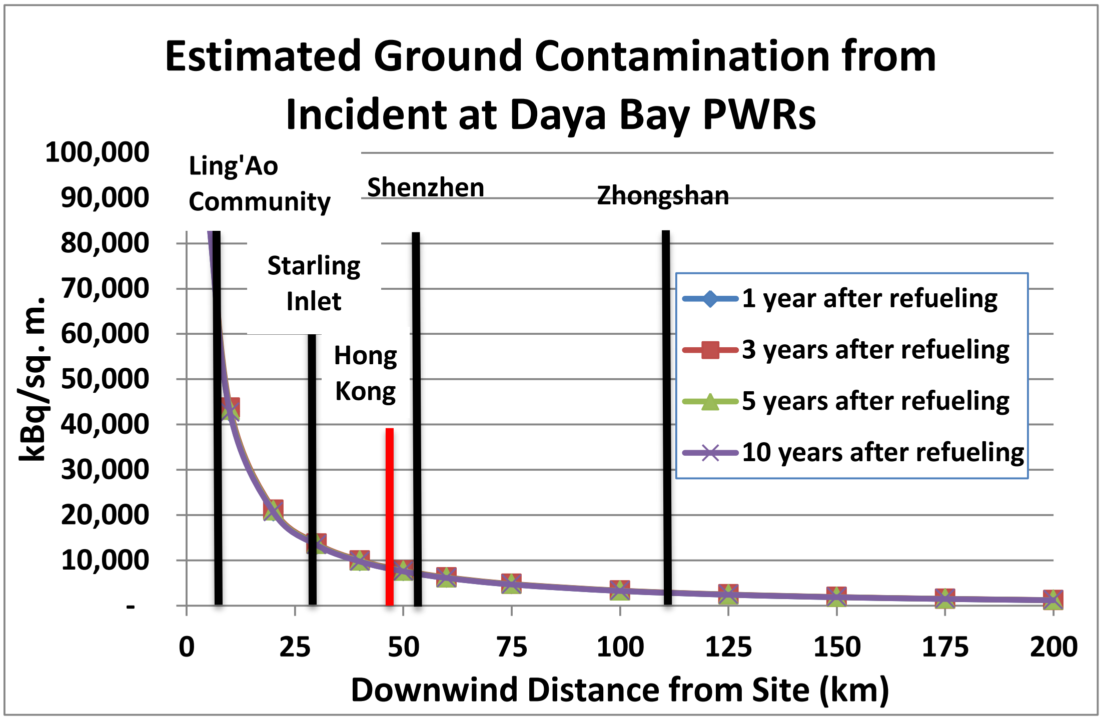


Figure 2-8 and Figure 2-9 show the estimated first-year dose for a person at various distances from the Daya Bay reactors for incidents involving releases of Cs-137 from a reactor core and a spent fuel pool, respectively. USEPA recommendations indicate that a first-year dose of 20 mSv (millisievert) is the threshold triggering abandonment of lands[25]. For scenario 1, varying somewhat with when during the refueling cycle the incident occurs, the modeled area over 20 mSv falls just short of the heavily populated areas near Daya Bay. The radius of land area nominally contaminated to a dose threshold of 20 mSv would be about 30-40 kilometers in this scenario. In Scenario 2, involving the spent fuel pool of one of the reactors, the radius contaminated to a dose threshold of 20 mSv expands to about 100 km, intersecting with the major population centers of Shenzhen (for a prevailing wind blowing toward the west) and Hong Kong (for a wind blowing to the southwest), but falling short of the Zhongshan area.

[25] Gordon Thompson (2013, ibid) describes the EPA's threshold value as follows: "In its guidance manual for nuclear incidents, the US Environmental Protection Agency (EPA) recommends that the general population be relocated if the cumulative 1st-year dose to an individual at a radioactively-contaminated location is projected to exceed 0.02 Sv. EPA states that the projected dose should account for external gamma radiation and inhalation of re-suspended material during the 1st year, but should not account for shielding from structures or the application of dose reduction techniques." (Note (f) for Table II.6-6.) The description refers to the US Environmental Protection Agency document, *Manual of Protective Action Guides and Protective Actions for Nuclear Incidents* (Washington, DC: EPA, Revised 1991, Second printing May 1992).

Figure 2-8: First-year Estimated External Dose from a Radiological Release Incident at One of the Daya Bay Reactors Involving the Reactor Core (Scenario 1)

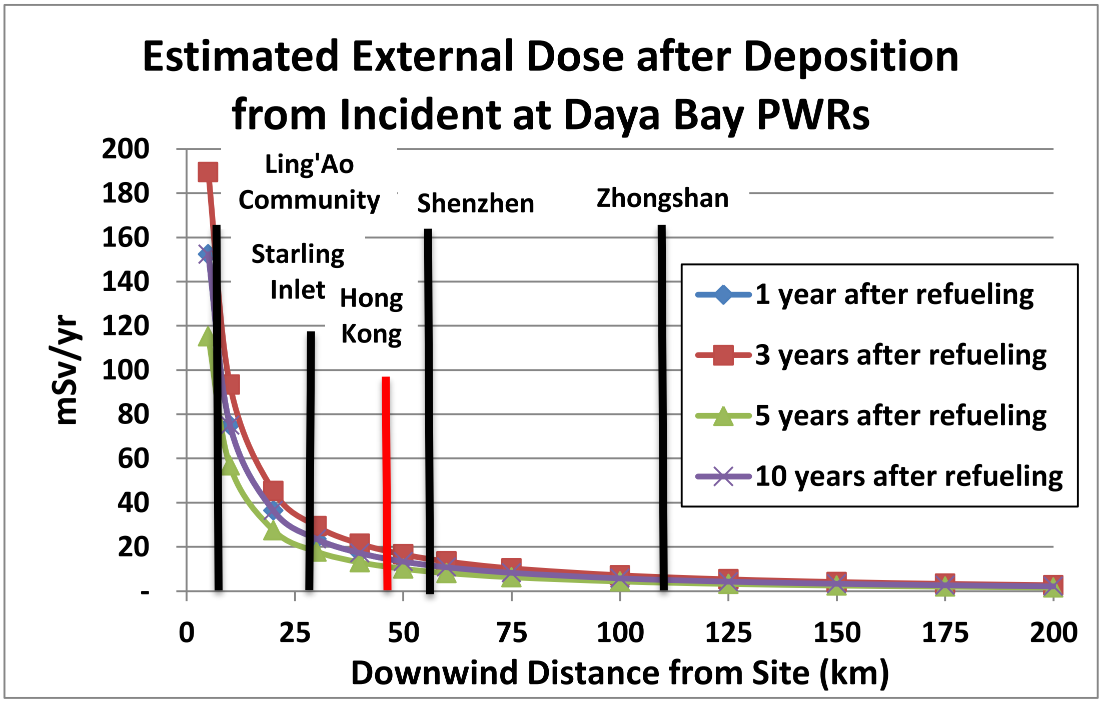


Figure 2-9: First-year Estimated External Dose from a Radiological Release Incident at One of the Daya Bay Reactors Involving the Spent Fuel Pool (Scenario 2)

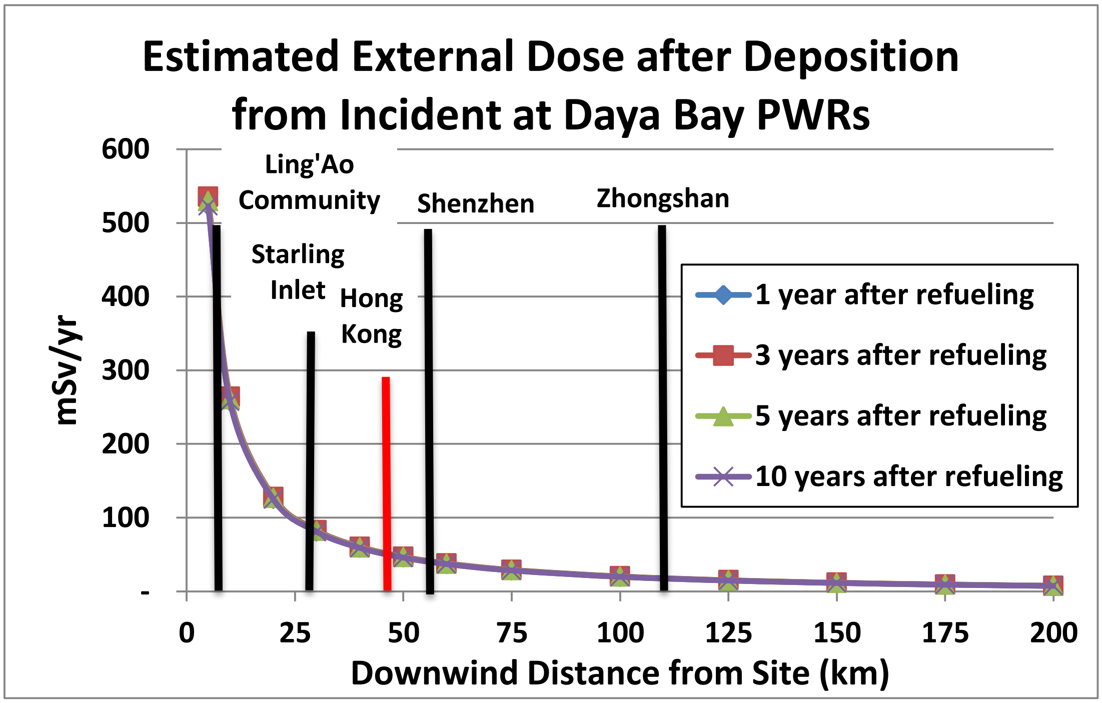


Figure 2-10 and Figure 2-11 show the cumulative dose over time for exposures resulting from radiological release incidents involving one of the Daya Bay reactors and one of the spent fuel pools, respectively. Here, even for Scenario 1, exposure at the major nearby population centers up to about the center of Zhongshan exceed the USEPA's cumulative 50 mSv 50-year dose guideline for an exposed individual[26], with cumulative doses under Scenario 2 considerably exceeding the USEPA guidelines over a radius of over 200 km. In both cases, releases were modeled as occurring 3 years after the first refueling modeled.

[26] As described by Gordon Thompson (2013, ibid).

Figure 2-10: Cumulative Estimated External Dose from a Radiological Release Incident at One of the Daya Bay Reactors Involving the Reactor Core (Scenario 1)

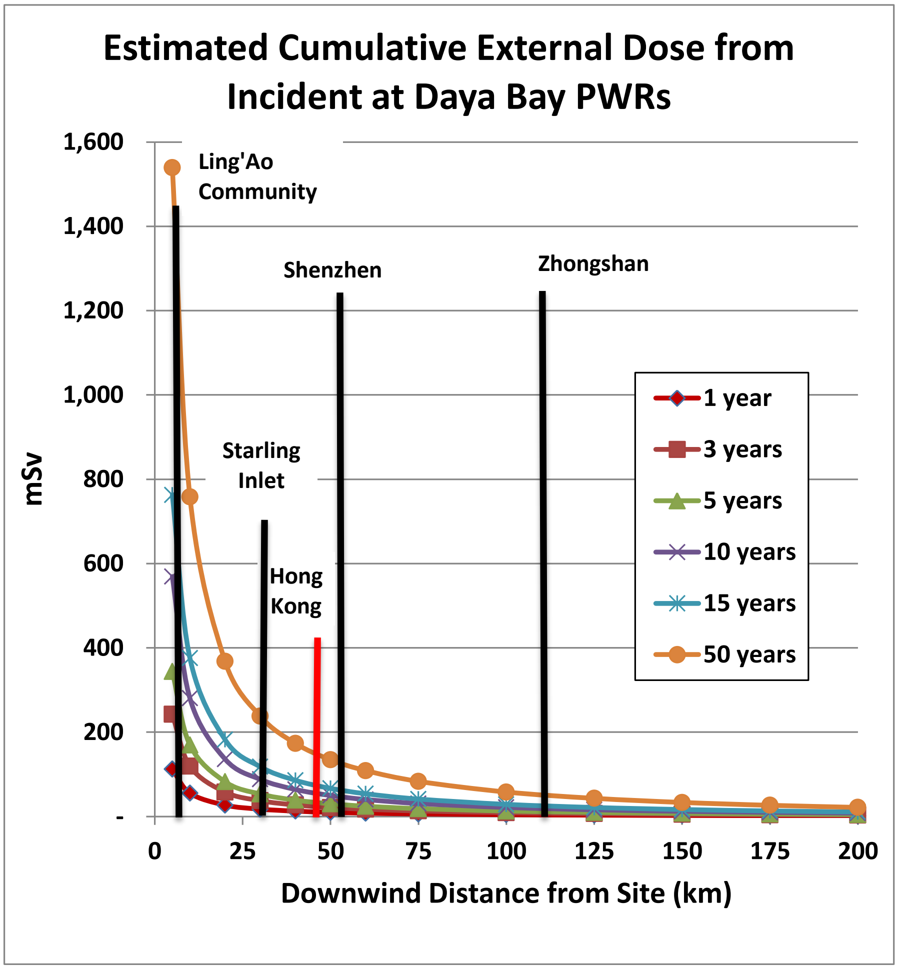


Figure 2-11: Cumulative Estimated External Dose from a Radiological Release Incident at One of the Daya Bay Reactors Involving the Spent Fuel Pool (Scenario 2)

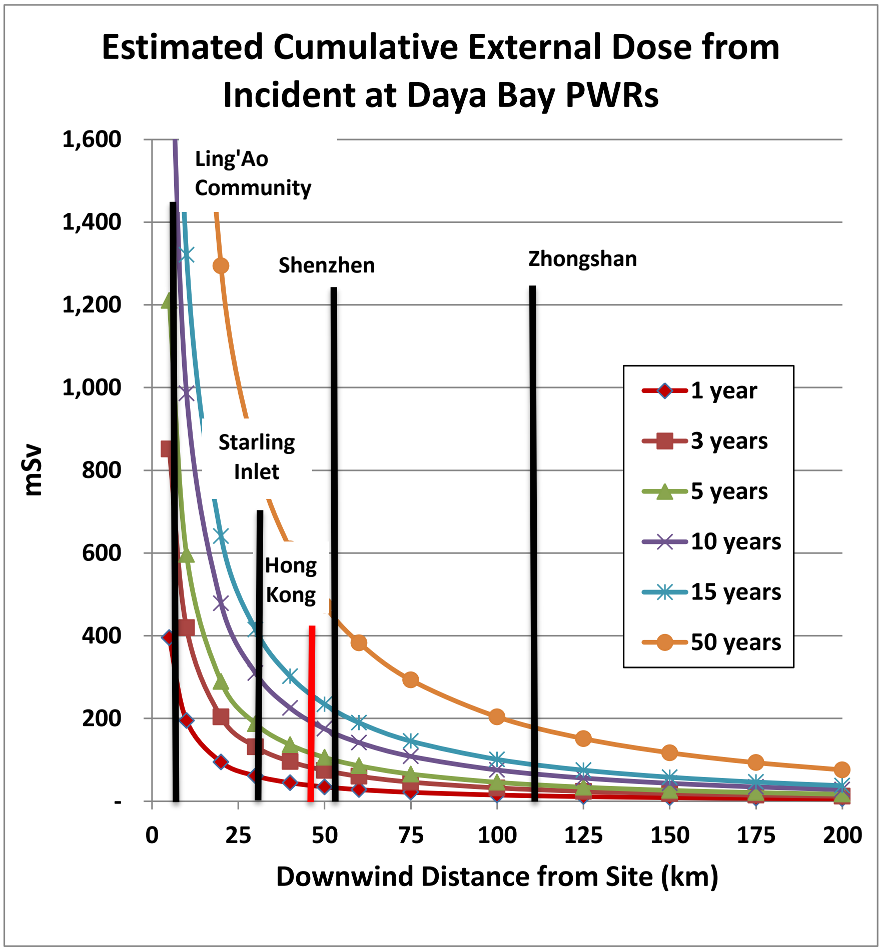


Table 2-2 and Table 2-3 estimate the number of early, or premature,[27] deaths from cancers resulting from the exposures associated with reactor and spent fuel pool incidents at Daya Bay. For a reactor incident, about 30,000 premature deaths (in the communities included in this assessment) result at rates ranging from about 7% in the community closest to Daya Bay to under 1% in the nearby big urban areas. For the scenario postulating an incident involving a spent fuel pool, the impacts are greater, with about 80,000 premature deaths in the included communities, and rates of premature death of more than 20% in the closest community and more than 2 percent in the big nearby cities.

[27] That is, deaths that occur earlier than they would otherwise would have occurred as a result of a radiation-induced cancer.

Table 2-2: Calculation of Collective Dose at Selected Locations along Deposition Paths from Daya Bay for Release 3 Years after First Refueling Modeled for Scenario 1, Reactor Incident

	Diameter (km)		Population Density	First Year Collective Radiation Dose
Location	Inner	Outer	persons/km^2	person-Sv/yr
Ling'Ao Community	5.5	7.5	10,308	4,862
Starling Inlet	28	32	1,333	1,173
Shenzhen	40	64	7,500	37,072
Zhongshan	104	120	3,600	9,918
Hong Kong	44	52	32,720	54,547

	Cumulative Collective Radiation Dose	Exposed Population	Percent Premature Deaths	Implied Number of Premature Deaths
Location	person-Sv	People	%	
Ling'Ao Community	49,122	33,500	7.478	2,505
Starling Inlet	11,848	40,000	1.511	604
Shenzhen	374,555	2,340,000	0.816	19,102
Zhongshan	100,206	1,612,800	0.317	5,111
Hong Kong	551,118	3,141,120	0.895	28,107
TOTAL of first four locations (not total of exposed area)	535,731	4,026,300	0.679	27,322

Table 2-3: Calculation of Collective Dose at Selected Locations along Deposition Paths from Daya Bay for Release 3 Years after First Refueling Modeled for Scenario 2, Spent Fuel Pool Incident

	Diameter (km)		Population Density	Initial Collective Radiation Dose
Location	Inner	Outer	persons/km^2	person-Sv/yr
Ling'Ao Community	5.5	7.5	10,308	13,745
Starling Inlet	28	32	1,333	3,315
Shenzhen	40	64	7,500	104,804
Zhongshan	104	120	3,600	28,039
Hong Kong	44	52	32,720	154,209

	Cumulative Collective Radiation Dose	Exposed Population	Percent Premature Deaths	Implied Number of Premature Deaths
Location	person-Sv	People	%	
Ling'Ao Community	138,872	33,500	21.142	7,082
Starling Inlet	33,495	40,000	4.271	1,708
Shenzhen	1,058,891	2,340,000	2.308	54,003
Zhongshan	283,290	1,612,800	0.896	14,448
Hong Kong	1,558,049	3,141,120	2.530	79,460
TOTAL of first four locations (not total of exposed area)	1,514,549	4,026,300	1.918	77,242

As with the estimates of radiological exposure prepared for nuclear plants in Japan and the DPRK, as described in subsequent sections of this Chapter, we prepared rough estimates of damages related to premature human deaths based on two estimates of the "value of a statistical life" compiled in a review of a number of studies. One of these values is from the United States (about $10 million per person in 2012 dollars) and one is from the ROK (about $1.1 million per person).[28] These particular values were not chosen as representative of or applicable to the residents of any given county—they just represent an illustrative range from the estimates that have been prepared. Applying these estimates—and remembering that these calculations include both the extrapolation of the calculation of premature deaths to very low doses of radioactivity *and* the application of the value of a statistical life, each of which involves many assumptions about which there is considerable debate—yields values in the range of $30 to $400 billion for an incident involving a Daya Bay reactor, and perhaps $80 billion to $1 trillion for an incident involving a spent fuel pool. These totals do not factor in population areas that the plume of

[28] ROK value from p. 27 of W. Kip Viscusi and Joseph E. Aldy (2003), "The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World", *The Journal of Risk and Uncertainty*, 27:1; 5–76, 2003, one version of which is available as http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0483-09.pdf/$file/EE-0483-09.pdf. The US value roughly of $10 million per premature death from solid cancer corresponds to the high end of a range cited in Gordon R. Thompson (2013), Handbook to Support Assessment of Radiological Risk Arising from Management of Spent Nuclear Fuel, and is used in the Methodology set out in the Handbook.

material released will encounter that are not included in the Tables above. Note, however, that the range of values per excess death that has been used here is adopted with no attempt to adapt it to Chinese conditions or practices. It is important for readers to keep in mind that the range of premature deaths and value thereof is enormous in this sensitivity analysis due to the combination in the calculations of high-low dose response assumptions with high-low estimated values of excess deaths.

2.3.2 Radiological Risk Estimate for Ling'Ao Nuclear Power Station

Reactor and Spent Fuel Pool Operational Parameters

The Ling'Ao Nuclear Power Station is located 1 km east of the Daya Bay Power Station on the coast of Guangdong Province. The Ling'Ao station was built in two phases. Phase I included two nuclear units of 990 MWe gross capacity each, which entered commercial operation in May of 2002 and January of 2003, respectively.[29] Phase II, with two additional units, was added in 2010 and 2011. The analysis below, however, focuses on the Phase I reactors.

The Ling'Ao Phase I units are model CPR-1000 units based on the French 900 MWe three-cooling loop PWR design.[30] Their output is sent to Guangdong Province. Figure 2-12 shows a photo of the Ling'Ao Phase I reactors and related buildings. Through 2013, the two Phase I reactors operated at capacity factors averaging 88 and 89 percent. Spent fuel in the Daya Bay plants is stored in at-reactor spent fuel pools. Based on data from the World Nuclear Organization, as noted above (and like the Daya Bay plants), the Ling'Ao plants use a standard 18-month fuel cycle and, we assume an average burn-up of 43 GWd/tHM and U-235 enrichment of 4.45%. The reactor core in each unit contains 72.4 tHM. As with the Daya Bay plants, we assume that 40% of the fuel in each of the reactors is replaced every 18 months, which implies that the fuel that is removed during refueling has been in the reactor for about 45 months, that the burnup in the fuel removed from the cores is about 1,396 GWth-days, and that there is about 2,374 total GWth-days of burnup in the core at the time of refueling, under routine loading/discharge conditions.

[29] See, for example, the IAEA reactor database documents http://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=63, and http://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=67; and http://nuclear-power-plants.findthedata.com/l/601/Ling-ao-Nuclear-Power-Plant-Unit-1.

[30] See, for example, Nuclear Threat Initiative (NTI, 2012), "Ling Ao Nuclear Power Plant (LANPP)", available as http://www.nti.org/facilities/780/, and Government of Hong Kong Special Administrative Region (2015), "Daya Bay Contingency Plan: Nuclear Power Plants", available as http://www.dbcp.gov.hk/eng/safety/plants.htm.

Figure 2-12: Photo of Ling'Ao Phase I Nuclear Power Units[31]

Given the time that the reactors have been operating, the implied number of discharges for reactor 1 would be 7.79 through 1/1/2014, with 7.34 discharges for reactor 2, or a total of 15.13 discharges as of the end of 2013. This implies that the inventory of spent fuel in the two pools as of that time was 21,121 GWth-days, equivalent to 405.44 tHM discharged total, or 202.72 tHM for reactor 1 and 202.72 for reactor 2 (counting full discharges only). Framatome reports spent fuel pool capacity of 1200 assemblies (presumably per reactor), which appears to correspond to about 553.38 tHM per pool (one pool per reactor).[32] The description provide by Framatome suggests that typical operations leave room for the equivalent of about 3.50 fuel replacement cycles (for one reactor), suggesting that maximum effective working capacity would be 452.02 tHM per pool (at one pool per reactor). Some references below (and elsewhere) list the design capacity of the Ling'Ao spent fuel pools as 20 years with dense packing. This seems close to the estimated capacity above, based on an estimated 19.31 tHM/yr discharge per reactor.

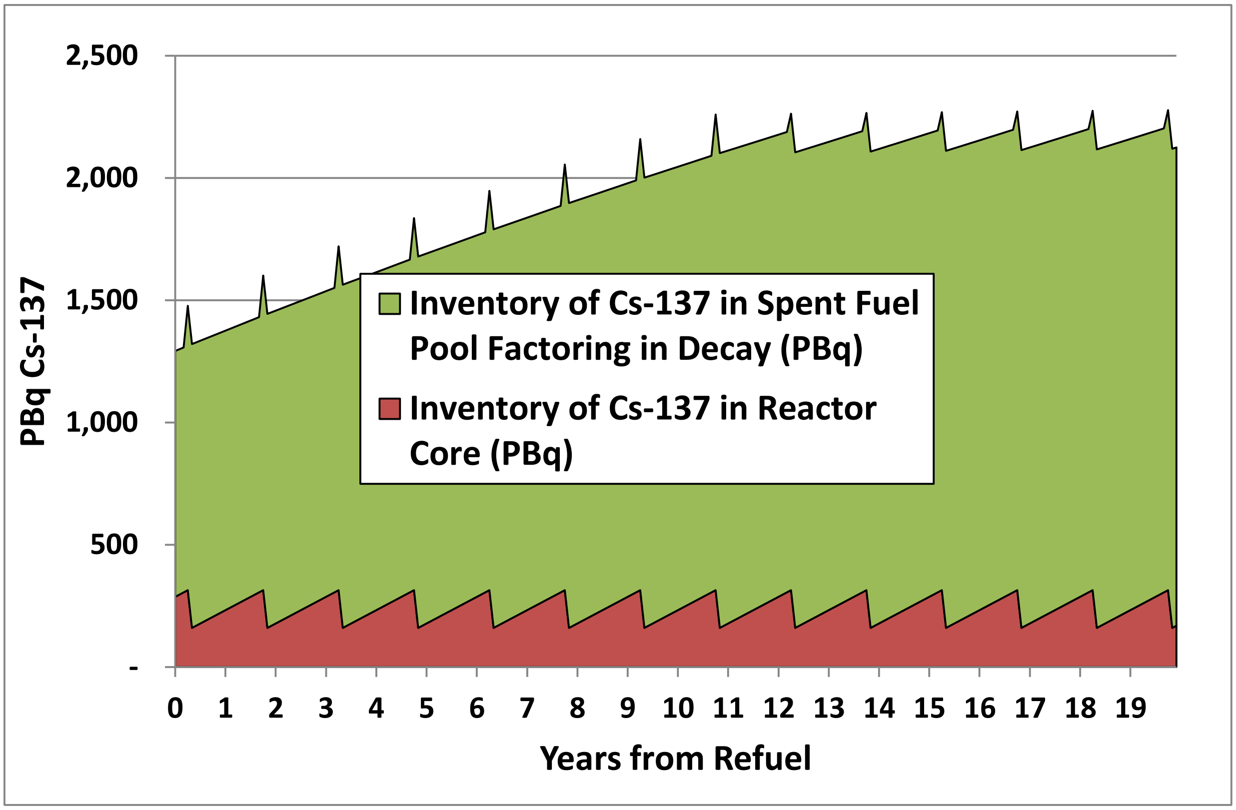
The combination of the assumptions regarding reactor loading/unloading and spent fuel management listed above yields the Cs-137 inventories shown in Figure 2-13. Here, radioactivity in the reactor core builds up after refueling until the next refueling cycle (the area shown in red), while the radioactivity in the spent fuel pool, as well as in the combined reactor and spent fuel pool for each reactor, builds up over time until the pool is full (assuming dense packing) at an inventory of slightly under 2000 PBq in about 2026 (12 years from the start of modeling), at which point we assume that cooled fuel begins to be removed for dry storage either

[31] Photo from Hong Kong Observatory (2012), "Lingao Nuclear Power Station (LNPS)", available as http://www.hko.gov.hk/education/dbcp/pow_stat/eng/r2.htm

[32] Framatome ANP (2010), "LING AO 2 x 1000 MWe PWR: A success story", available as http://ecolo.org/documents/documents_in_english/china-LingAo-success-story.pdf (see page 20).

at or near the nuclear power plant complex, or at an intermediate storage facility such as Lanzhou.

Figure 2-13: Cs-137 Inventory in One Ling'Ao Phase I Reactor Core and Spent Fuel Pool as Modeled (Unit #2 shown, Unit #1 would be similar)



<u>**Incident Modeling Assumptions**</u>

We consider three main scenarios for incidents involving the Ling'Ao reactors and spent fuel pools. For the first scenario, which we call "Worst-case Reactor Incident" (or "S1"), one of the reactors is assumed to suffer a core breach and subsequent loss of coolant due to an extreme seismic event or attack. In this case, the spent fuel pool may or may not suffer an initial loss of coolant, either through being breached by the same event or by losing cooling capacity when utilities (power and/or water) are lost as a result of the incident, but because cooling is assumed to be restored to the pool, the spent fuel in the pool is able to be cooled sufficiently that a zirconium cladding fire does NOT ensue. We assume, in scenario 1, since the two Ling'Ao Phase I units are physically separated, that the second reactor core remains intact, and standard or emergency cooling can be maintained, even if there is damage to the second reactor. This scenario therefore does not include common mode failures--such as the interruption of pumping and water utilities affecting both units, coupled with radiation or other conditions that prevent emergency cooling measures from being undertaken.

For the second scenario, which we call "Worst-case Spent Fuel Pool Incident" (or "S2"), we assume that as a result of a seismic event, catastrophic operational accident (such as dropping a transport cask into the pool), or terrorist attack, the pool suffers a coolant loss and cooling cannot be restored before cooling water mostly or completely evaporates. Further, because the spent fuel pool is dense-packed, fuel that has been most recently off-loaded from the reactor is assumed to reach temperatures high enough for cladding failure and ignition, resulting in a zirconium fire that ultimately engulfs all of the fuel in the pool.

For the third scenario, which we call "Worst Case Reactor and Spent Fuel Pool Incident" (or "S3"), we assume that one of the spent fuel pools and one of the reactors (probably for the same unit) are compromised to the extent that the reactor suffers a meltdown as in S1 and the spent fuel pool has a pool fire as in S2. This could come as a result of an accident or attack that breaches reactor containment and the spent fuel pool at the same time, or damages a unit's reactor or pool, causing common-mode failures in cooling utilities (electricity for pumps and/or water supplies), that cannot be rectified in time to prevent the failure of the unit's pool or reactor.

The "Participation Fraction" ("PART FRAC") of the material in the spent fuel pool is assumed to be a function of the density of racking in the pool. We assume that the racking continues to be high-density in all scenarios. In S1 we assume that even if the incident focused on the reactor does cause a loss of coolant in the spent fuel pool, restored cooling happens rapidly enough that the cladding does not reach ignition temperature, and thus the Participation Fraction for the spent fuel pool in S1 is zero, and the release fraction is similarly zero. In S2 and S3, however, we assume that the full complement of fuel in the pool, which varies based on the time of the incident for each reactor, does participate in a pool fire. The Participation Fraction for the spent fuel pool in scenarios 2 and 3 for reactor 1 or 2 would therefore be by definition 1.00. In the scenarios involving cladding failure and significant Cs-137 emissions (S2 and S3), a release fraction of 0.3 is assumed.

Spent fuel in the second spent fuel pool is assumed to suffer no damage in the incident under any scenarios, and thus its participation and release fractions are both assumed to be zero. We assume that one of the reactors, in both S1 and S3, experiences a core melt, and thus its participation fraction is 1.00, although the participation fraction for the second reactor is assumed to be zero, and the release fraction is similarly zero.

As in the Daya Bay analysis, we assume a release fraction of 0.05 for one of the reactors for S1 and S3, which assumes an incident that would breach containment and the reactor vessel, and severely damage the reactor and the fuel within. For both of the reactors, for S2, we assume that the incident involving the spent fuel pool does not affect the reactors enough to cause a core melt (or emergency procedures are sufficient to prevent a core melt if the reactors is damaged, and thus the participation fraction for both reactors is by definition zero. The release fraction ("REL FRAC") for S2 for the reactors is assumed to be zero, since the neither reactor is assumed to undergo a core melt. In all three scenarios, though dry casks or transport casks may be present at the time of the incident (especially if the incident occurs after about 2024), we assume that the casks will be sufficiently distant from the reactor and spent fuel pool and/or sufficiently robust that their participation and release fractions are all zero. As with Daya Bay, a possible exceptional case might be if the incident (accident or attack) occurs the period when transport casks are being loaded, in which case, depending on where they are physically located near the spent fuel pool and how much fuel is in them at the time of the incident, there could be additional complications. The spent fuel placed in transport casks, however, will have been cooled for many years (perhaps even 20), and is thus likely to be passively cooled if coolant is lost. The spent fuel in a not-yet-closed transport cask might be vulnerable to terrorist attack with an incendiary device that would ignite the cladding in the spent fuel in the cask, but this eventuality is not explicitly considered in our scenarios.

Nearby Populations

Guangdong Province, with a population that would rank 12th globally as a country if it were its own nation, is home to both the Daya Bay and Ling'Ao nuclear stations. Please see the description of nearby populations provided for the Daya Bay plant, above.

Modeling Results

Table 2-4 summarizes the atmospheric releases of Cs-137 in each of the three scenarios evaluated for incidents occurring at various time intervals after January 2014, which is used as the start time for modeling of an incident at the Ling'Ao reactors. As with the Daya Bay and most other light-water reactors, because the inventory of radioactivity in the reactor cores varies significantly over the refueling cycle, the total release in Scenario 1, which affects the reactor core, can change depending on when the incident occurs. The spent fuel pool inventories of Cs-137 for the Ling'Ao reactors, as noted above, increases through about year 12 as the pools fill up, but then vary relatively little over the refueling cycle, because cooled fuel is removed whenever new spent fuel is added to the pool, so the variation of emissions of Cs-137 depending on when the release occurs is relatively small for Scenario 2 and 3 after about year 12.

Table 2-4: Summary of Cs-137 Emissions Results from All Three Scenarios Based on Timing of Incident

	Atmospheric Emissions of Cs-137 (PBq) for an Incident Occuring				
Scenario	1 year after Jan. 2014	3 years after Jan. 2014	5 years after Jan. 2014	10 years after Jan. 2014	20 years after Jan. 2014
S1: Worst-case Reactor Incident	11.2	13.9	8.4	11.2	8.4
S2: Worst-case Spent Fuel Pool Incident	343.7	375.9	454.9	545.2	586.9
S3: Worst-case Reactor and Fuel Pool Incident	354.8	389.7	454.9	556.3	595.4

Figure 2-14, Figure 2-15, and Figure 2-16, respectively, show the estimated ground contamination from a radiological release incident at one of the Ling'Ao units for Scenario 1 (reactor incident) and Scenario 2 (spent fuel pool incident), and Scenario 3 (reactor and spent fuel pool incident). Because so much of the inventory of the dense-racked spent fuel pools are assumed to be involved in a pool factor, and thus released, in Scenarios 2 and 3, the resulting ground contamination for those scenarios is on the order of 40 or 50 times as high as that estimated for Scenario 1. In Scenarios 2 and 3, which are not very different in terms of their results, ground contamination increases for incidents that happen later in time until the spent fuel pools are full, with incidents after that time—about 2025—having approximately the same impact.

Figure 2-14: Estimated Ground Contamination from a Radiological Release Incident at One of the Ling'Ao Reactors Involving the Reactor Core (Scenario 1)

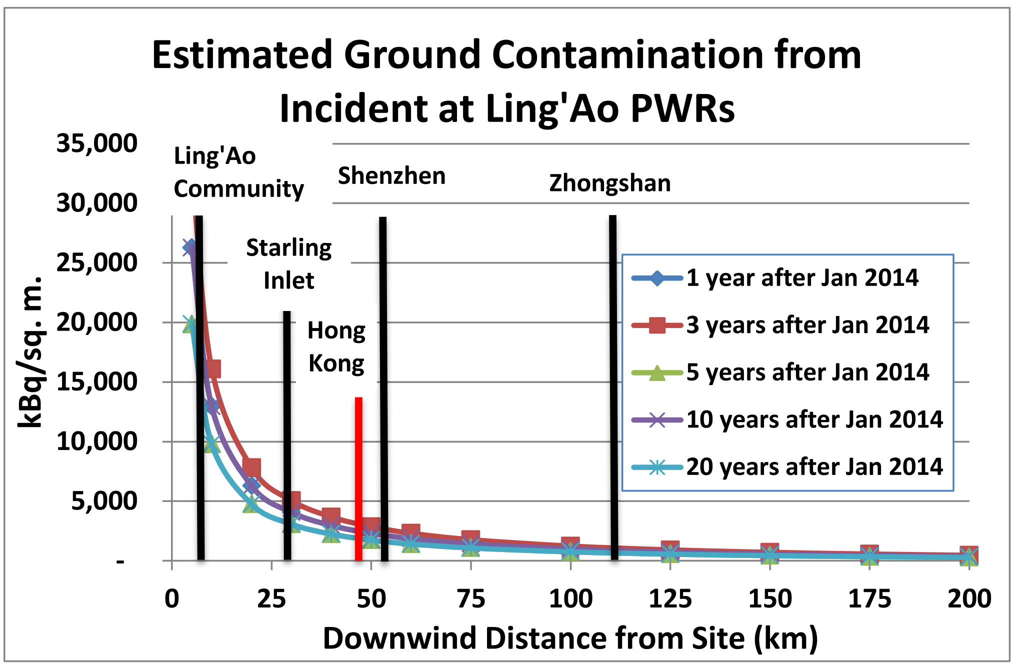


Figure 2-15: Estimated Ground Contamination from a Radiological Release Incident at One of the Ling'Ao Reactors Involving the Spent Fuel Pool (Scenario 2)

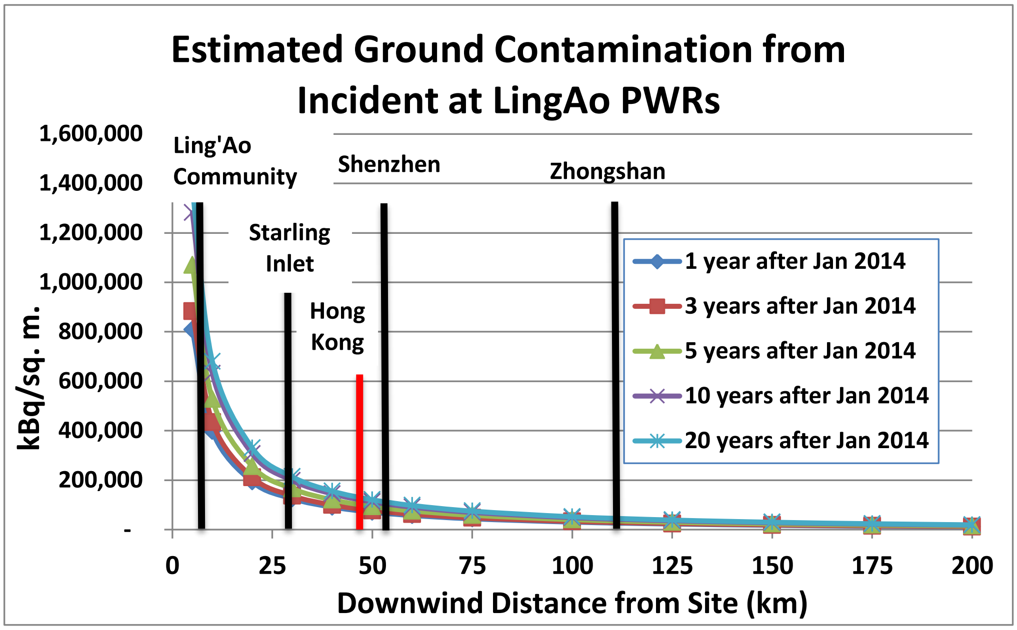


Figure 2-16: Estimated Ground Contamination from a Radiological Release Incident at One of the Ling'Ao Reactors Involving the Reactor and Spent Fuel Pool (Scenario 3)

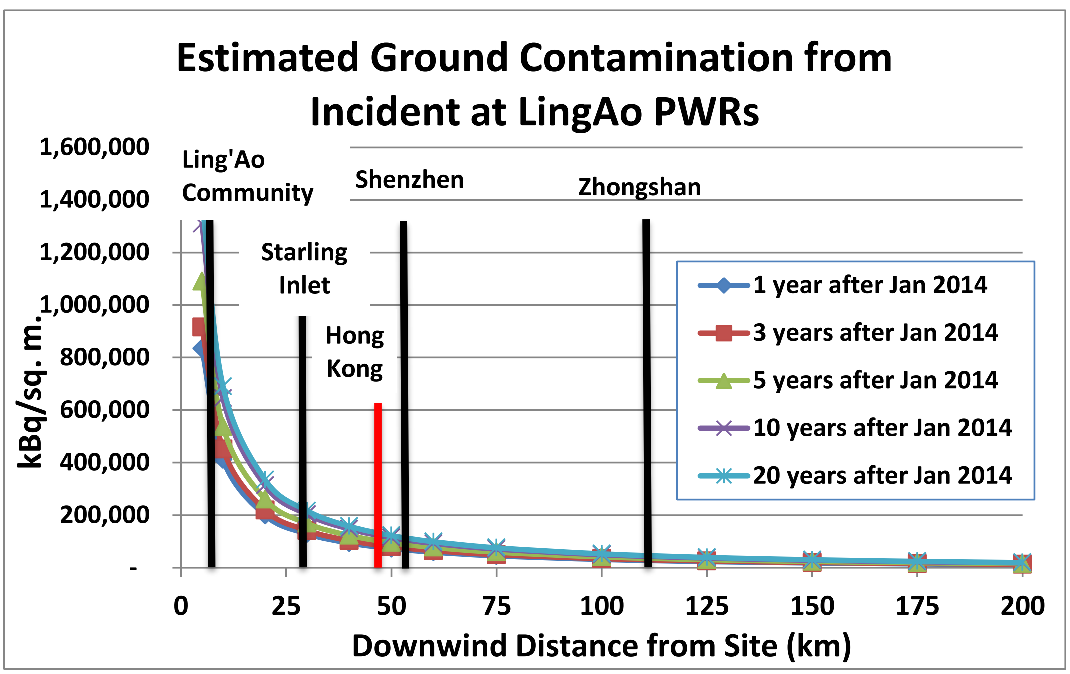


Figure 2-17, Figure 2-18, and Figure 2-19 show the estimated first-year dose of radiation for a person at various distances from the Ling'Ao reactors for incidents involving releases of Cs-137 from a reactor core and a spent fuel pool, respectively. As with Scenario 1 for Daya Bay, the first-year dose estimated based on scenario 1 for one of the Ling'Ao reactors falls just below the USEPA recommended first-year threshold dose of 20 mSv triggering abandonment of lands at a radius of about 30-40 km, which is just short of the major cities in the area. For Scenario 2 and 3, the involvement of a spent fuel pool in Cs-137 releases means that the modeled area with a first year dose of over 20 mSv is very large, with first-year dose ranging from about 70 to 120 mSv even at a distance of 200 km from the reactors. At that distance, for a prevailing wind blowing toward the west, the plume would intersect population sectors well past the Zhongshan area. For a wind blowing to the southwest, the modeling results suggest that Hong Kong residents would receive a first-year dose on the order of 20 to 50 times the USEPA recommended level for abandonment of lands.

Figure 2-17: First-year Estimated External Dose from a Radiological Release Incident at One of the Ling'Ao Reactors Involving the Reactor Core (Scenario 1)

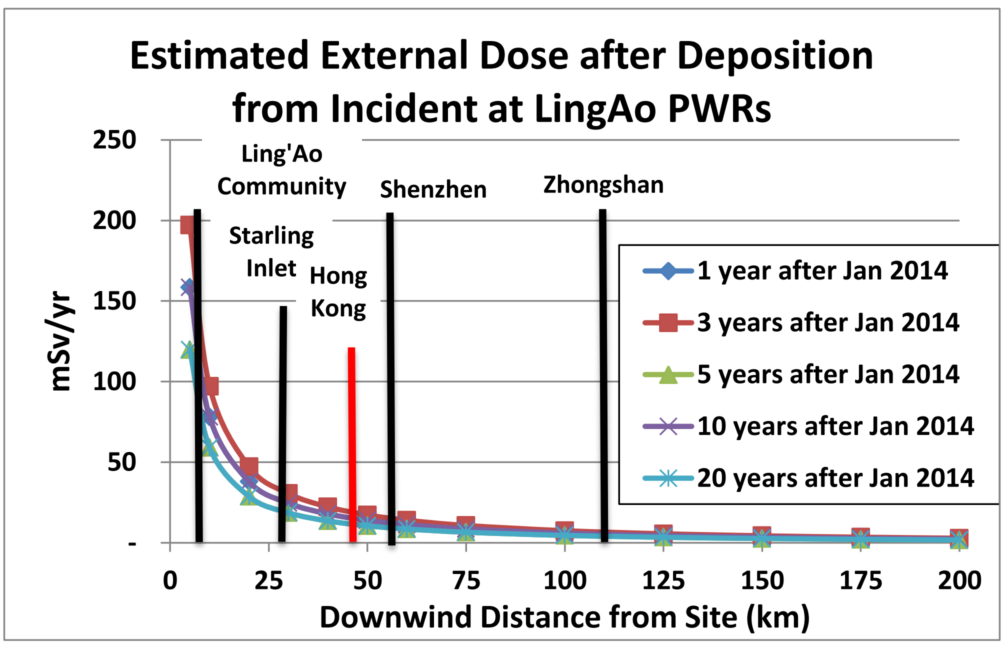


Figure 2-18: First-year Estimated External Dose from a Radiological Release Incident at One of the Ling'Ao Reactors Involving the Spent Fuel Pool (Scenario 2)

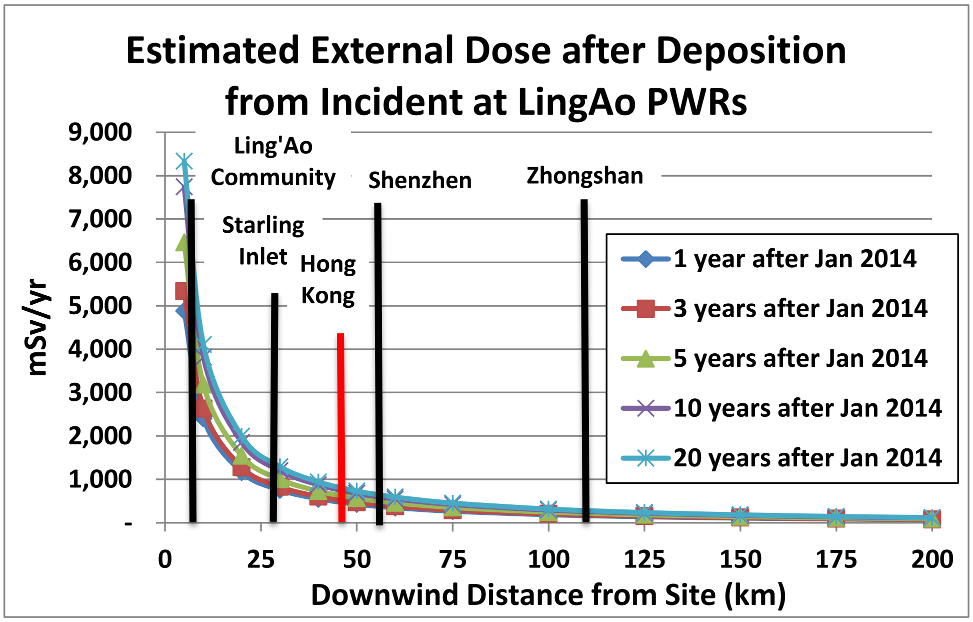


Figure 2-19: First-year Estimated External Dose from a Radiological Release Incident at One of the Ling'Ao Reactors Involving the Reactor and Spent Fuel Pool (Scenario 3)

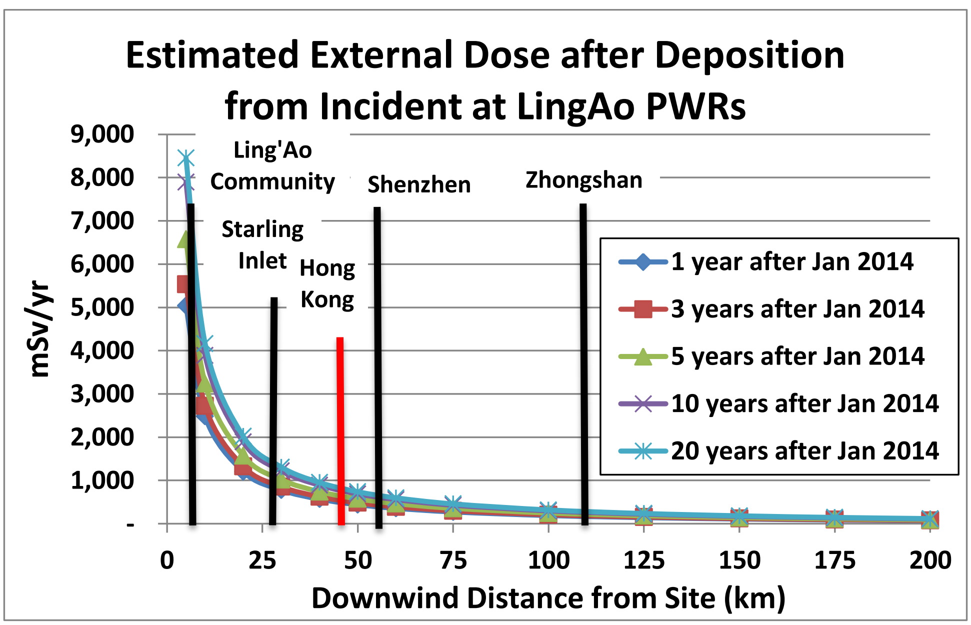


Figure 2-20, Figure 2-21, and Figure 2-22 show the cumulative dose over time for exposures resulting from radiological release incidents involving one of the Ling'Ao reactors, one of the spent fuel pools, and a reactor and a spent fuel pool, respectively. For Scenario 1, exposure at the major nearby population centers up to about the center of Zhongshan exceed the USEPA's cumulative 50 mSv 50-year dose guideline for an exposed individual, with cumulative doses under Scenarios 2 and 3 exceeding the USEPA guidelines by a factor of 15 to 20 over a radius of 200 km. In all cases, releases were modeled as occurring 3 years after the start of the period modeled in January 2014. For an incident occurring later (when spent fuel pools have higher Cs-137 inventories, cumulative doses under Scenarios 2 and 3 are even higher.

Figure 2-20: Cumulative Estimated External Dose from a Radiological Release Incident at One of the Ling'Ao Reactors Involving the Reactor Core (Scenario 1)

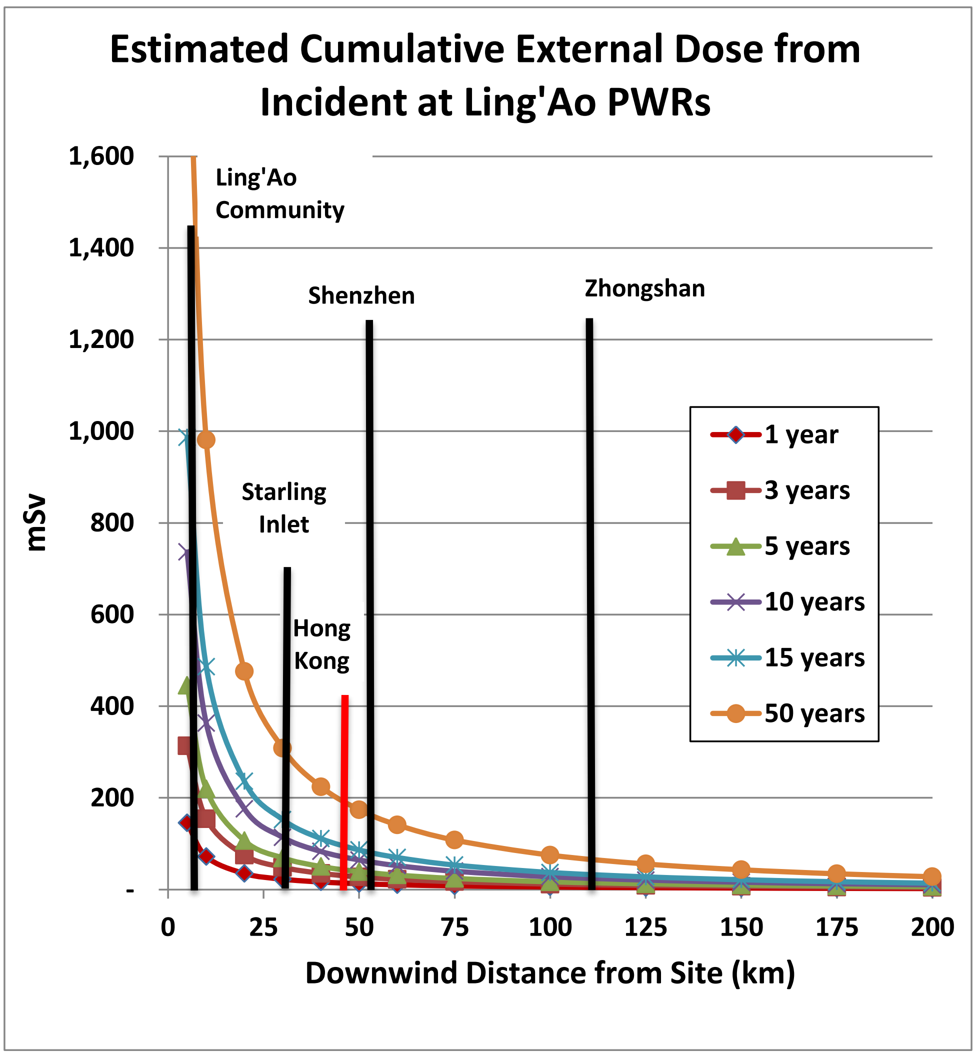


Figure 2-21: Cumulative Estimated External Dose from a Radiological Release Incident at One of the Ling'Ao Reactors Involving the Spent Fuel Pool (Scenario 2)

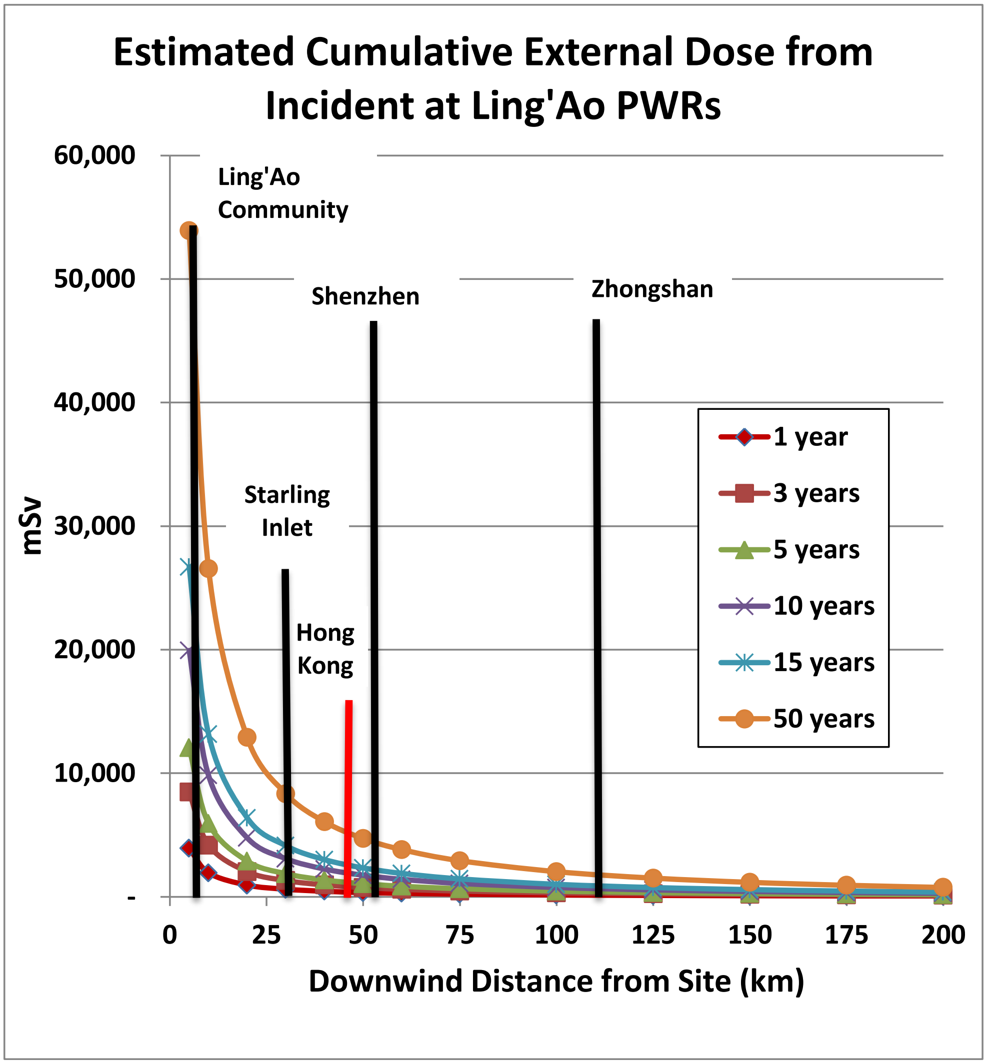


Figure 2-22: Cumulative Estimated External Dose from a Radiological Release Incident at One of the Ling'Ao Reactors Involving the Reactor and Spent Fuel Pool (Scenario 3)

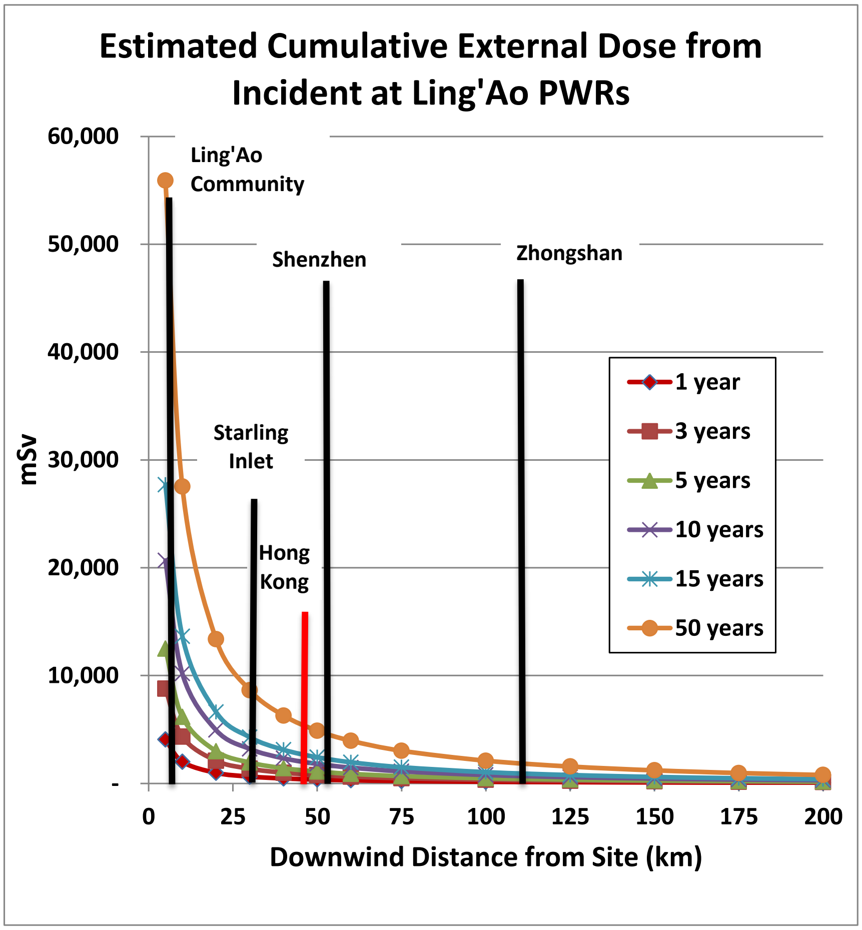


Table 2-5 and Table 2-6 present estimates of the number of premature deaths from cancers resulting from 50-year exposures associated with reactor and reactor/spent fuel pool incidents at the Ling'Ao reactors (Scenarios 1 and 3). (Results for Scenario 2, an incident involving a spent fuel pool only, are not shown, but are just slightly lower than those shown for Scenario 3, since the release of radioactivity from the spent fuel pool dominates the Scenario). Similar to the results for the Daya Bay plant, for a reactor-only incident, about 30,000 premature deaths in the communities included in this assessment result at rates ranging from about 8% in the community closest to the nuclear plants, to under 1% in the nearby big urban areas (Shenzhen or Hong Kong, depending on wind direction). For the scenario postulating an incident involving a spent fuel pool and a reactor, the impacts are much greater, with about 800,000 premature deaths in the included communities, and rates of premature death of 100% in the closest community and on the order of 25 percent in the big nearby cities.

Table 2-5: Calculation of Collective Dose at Selected Locations along Deposition Paths from Ling'Ao for a Release 3 Years after January, 2014 Modeled for Scenario 1, Reactor Incident

Location	Diameter (km) Inner	Diameter (km) Outer	Population Density persons/km^2	Initial Collective Radiation Dose person-Sv/yr
Ling'Ao Community	5.5	7.5	10,308	5,058
Starling Inlet	28	32	1,333	1,220
Shenzhen	40	64	7,500	38,565
Zhongshan	104	120	3,600	10,318
Hong Kong	44	52	32,720	56,745

Location	Cumulative Collective Radiation Dose person-Sv	Exposed Population People	Percent Premature Deaths %	Implied Number of Premature Deaths
Ling'Ao Community	51,101	33,500	7.780	2,606
Starling Inlet	12,325	40,000	1.571	629
Shenzhen	389,643	2,340,000	0.849	19,872
Zhongshan	104,243	1,612,800	0.330	5,316
Hong Kong	573,320	3,141,120	0.931	29,239
TOTAL of first four locations (not total of exposed area)	557,313	4,026,300	0.706	28,423

Table 2-6: Calculation of Collective Dose at Selected Locations along Deposition Paths from Ling'Ao for Release 3 Years after First Refueling Modeled for Scenario 3, Reactor and Spent Fuel Pool Incident

	Diameter (km)		Population Density	Initial Collective Radiation Dose
Location	Inner	Outer	persons/km^2	person-Sv/yr
Ling'Ao Community	5.5	7.5	10,308	141,943
Starling Inlet	28	32	1,333	34,236
Shenzhen	40	64	7,500	1,082,306
Zhongshan	104	120	3,600	289,554
Hong Kong	44	52	32,720	1,592,500

	Cumulative Collective Radiation Dose	Exposed Population	Percent Excess Deaths	Implied Number of Excess Deaths
Location	person-Sv	People	%	
Ling'Ao Community	1,434,120	33,500	100.000	33,500
Starling Inlet	345,903	40,000	44.103	17,641
Shenzhen	10,935,073	2,340,000	23.833	557,689
Zhongshan	2,925,506	1,612,800	9.251	149,201
Hong Kong	16,089,825	3,141,120	26.124	820,581
TOTAL of first four locations (not total of exposed area)	15,640,603	4,026,300	18.827	758,031

As with the other radiological exposure results presented in this report, we prepared rough estimates of damages related to premature human deaths based on two estimates of the "value of a statistical life" compiled in a review of a number of studies, and bracketing a range from $1.1 million to $10 million per person in 2012 dollars. Applying these estimates yields values in the range of $30 to $400 billion for an incident involving a Ling'Ao reactor only, rising to perhaps $800 billion to $10 trillion for an incident involving a reactor and a spent fuel pool. Again, the vast bulk of the radiation release is from the spent fuel pool, and as in the Daya Bay plant estimates, these totals do not factor in population areas that the plume of material released will encounter that are not included in the Tables above. Once again, the reader is urged to bear in mind uncertainties in this calculation caused by the combination of high-low dose response assumptions with high-low estimated values of excess deaths.

2.3.3 Conclusions from Daya Bay and Ling'Ao Results

The results of the radiological release modeling of scenarios for the Daya Bay and Ling'Ao (Phase I) nuclear power facilities provide a convenient way to compare the impacts of near-identical reactors in essentially the same location, but with one crucial difference—the use of dense-packed spent fuel pools at the Ling'Ao Phase I units. For the Daya Bay plant, the radiological impacts of a reactor-only incident as modeled would, if Chinese authorities use criteria similar to that of the USEPA to identify areas to be abandoned, require the evacuation and at least temporary abandonment of an area stretching from the reactors to nearly the borders of Shenzhen or (depending on wind direction) Hong Kong, though in the latter case most of the intervening area is ocean. An incident at the Daya Bay plant involving the spent fuel pool, assuming the participation and release fractions we have used are plausible in a "worst case" event, would be much more serious, with accumulated (50-year) doses in big cities as far away as Zhongshan and beyond considerably exceeding USEPA guidelines. As serious as such an incident would be, however, an incident involving one of the Ling'Ao spent fuel pools could be far worse, with exposures sufficient to cause hundreds of thousands of premature cancer deaths and almost certainly require the abandonment of one or several big cities, depending on the prevailing wind direction at the time of the incident.

The sum of these results suggests the following:

- At both the Daya Bay and Ling'Ao reactors, stringent safety measures should be installed to reduce the risk of cooling failure in both the reactors and spent fuel pools, including the installation of redundant emergency systems for water and power supply, and attention to potential common-mode failures involving, for example, loss of water, power, and or safe access to reactors or spent fuel pools. Implementation of many such measures is likely already underway as a result of the post-Fukushima safety reviews required of Chinese reactors.
- In addition, the spent fuel pools at the Ling'Ao reactors should be reconverted to a non-dense-packed format to reduce the potential for radiological release in the event of a sustained loss-of-coolant incident. This implies moving some of the existing inventory of spent fuel in the Ling'Ao Phase I pools to dry cask storage at the reactors, or to similar storage away from the reactors, as is the practice at Daya Bay. The result would likely be that the Ling'Ao pools would reach a steady state of transfers in and out within the next few years.

However low the risk of an incident like those modeled for the spent fuel pools at Ling'Ao might be, the radiological results of such an incident are potentially so severe, we would argue, that the relatively modest investment[33] in out-of-pool spent fuel storage and related infrastructure cannot fail to be prudent and socially justifiable. See Annexes 1B and 1D to this Report for additional details of results of the analyses of incidents at the Daya Bay and Ling'Ao reactors, respectively.

[33] See discussions and analysis presented later in this report for estimates of the costs of moving from dense-packed spent fuel pools.

2.4 Radiological Risk Attitudes and Estimate in Japan

Below we explore the potential radiological releases associated with an accident at or attack on a nuclear power plant in Japan, with the Hamaoka plant, southwest of the Tokyo area, taken as an example. We explore several scenarios for radiological releases, in order to estimate the potential impacts of an accident or attack, and thus the potential benefits in measures taken to avoid those impacts, including measures reflected in the three Restart paths presented later in this Report. We do not, however, focus on determining how such a particular accident or terrorist attack might proceed and result in damage to reactors and/or spent fuel pools, as that is the subject of other presentations and papers prepared for the "Vulnerability to Terrorism in Nuclear Spent Fuel Management" Project and in a subsequent "scenarios" workshop held in September of 2015.[34]

2.4.1 Reactor and Spent Fuel Pool Description and Operational Parameters

Nautilus staff prepared a radiological risk assessment for the Hamaoka nuclear power plant, a complex of older and one newer BWR-type units located south and east of the Tokyo area. The Hamaoka site hosts five reactors, Units 1 and 2, at 540 and 840 gross MWe, respectively, went into service in 1980 and 1982, and were taken out of service in early 2009. Units 1 and 2 are now being decommissioned.[35] Units 3 and 4 have gross capacities of 1100 and 1137 MWe, respectively, and were commissioned in 1991 and 1997. Unit 5, an advanced BWR (ABWR) unit with a gross generation capacity of 1380 MWe, was commissioned in early 2005. Figure 2-23 provides a diagram of the Hamaoka power plant, and Figure 2-24 shows an aerial photo of the facility. Until they were taken off line for safety assessments following the Fukushima accident, Hamaoka units 3 and 4 had operated at average capacity factors of about 78 percent over their lifetimes, and unit 5 had operated at a capacity factor of 43 percent.[36] The Hamaoka complex is located near the town of Omaezaki in Shizuoka Prefecture, about 170 km from Yokohama and 200 km from Tokyo.

Our analysis of radiological releases from the Hamaoka plant focuses on the older operable (but as of this writing, still not restarted) units #3 and #4. Units 3 and 4 use uranium enriched to 3.0% U-235,[37] use about 140 tHM (each) in their reactor cores, and are assumed to be refueled every 12 months, with 20 percent of the core replaced, and an average capacity factor of 70 percent,[38] implying an average burn-up of about 30 GWth-d/tHM, 2524 GWth-days of burnup in

[34] Papers and presentations forthcoming at http://nautilus.org/projects/by-name/vulnerability-to-terrorism-in-nuclear-spent-fuel-management/.
[35] Data from IAEA reactor database, available as http://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=JP, and from http://hamaoka.chuden.jp/english/about/facilities.html.
[36] Data from IAEA reactor database, ibid. Unit 5 was offline for much of 2009 and all of 2010.
[37] Data from findthedata.com/l/468/Hamaoka-Nuclear-Power-Plant-Unit-3 and similar.
[38] This is an analytical assumption on our part, but is very close to the historical weighted average capacity factor for all Japanese nuclear power plants from 1970 through 2010 (that is, pre-Fukushima), which was about 69 percent.

the reactor core at the time of refueling and an annual spent fuel discharge of just under 28 tHM/yr per reactor. The website http://hamaoka.chuden.jp/english/about/management.html lists the end of fiscal year (FY) 2013 spent fuel pool inventory at Hamaoka Unit 3 as 2,060 assemblies, or 376.98 tHM, and the end-FY-2013 spent fuel pool inventory at Hamaoka Unit 4 as 1,977 assemblies, or 361.79 tHM. This suggests that each of the Unit 3 and Unit 4 spent fuel pools had room for about 7 fuel replacement cycles as of the end of 2013, and were thus effectively nearly full, given that typical operation leaves room in the pool for a full reactor core (in this case, the equivalent of five replacement cycles) and the fuel from one replacement cycle. See Annex 2A to this Report for additional details of input data and assumptions beyond those presented in this section and section 2.4.2, below.

Figure 2-23: Diagram of Hamaoka Nuclear Power Plant[39]

39 Diagram of plant layout from http://hamaoka.chuden.jp/english/about/layout.html.

Figure 2-24: Aerial Photo of Hamaoka Nuclear Power Plant[40]

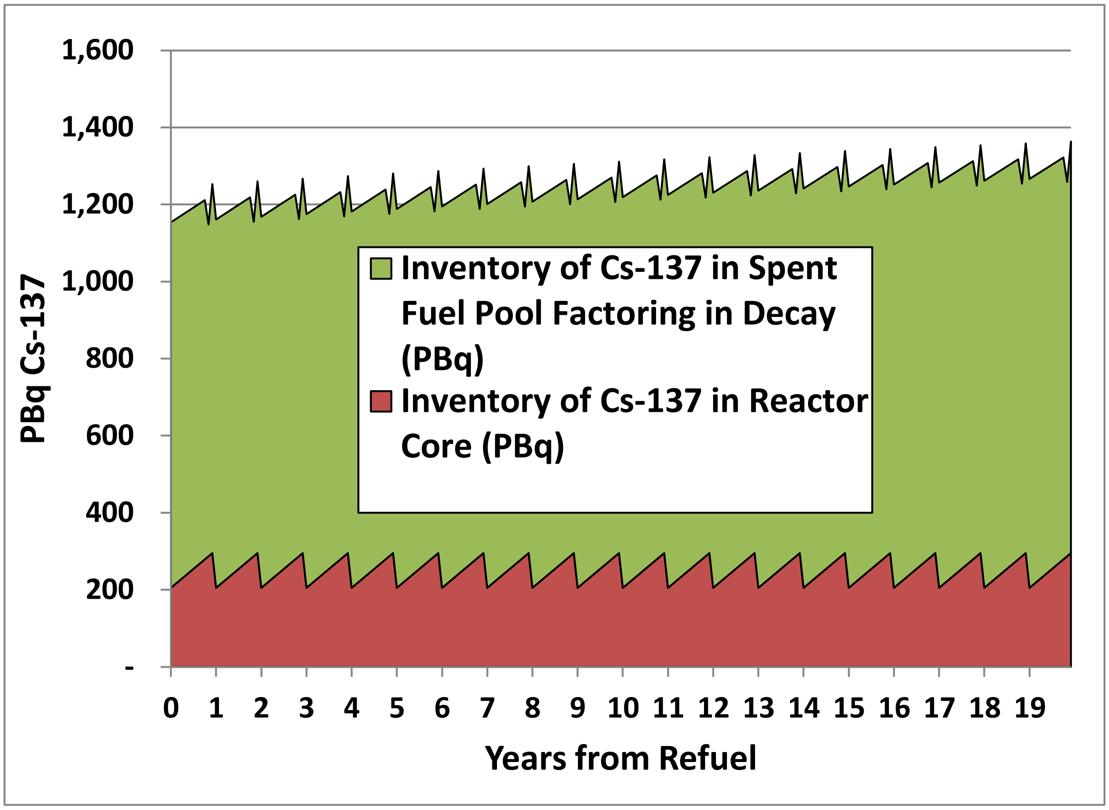
We assume that no transport casks are on site at the Hamaoka complex, as fuel is not being transported off-site (but this assumption should be confirmed). The article "Chubu Electric applies with NRA to build dry storage facility at Hamaoka nuclear plant",[41] suggests that the utility owners of the Hamaoka plants have applied to build a dry-cask storage facility with a capacity of 400 tonnes of spent fuel (assumed to be tHM), which would start operating as of fiscal 2018. An older reference[42] suggests an earlier start date (2016) and a larger size (700 tU) for this facility. Either size facility will be full in less than 10 years if all three Hamaoka units operate as above and the spent fuel pools are operated at a relatively steady state of fuel placement and removal, even if the pools remain dense packed (and will be full even more quickly if they are not), so we assume that the dry-cask storage facilities, when and if they are built, will be able to expand to accommodate additional casks as needed.

The combination of the assumptions regarding reactor loading/unloading and spent fuel management listed above yields the Cs-137 inventories shown in Figure 2-25. Here, radioactivity in the reactor core builds up after refueling until the next refueling cycle (the area shown in red), while the radioactivity in the spent fuel pool, as well as in the combined reactor and spent fuel pool for each reactor, remains at close to the same level over time as the pool is

[40] Photo from Asahi Shinbun (2011) "Chubu Electric to halt reactors in line with Kan request", dated May 7, 2011, and available as http://ajw.asahi.com/article/0311disaster/fukushima/AJ201105071833.
[41] Available at http://www.fukushima-is-still-news.com/2015/01/dry-storage-for-hamaoka.html.
[42] https://www.inmm.org/AM/Template.cfm?Section=Spent_Fuel_Seminar_2012&Template=/CM/ContentDisplay.cfm&ContentID=3603.

essentially full (assuming dense packing) at an inventory of about 1200 PBq even after restart, rising very slightly over time as fresher spent fuel replaces older spent fuel. We assume that cooled fuel begins to be removed for dry storage either at or near the nuclear power plant complex as soon as the first refueling following reactor restart, given the need to provide space in the pool for subsequent spent fuel off-loadings.

Figure 2-25: Cs-137 Inventory in One Hamaoka Reactor Core and Spent Fuel Pool as Modeled (Unit #3 shown, Unit #4 would be similar)



2.4.2 Incident Modeling Assumptions

We consider three main scenarios for incidents involving the Hamaoka reactors and spent fuel pools. For the first scenario, which we call "Worst-case Reactor Incident" (or "S1"), one of the reactors (unit #3 or 4) is assumed to suffer a core breach and subsequent loss of coolant due to an extreme seismic event or attack. In this case, the spent fuel pool or pools may or may not suffer a loss of coolant, either through being breached by the same event or by losing cooling capacity when utilities (power and/or water) are lost as a result of the incident, but because cooling is assumed to be restored to the pool(s), the spent fuel in the pool(s) is able to be cooled sufficiently that a zirconium cladding fire does NOT ensue. We assume, in S1, that even though Hamaoka units #3 and 4 are not significantly physically separated, even if the second reactor core also suffers damage, emergency cooling can be maintained for the second reactor due to the installation of post-Fukushima redundant safety measures. This scenario therefore does not include common mode failures--such as the interruption of pumping and water utilities affecting both units, coupled with radiation or other conditions that prevent emergency cooling measures from being undertaken.

For the second scenario, which we call "Worst-case Spent Fuel Pool Incident" (or "S2"),we assume that as a result of a seismic event, catastrophic operational accident (such as dropping a transport cask into the pool), or terrorist attack, the pool in Unit #3 suffers a coolant loss and cooling cannot be restored before cooling water mostly or completely evaporates. Further, those regions of the stored spent fuel that have most recently (within the past few months) been off-loaded from the two reactors are assumed to reach temperatures high enough for cladding failure and ignition, resulting in a zirconium fire that engulfs an amount of spent fuel equal to the most recent off-loading.

For the third scenario, which we call "Worst Case Reactor and Spent Fuel Pool Incident" (or "S3"), we assume that one of the spent fuel pools and one of the reactors (probably for the same unit) are compromised to the extent that the reactor suffers a meltdown as in S1 and the spent fuel pool suffers a pool fire as in S2. This combination of circumstances could come as a result of an accident or attack that breaches reactor containment and the spent fuel pool at the same time, or damages to a unit's reactor or pool, causing common-mode failures in cooling utilities (electricity for pumps and/or water supplies), that cannot be rectified in time to prevent the failure of the unit's pool and reactor.

The "Participation Fraction" ("PART FRAC") of the material in the spent fuel pool, which describes how much of the material in the spent fuel pool is affected by a incident, is assumed to be a function of the density of racking in the pool. We assume that the racking continues to be high-density in all scenarios. In S1 we assume that even if the incident focused on the reactor does cause a loss of coolant in the spent fuel pool, restored or emergency cooling happens rapidly enough that the cladding does not reach ignition temperature, and thus the Participation Fraction for the spent fuel pool in S1 is 0, and the release fraction is similarly 0.

In S2 and S3, however, we assume that the full complement of fuel in the pool, which at the time of an incident for reactor #3 occurring 3 years after restart (for example) is 376.98 tHM, and for reactor #4 is a similar 361.79 tHM, does participate in a pool fire. The Participation Fraction for the spent fuel pool in scenarios 2 and 3 for reactor #3 or #4 would therefore be 1.00. In these scenarios involving cladding failure and significant Cs-137 emissions (S2 and S3), a release fraction of 0.3 is assumed. Spent fuel in the other spent fuel pools is assumed to suffer no damage in the incident under any scenarios, and thus its participation and release fractions are both assumed to be zero.

For one of the reactors, for S1, we assume that it experiences a core melt, and thus its participation fraction is 1.00, though the participation fraction for the second reactor is assumed to be zero, and the release fraction is similarly zero.

Based on consideration of Table II.3-7 in the Handbook prepared by Gordon Thompson,[43] as well as estimates of fraction of the Cs-137 inventory in the Fukushima reactor cores that were released to the atmosphere[44], we assume a release fraction of 0.05 for one of the reactors for S1 and S3, which assumes an incident that would both breach containment and the reactor vessel, and severely damage the reactor and the fuel within.

For both of the reactors, for S2, we assume that the incident involving one of the spent fuel pools does not affect the reactors enough to cause a core melt (or emergency procedures are sufficient to prevent a core melt if the reactors is damaged), and thus the participation fraction for both reactors is by definition zero. The release fraction ("REL FRAC") for S2 for the reactors is similarly assumed to be zero, since neither reactor is assumed to undergo a core melt.

In all three scenarios, though dry casks or transport casks may be present at the time of the incident (and dry casks, at least, may well be), we assume that the casks will be sufficiently distant from the reactor and spent fuel pool and/or sufficiently robust that their participation and release fractions are all zero. As with the Chinese reactors considered above, a possible exceptional case might be if the incident (accident or attack) occurs during the period when dry casks are being loaded, in which case, depending on where they are physically located near the spent fuel pool and how much fuel is in them at the time of the incident, there could be additional complications.

The spent fuel placed in transport casks, however, has been cooled for several years, and is thus likely to be passively cooled if coolant is lost. The spent fuel in a not-yet-closed transport cask might be vulnerable to terrorist attack with an incendiary device that would ignite the cladding in the spent fuel in the cask, but this eventuality is not explicitly considered in our scenarios.

We assume an average wind speed of 10 miles per hour, or 4.5 meters/second, based very roughly on considerations of recent annual windspeed values for the summer, when prevailing winds are mostly from the Southwest (or SSW) to Northeast (or ENE) at Omaezaki, which is along the coast and within a few miles of the Hamaoka Plant. Tokyo and nearby cities are North and East of Hamaoka.[45] Except for the months of September and October, dominant winds in the area are generally West to East. We use a deposition velocity ("DEP VEL") of 1 cm/second, or 0.01 meter/second, which is a typical value used with the wedge model.

Nearby Populations

The Hamaoka nuclear station is located on a promontory on the southern coastline of relatively lightly-populated Shizoka Province. We assume a prevailing wind at the time of the incident

[43] The radiological risk methodology and related tools were prepared for Nautilus by Dr. Gordon D. Thompson, and is available as *Handbook to Support Assessment of Radiological Risk Arising From Management of Spent Nuclear Fuel*, Nautilus Institute Special Report dated May 14, 2013, http://nautilus.org/napsnet/napsnet-special-reports/handbook-to-support-assessment-of-radiological-risk-arising-from-management-of-spent-nuclear-fuel/.

[44] See, for example, Stohl et al, 2012, and Koo et al, 2014, ibid.

[45] From Windfinder.com (2015), "Wind Statistics: Omaezaki", available as http://www.windfinder.com/windstatistics/omaezaki?fspot=honshu_omaezaki. Data shown in Figure 2-26 are from observations taken between 5/2006 and 4/2015.

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from the southwest, which is common in the area during the summer, though a wind from west to east is more common over the entire year. A plume headed northeast from Hamaoka would pass over Suruga Bay and the northern part of the fairly lightly-populated Izu Peninsula before encountering the major population centers—Fujisawa and multi-million-resident Yokohama and Tokyo—starting at about 150 km from the plants. Figure 2-27 shows a map of the area overlaid with trajectories for emissions clouds traveling in the wind direction modeled, assuming a wedge angle of about 0.25 radians.[46]

An annual average "wind rose" for the Omaezaki area is shown in Figure 2-26, along with the direction of the prevailing winds in each month in the area. Note that the wind rose indicates the average fraction of the time that the wind is blowing **from** a particular direction, while the arrows in the table at the top of Figure 2-26 point in the direction that prevailing winds most typically blow. Winds in the vicinity of Hamaoka blow from the southwest and west-southwest—that is, in the direction of Tokyo and nearby cities—about 20 percent of the time over an entire year. In particular months the frequency of winds toward Tokyo deviate substantially from the annual average. In July and August, for example, winds blow from the southwest and west-southwest on the order of 40 percent of the time, whereas in December and January prevailing winds have only few percent probability of blowing in that direction.

[46] Map adapted from Google Maps.

Figure 2-26: Monthly and Annual Wind Direction Data for Omaezaki (Hamaoka area; from Windfinder.com)

Month of year	Jan 01	Feb 02	Mar 03	Apr 04	May 05	Jun 06	Jul 07	Aug 08	Sep 09	Oct 10	Nov 11	Dec 12	Year 1-12
Dominant Wind dir.	→	→	→	→	↗	↗	↗	↗	↗	↗	→	→	→
Wind probability >= 4 Beaufort (%)	63	51	54	40	33	21	28	19	23	26	42	59	**38**
Average Wind speed (mph)	15	14	14	13	12	9	10	9	10	10	13	15	**12**
Average air temp. (°F)	46	48	53	60	68	73	78	82	77	69	60	50	**62**

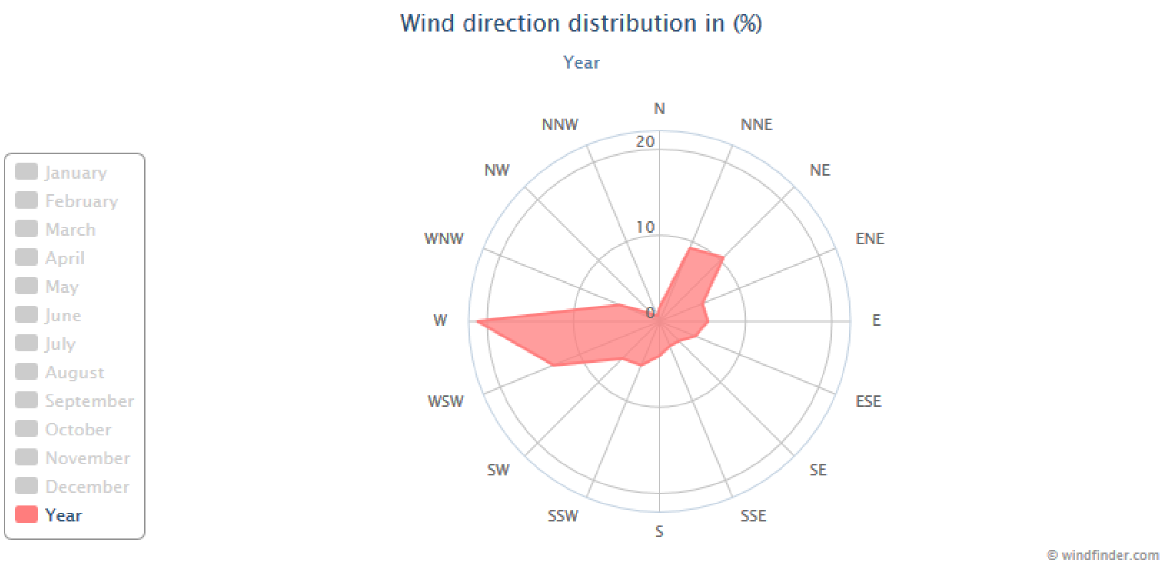
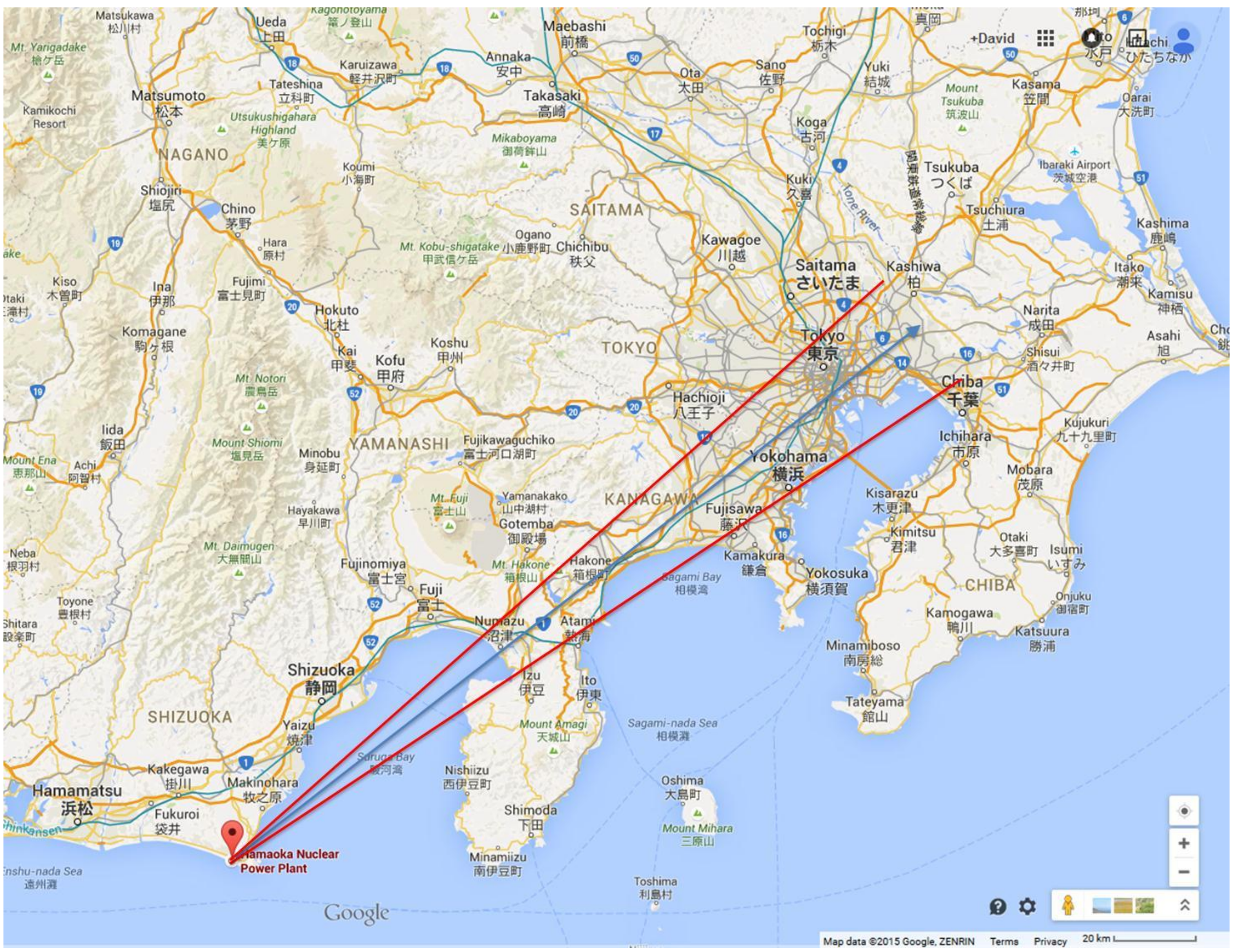


Figure 2-27 shows a map of the area overlaid with trajectories for emissions clouds traveling in the wind direction modeled, assuming a wedge angle of about 0.25 radians.[47] It should be emphasized that the wind direction used in this modeling effort, though not improbable, particularly in the summer, based on wind data for the area, does represent a worst case for impacts on human populations. A plume that takes a more southerly track, consistent with the wind directions dominant in the late fall, winter, and spring, or a plume heading west-southwest, consistent with dominant winds in September and October, would miss most heavily inhabited areas, with Cs-137 deposited mostly into the sea. Perhaps 50 percent of the time in a given year, a plume originating at Hamaoka would be directed by prevailing winds largely over the ocean, and another 30 percent of the time, a plume would be directed over land areas that are generally less inhabited but by no means exclusively so; about 10 percent of the time, winds from Hamaoka are blowing to the west or west-northwest, in the directions of Nagoya, which is closer

[47] Map adapted from Google Maps.

to Hamaoka than Yokohama, and of Osaka and Kyoto, which are only slightly further from the Hamaoka area than is Tokyo, Another complicating factor is that winds may shift in the middle of an incident, as they did during the Fukushima accident, potentially rendering deposition and exposure patterns much more complex.

Figure 2-27: Google Earth Image of the Hamaoka-to-Tokyo Area with Assumed Directions of Emissions Plume



2.4.3 Modeling Results

Table 2-7 summarizes the atmospheric releases of Cs-137 in each of the three scenarios evaluated for incidents occurring at various time intervals after Hamaoka reactor restarts, which is used as the start time for modeling of an incident involving a reactor and/or spent-fuel pool. Because the inventory of radioactivity in the reactor cores varies significantly over the refueling cycle, the total release in Scenario 1, which affects the reactor core, can change depending on when the incident occurs. This variation, however, is not explicitly shown in Table 2-7 because the reactor is assumed to be refueled annually. The spent fuel pool inventories of Cs-137 for the Hamaoka reactors, as noted above, rises only slowly over time, as the pools start essentially full and are already dense-packed, with dense-packed operations assumed to continue through the modeling period, As cooled fuel is removed whenever new spent fuel is added to the pool, the variation of emissions of Cs-137 over time depends relatively little on when the release occurs for Scenarios 2 and 3. See Annex 2B to this Report for additional details of results of this analysis.

Table 2-7: Summary of Cs-137 Emissions Results from All Three Hamaoka Scenarios Based on Timing of Incident

	Atmospheric Emissions of Cs-137 (PBq) for an Incident Occuring				
Scenario	1 year after refueling	3 years after refueling	5 years after refueling	10 years after refueling	20 years after refueling
S1: Worst-case Reactor Incident	14.8	14.8	14.8	14.8	14.8
S2: Worst-case Spent Fuel Pool Incident	287.3	291.5	295.6	304.8	320.4
S3 Worst-case Reactor and Spent Fuel Pool Incident	302.1	306.3	310.3	319.6	335.2

Figure 2-28, Figure 2-29, and Figure 2-30, respectively, show the estimated ground contamination from a radiological release incident at Hamaoka unit #3 or #4 Scenario 1 (reactor incident), Scenario 2 (spent fuel pool incident), and Scenario 3 (reactor and spent fuel pool incident). Because so much of the inventory of the dense-racked spent fuel pools are assumed to be involved in a pool factor, and thus released, in Scenarios 2 and 3, the resulting ground contamination for those scenarios is on the order of 30 times as high as that estimated for Scenario 1. None of the scenarios show significant variation of ground contamination for incidents that happen later in time, as the spent fuel pools are essentially full at the start of the modeling period.

Figure 2-28: Estimated Ground Contamination from a Radiological Release Incident at Hamaoka Unit #3 or #4 Involving the Reactor Core (Scenario 1)

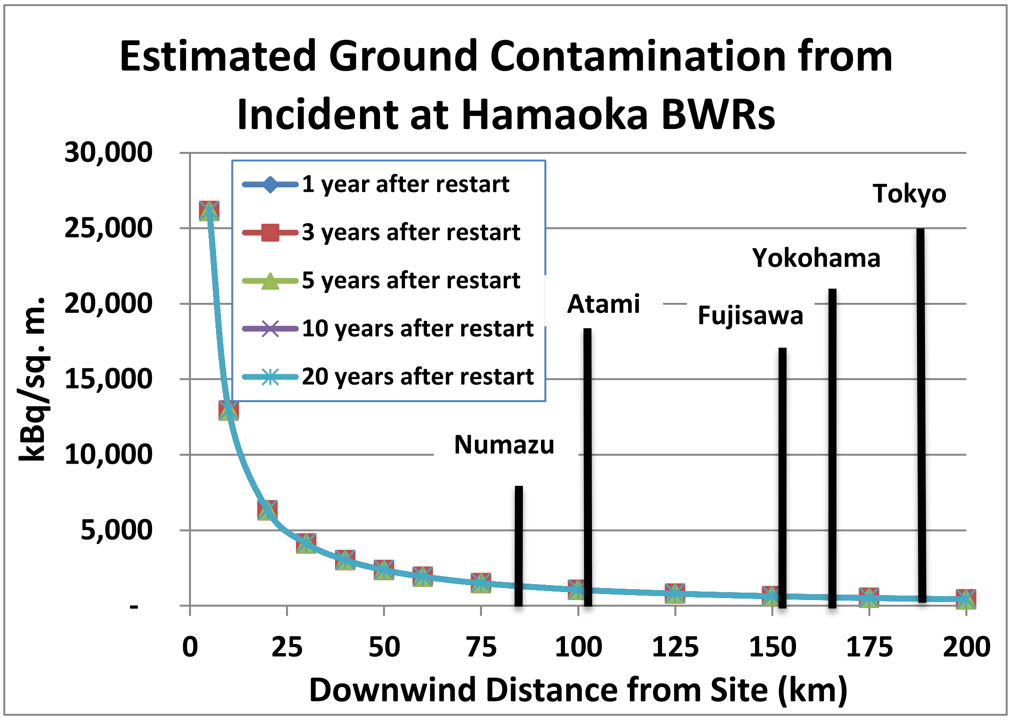


Figure 2-29: Estimated Ground Contamination from a Radiological Release Incident at Hamaoka Unit #3 or #4 Involving the Spent Fuel Pool (Scenario 2)

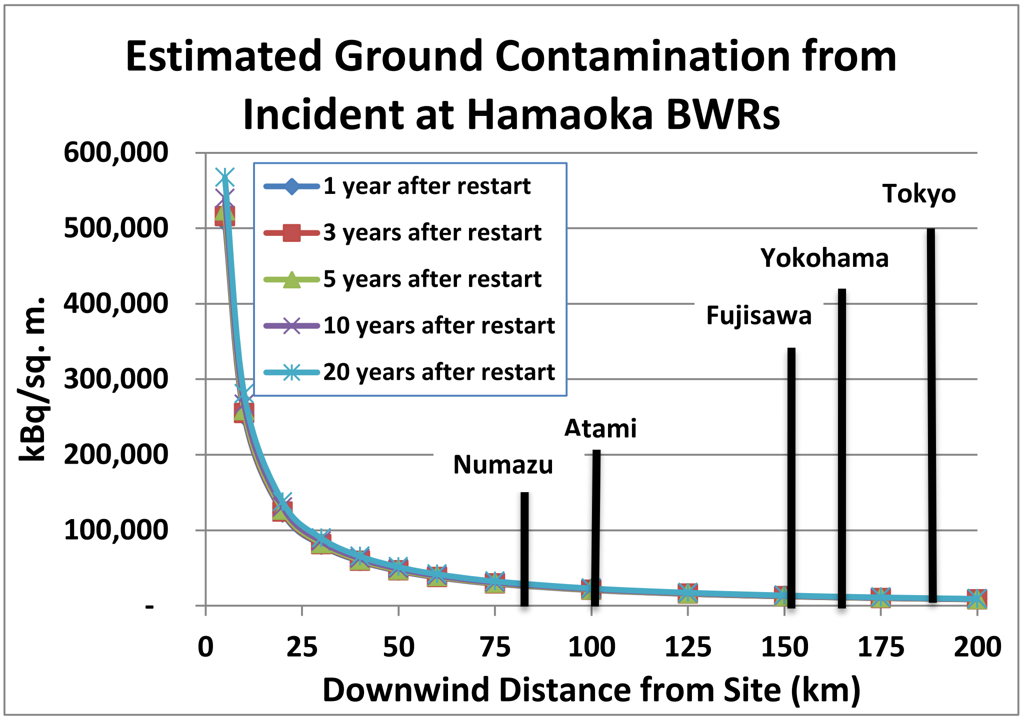


Figure 2-30: Estimated Ground Contamination from a Radiological Release Incident at Hamaoka Unit #3 or #4 Involving the Reactor and Spent Fuel Pool (Scenario 3)

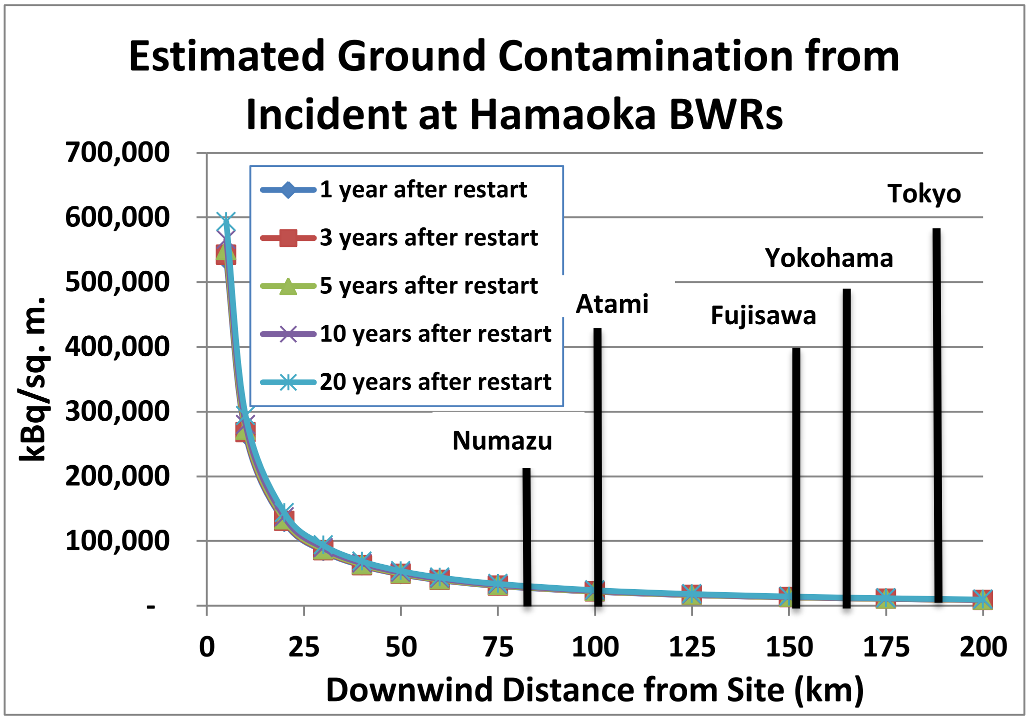


Figure 2-31, Figure 2-32, and Figure 2-33 show the estimated first-year dose of radiation for a person at various distances from the Hamaoka reactors for incidents involving releases of Cs-137 from a reactor core and a spent fuel pool, respectively. Because a radiological release carried by winds toward the northeast away from Hamaoka would be carried over the ocean for 60 km or more before reaching significant populations, the first-year dose estimated based on scenario 1 for one of the reactors falls well below the USEPA recommended first-year threshold dose of 20 mSv in both the small and major cities in the area. For Scenario 2 and 3, the involvement of a spent fuel pool in Cs-137 releases means that the modeled area with a first year dose of over 20 mSv is very large, with first-year dose ranging from about 50 to 60 mSv even at a distance of 200 km from the reactors. At that distance, for a prevailing wind blowing toward the northeast, the plume would intersect population sectors including Yokohama, Tokyo, and beyond.

Figure 2-31: First-year Estimated External Dose from a Radiological Release Incident at Hamaoka Unit #3 or #4 Involving the Reactor Core (Scenario 1)

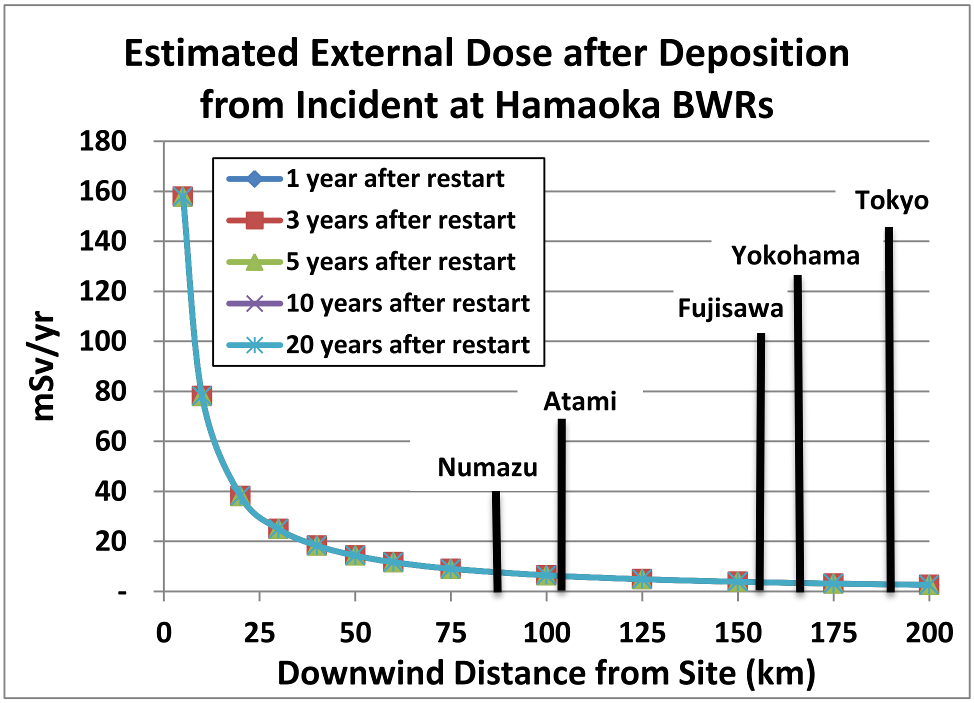


Figure 2-32: First-year Estimated External Dose from a Radiological Release Incident at Hamaoka Unit #3 or #4 Involving the Spent Fuel Pool (Scenario 2)

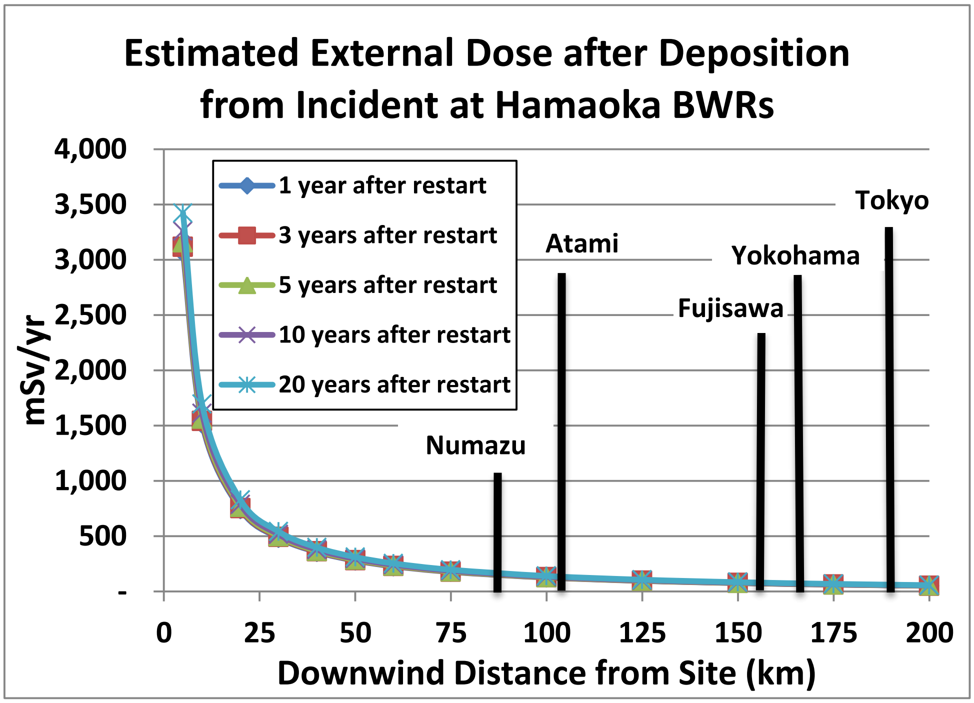


Figure 2-33: First-year Estimated External Dose from a Radiological Release Incident at Hamaoka Unit #3 or #4 Involving the Reactor and Spent Fuel Pool (Scenario 3)

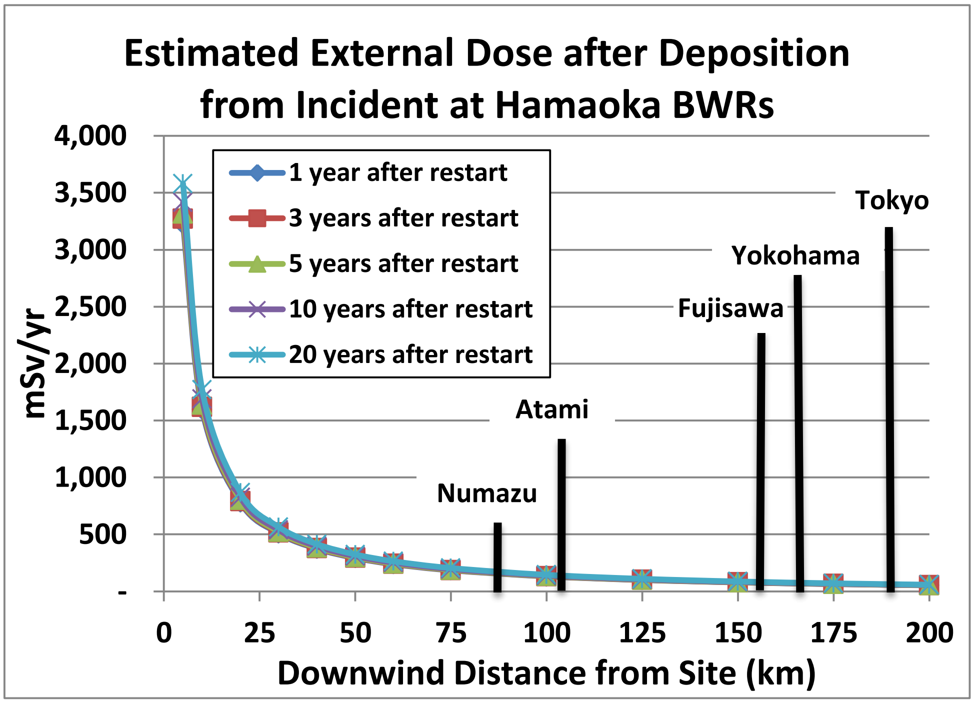


Figure 2-34, Figure 2-35, and Figure 2-36 show the cumulative dose over time for exposures resulting from radiological release incidents involving one of the Hamaoka reactors (again, Unit #3 or Unit #4), one of the spent fuel pools, and a reactor and a spent fuel pool, respectively. For Scenario 1, exposure at the smaller population centers of Numazu and Atami exceed the USEPA's cumulative 50 mSv 50-year dose guideline for an exposed individual, but exposure at the larger population centers of Fujisawa, Yokohama, and Tokyo would not. Cumulative doses under Scenarios 2 and 3, however, would exceed USEPA guidelines by a factor of 10 over a radius of 200 km, that is, past Tokyo. In all cases, releases were modeled as occurring 3 years after the restart of the reactors. For an incident occurring later (when spent fuel pools have slightly higher Cs-137 inventories), cumulative doses under Scenarios 2 and 3 are marginally higher.

Figure 2-34: Cumulative Estimated External Dose from a Radiological Release Incident at Hamaoka Unit #3 or #4 Involving the Reactor Core (Scenario 1)

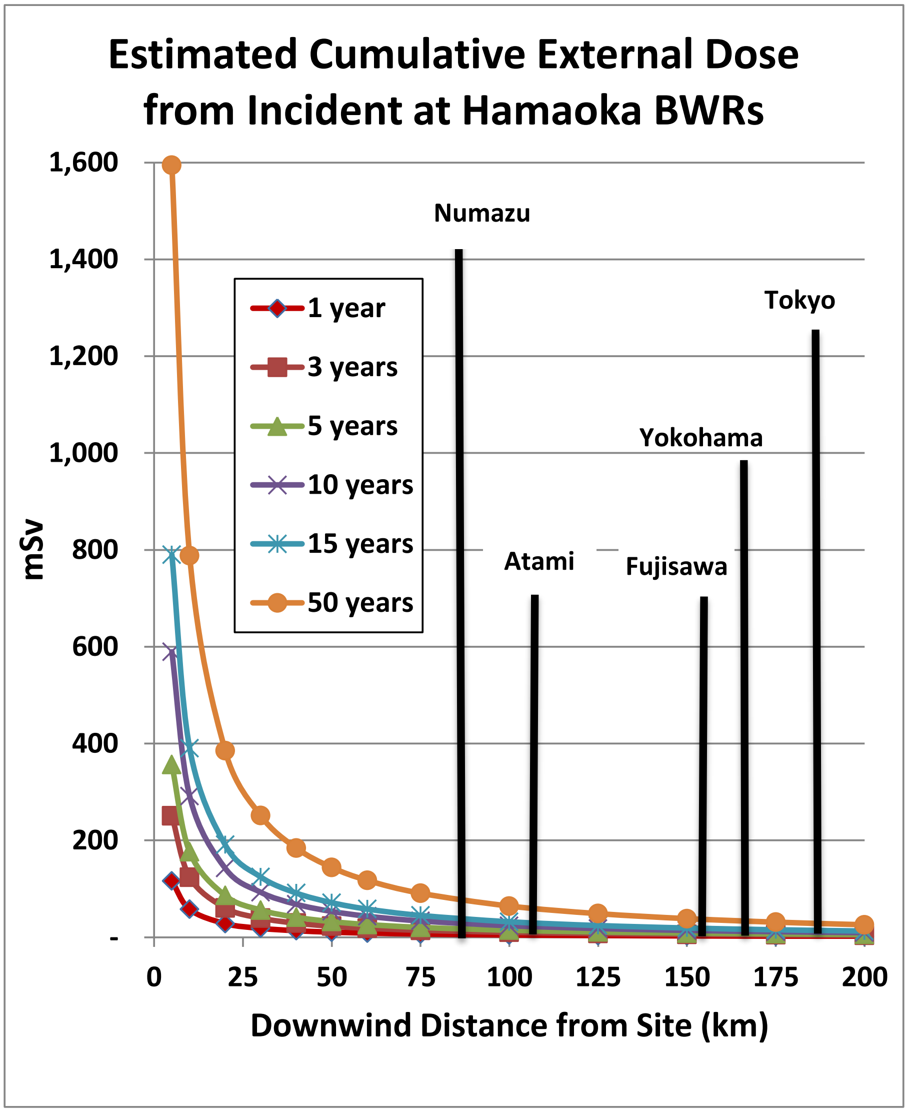


Figure 2-35: Cumulative Estimated External Dose from a Radiological Release Incident at Hamaoka Unit #3 or #4 Involving the Spent Fuel Pool (Scenario 2)

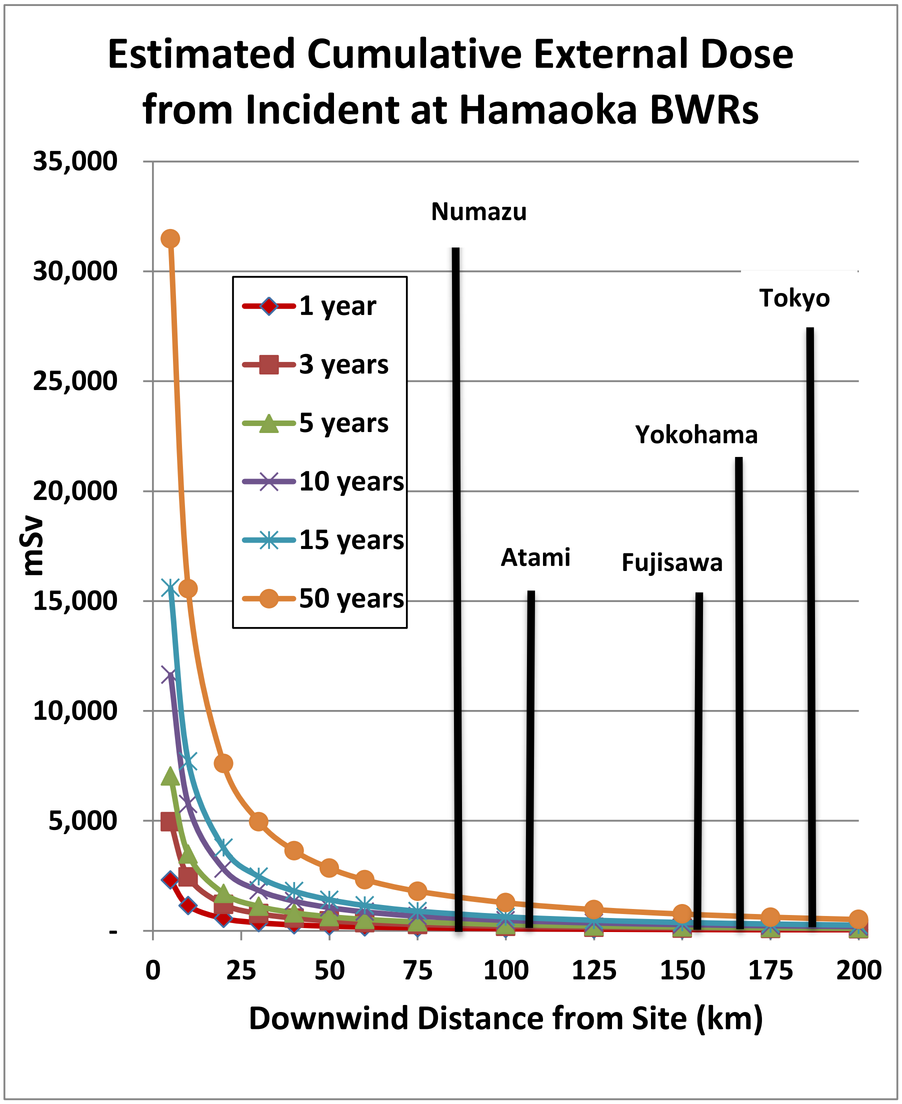


Figure 2-36: Cumulative Estimated External Dose from a Radiological Release Incident at Hamaoka Unit #3 or #4 Involving the Reactor and Spent Fuel Pool (Scenario 3)

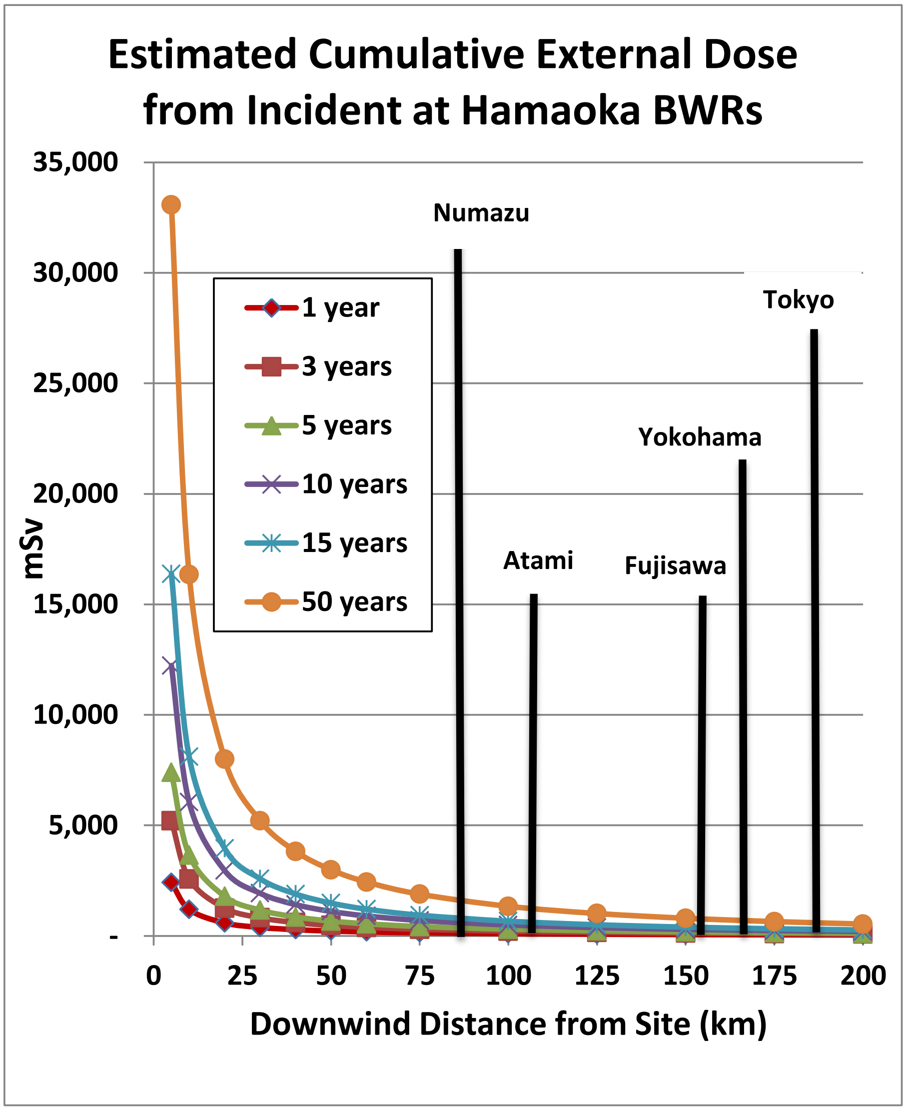


Table 2-8 and Table 2-9 present estimates of the number of premature deaths from cancers resulting from 50-year exposures associated with reactor and reactor/spent fuel pool incidents at Hamaoka reactors Units #3 or #4 (Scenarios 1 and 3). The assumed exposure time is 50 years. (Results for Scenario 2, an incident involving a spent fuel pool only, are not shown, but are just slightly lower than those shown for Scenario 3, since the release of radioactivity from the spent fuel pool dominates the Scenario). In Scenario 1, about 20,000 premature deaths in the communities included in this assessment result at rates ranging from about 0.4% in the community closest to the nuclear plants, to under 0.2% in the nearby big urban areas, including Yokohama and Tokyo. For the scenario postulating an incident involving a spent fuel pool and a reactor, the impacts are much greater, with about 450,000 premature deaths in the included communities, and rates of premature death of about 8% in the closest community and on the order of 3 to 4 percent in the big nearby cities.

Table 2-8: Calculation of Collective Dose at Selected Locations along a Northeast Deposition Path from Hamaoka for a Release 3 Years after Reactor Restart Modeled for Scenario 1, Reactor Incident

	Diameter (km)		Population Density	Initial Collective Radiation Dose
Location	Inner	Outer	persons/km^2	person-Sv/yr
Numazu	80	90	913	1,506
Atami	100	105	294	233
Fujisawa	150	160	1,084	1,528
Yokohama	160	180	5,667	15,457
Tokyo	180	210	6,038	23,363

	Cumulative Collective Radiation Dose	Exposed Population	Percent Excess Deaths	Implied Number of Excess Deaths
Location	person-Sv	People	%	
Numazu	15,212	193,978	0.400	776
Atami	2,355	37,664	0.319	120
Fujisawa	15,441	419,916	0.188	787
Yokohama	156,168	4,816,667	0.165	7,965
Tokyo	236,051	8,830,575	0.136	12,039
TOTAL of all locations (not total of exposed area)	425,226	14,298,800	0.152	21,687

Table 2-9: Calculation of Collective Dose at Selected Locations along Deposition Paths from Hamaoka Nuclear Power Plants for Release 3 Years after First Refueling Modeled for Scenario 3, Reactor and Spent Fuel Pool Incident

	Diameter (km)		Population Density	Initial Collective Radiation Dose
Location	Inner	Outer	persons/km^2	person-Sv/yr
Numazu	80	90	913	31,233
Atami	100	105	294	4,836
Fujisawa	150	160	1,084	31,703
Yokohama	160	180	5,667	320,643
Tokyo	180	210	6,038	484,660

	Cumulative Collective Radiation Dose	Exposed Population	Percent Excess Deaths	Implied Number of Excess Deaths
Location	person-Sv	People	%	
Numazu	315,558	193,978	8.297	16,093
Atami	48,859	37,664	6.616	2,492
Fujisawa	320,311	419,916	3.890	16,336
Yokohama	3,239,619	4,816,667	3.430	165,221
Tokyo	4,896,758	8,830,575	2.828	249,735
TOTAL of all locations (not total of exposed area)	8,821,105	14,298,800	3.146	449,876

As with the other radiological exposure results presented in this report, we prepared rough estimates of damages related to premature human deaths based on two estimates of the "value of a statistical life" compiled in a review of a number of studies, and bracketing a range from $1.1 million to $10 million per person in 2012 dollars. Applying these estimates yields values in the range of $20 to $300 billion for an incident involving a Hamaoka reactor only, rising to perhaps $500 billion to $6 trillion for an incident involving a reactor and a spent fuel pool. Again, the vast bulk of the radiation release is from the spent fuel pool, and as in the Daya Bay and Ling'Ao plant estimates, these totals do not factor in population areas that the plume of material released will encounter that are not included in the Tables above. Once more, the reader is urged to bear in mind uncertainties in this calculation caused by the combination of high-low dose response assumptions with high-low estimated values of excess deaths. In addition, if prevailing winds at the time of an incident resulting in radiological release are not blowing in the northeastern direction posited here, population exposures and damages would be different, and likely much lower, than indicated in the tables and figures above, essentially, all the way down to zero or near-zero. As noted above, if the prevailing wind direction at the time of a radiological release is to the east or to the west-southwest, which are also consistent with dominant winds near Hamaoka at different times of the year, the exposure versus distance data shown in Figure 2-28 through Figure 2-36 would still hold, but the exposed populations, collective dose, and excess deaths results shown in Table 2-8 and Table 2-9 would be much lower, on the order of a fraction of a percent to a few percent of that of a plume headed toward the Tokyo area. A plume that headed toward the Nagoya or Osaka/Kyoto areas, which is consistent with wind directions during about 10 percent of the year, would cause somewhat lower aggregate exposures—perhaps a quarter to a half—of the exposures we estimate for a plume headed toward Tokyo. If the plume heads only over the ocean, with is consistent with winds that prevail about half of the time over the year, aggregate exposure could possibly be zero (except for the few people unfortunate enough to be on vessels in the path of the plume).[48] This range—from the results shown for a plume heading toward Tokyo to one that heads out to sea—represent the true uncertainty and unpredictability of such extreme events, the probability of which cannot be determined except to say that it is finite.

Although we have not performed the calculation explicitly, it is likely that the weighted averages of total exposures and excess deaths over the annual average of all wind directions in a year, taking into account all possible wind directions, probabilities, and exposed populations, would be on the order of 25 to 35 percent of the totals shown in Table 2-8 and Table 2-9.

The wind patterns in the Hamaoka area in this case provide a period of "natural protection" during which a non-state actor attack would be defeated, even in the worst release scenario, by wind directions, limiting the period for a successful attack that is likely to cause damaging exposure to significant populations to a relatively narrow period each year (mostly summer).

As noted above, this analysis is a first-order estimate only, taking into account only one wind direction at a time. As such, it does not, for example, include explicit modeling of a return of the plume from offshore when winds shift, directing radioactive aerosols back over Japan or over other landmasses or islands to potentially irradiate populations. The estimate provided in this analysis is therefore only a first order estimate of worst-, intermediate-, and best-case vulnerability of local populations to radiological releases caused by an accident at or attack on the Hamaoka nuclear plants.

2.5 Radiological Risk Estimate for DPRK LWR

The Democratic People's Republic of Korea, after the failure of the Six-Party Talks (and subsequent negotiations) on the DPRK's nuclear weapons program, announced that, in the absence of international assistance to complete a pair of commercial-scale (1000 MW) light-water reactors (LWRs) begun at Simpo in the 1990s, the DPRK was building its own domestically designed LWR. The plan to develop a domestic LWR, and initial work at the site

[48] Even a plume directed only over the ocean does not rule out secondary sources of exposure and other impacts of the deposition of radioactivity resulting from an accident or attack, as there would almost certainly be impacts on fisheries and exposure related to humans and animals consuming marine products from the affected area. Such would be the case even for a plume that headed toward the Tokyo area, which would cross bays in several areas.

of the plant—the Yongbyon nuclear complex in the northern part of the DPRK— were revealed to Western visitors in late 2010.[49] Satellite imagery confirms that construction on this small LWR has continued through 2012, 2013, and early 2014. Many of the details of the plant's design, however, including the safety, control, and other systems that it will employ, remain unknown.

As an illustrative application of Dr. Thompson's methodology of radiological risk assessment, as described above, Nautilus has undertaken a study of the potential radiological releases from the small LWR being built by the DPRK. Given the many unknowns about the DPRK reactor, this study is of necessity quite approximate and indicative in nature, and its results should be considered in that light.[50]

Below we provide a summary of what is known (and assumed) about the DPRK's under-construction LWR, followed by a discussion of the other assumptions included in our application of the radiological release methodology. We then present the results of our analysis of potential radiological releases resulting from an accident at or attack on a completed Yongbyon LWR, and conclude with a discussion of potential lessons from, and implications of, the analysis.

We focus herein solely on the small LWR, and do not examine the safety dimensions of operating the co-located small graphite-moderated reactor reportedly restarted in 2013, or possible interactions between the failure of one reactor and the safe operation of the other. graphite-moderated reactors using magnox fuel cladding are subject to fire should the heat removal fluid (carbon dioxide) be lost in the core, potentially leading to radiological release. There is no reason to believe that the DPRK's graphite-moderated reactor is exempt from this problem—however, it was not the subject of our current analysis.[51]

In a visit to the DPRK's Yongbyon nuclear complex in late 2010, a delegation from the United States including Siegfried Hecker of Stanford University were shown an operating uranium enrichment facility previously unknown to international observers, and were told that the DPRK was constructing an experimental Light Water Reactor (LWR), as part of a DPRK effort to develop a domestic nuclear energy source.

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[49] Siegfried S. Hecker (2010), *A Return Trip to North Korea's Yongbyon Nuclear Complex*. NAPSNet Special Report, dated November 22, 2010, and available as http://www.nautilus.org/publications/essays/napsnet/reports/a-return-trip-to-north-korea2019s-yongbyon-nuclear-complex.

[50] The report summarized here updates our earlier analysis of the DPRK small LWR in D. von Hippel, P. Hayes, "*Engaging the DPRK Enrichment and Small LWR Program: What Would It Take?*, *NAPSNet Special Report* December 23, 2010, at: http://nautilus.org/napsnet/napsnet-special-reports/engaging-the-dprk-enrichment-and-small-lwr-program-what-would-it-take/#axzz2jbioAuWt

[51] J. Ryall, "North Korean nuclear reactor work 'could end in catastrophe,' *The Telegraph*, September 12, 2013 at:http://www.telegraph.co.uk/news/worldnews/asia/northkorea/10304233/North-Korean-nuclear-reactor-work-could-end-in-catastrophe.html For an historical example involving the UK's Calder Hall graphite moderated reactor and fire, see: S. Reid, "Britain's nuclear inferno: How our own Government covered up Windscale reactor blaze that's caused dozens of deaths and hundreds of cancer cases," *Mail Online*, March 19, 2011, at: http://www.dailymail.co.uk/news/article-1367776/UK-Government-covered-nuclear-reactor-blaze-caused-death-cancer.html#ixzz2jc7EYGXg

Shortly thereafter, Hecker described his visit in a report that also expressed concerns about the potential safety shortcomings of a DPRK reactor. If those safety concerns are realized, the DPRK LWR could, once commissioned, be vulnerable to accidents causing significant radioactive releases.

2.5.1 Modeling Assumptions

The under-construction DPRK LWR was planned to have (and, we assume, has or will have) the following approximate characteristics:

- Designed heat output: 100 thermal megawatts (MWth)
- Electricity generation capacity: 25-30 MWe (megawatts electric output, by Hecker's estimate). We assume for the sake of this calculation that the output is 25 MWe, implying a relatively low conversion efficiency of 25 percent. A relatively low conversion efficiency would be expected for a first-of-its-kind technology.
- Level of enrichment in U_{235}: 3.50 percent.
- Mass of Uranium in the reactor core: 4 tonnes heavy metal (tHM).
- Implied rate at which the reactor uses fuel per unit output: 40 kg HM per MWth.
- Height of containment structure: 40 meters.
- Diameter of containment structure and reactor dome: 22 meters.

Construction of the DPRK LWR in recent years has not been on site by international visitors, but satellite photos taken over the last two years have shown continuous progress in construction of structures in the area of the reactor. Figure 2-37 shows a photo of the reactor complex area in late 2010, probably about the time that Hecker and his colleagues visited the site. Figure 2-38 shows the site as of early 2014, with the reactor building complete and the reactor vessel apparently installed inside. Figure 2-39 show the site as it looked in mid-2015, with additional site work done and the building adjacent to the reactor building looking more complete.

Figure 2-37: DPRK LWR Reactor Site, Late 2010[52]

[52] From "North Korea Makes Significant Progress in Building New Experimental Light Water Reactor (ELWR)", *38 North*, 14 November 2011, http://38north.org/2011/11/elwr111411/. In addition, and relevant to Figure 2-2, Choe Sang-Hun (2012), "Progress Is Cited on New Reactor in North Korea", *New York Times*, dated, August 21, 2012, and available as http://www.nytimes.com/2012/08/22/world/asia/progress-on-new-nuclear-reactor-in-north-korea.html includes the following related to construction of the DPRK LWR: "Allison Puccioni, a satellite image analyst at IHS *Jane's Defence Weekly*, said Tuesday that North Korea had completed a major step in the construction by placing a 69-foot dome on the reactor building. She based her conclusion on images taken by the GeoEye-1 satellite on Aug. 6."

Figure 2-38: Satellite Photo of Yongbyon Reactor, Early 2014[53]

[53] From Google Maps. Photo showing most elements of site looking similar to how they appear in image in mid-2013 images. Photo taken in January or early February of 2014 (extracted 2/12/2014).

Figure 2-39: Satellite Photo of Yongbyon Reactor, Late Spring or Early Summer, 2015[54]

Not yet described in available reports, however, are other details of the reactor, such as the size, number, and other characteristics of the fuel rods/bundles, though Hecker reported that the North Koreans planned to use uranium oxide (UO_2) fuel. Hecker reports that North Korean engineers have told him that that the LWR is to be a PWR (pressurized water reactor).[55]

We also assume that the DPRK LWR will use stainless steel cladding for the fuel rods, rather than the Zircaloy (typically 98 or more percent zirconium alloyed with small amounts of other metals)[56] cladding usually used on LWR fuel rods. We make this assumption because we assume that the DPRK would have difficulty with Zircaloy metallurgy, and might have difficulty importing Zircaloy due to international sanctions. In conversations with DPRK nuclear engineers, Hecker was told that a decision had not yet been made as to the composition of the cladding of the fuel for the DPRK LWR. The assumption of the use of stainless steel cladding is of importance in terms of radiological risk because in the presence of oxygen and water vapor at high temperatures, Zircaloy reacts with steam to produce hydrogen, and can also ignite, causing a fire that can spread radioactive materials into the atmosphere. Stainless steel cladding can also

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[54] From Google Maps. Photo showing most elements of site looking similar to how they appear in image in mid-2013 images. Based on the status of crops in nearby fields and trees in nearby forests, the photo appears to have been taken in late Spring or early Summer of 2015 (extracted 7/17/2015).

[55] S. Hecker, personal communication, 1/19/2014.

[56] See, for example, C.L. Whitmarsh (1962), *Review of ZIRCALOY-2 and ZIRCALOY-4 Properties Relevant to N.S. Savannah Rector Design*, Report ORNL-3281, UC-80 - Reactor Technology, TID-4500 (17th ed.), apparently dated July 9, 1962, and available as http://web.ornl.gov/info/reports/1962/3445605716311.pdf; and Atom.com (2012), "Zircaloy-4(Alloy Zr4) (UNS R60804)", updated: Jun 11, 2013, and available as http://www.azom.com/article.aspx?ArticleID=7644.

evolve hydrogen under similar conditions, but stainless steel's rates of hydrogen evolution is less, by a factor of two or more, than that of Zircaloy under the same conditions.[57] A comprehensive evaluation of the relative costs and benefits of the two cladding materials from a radiological release and in-reactor performance perspective apparently remains to be done.[58] The United States Nuclear Regulatory Commission has released an extensive review of the potential environmental impacts of different modes of spent fuel storage, in which a discussion of spent fuel pool "fires" is included.[59]

The methodology requires a description of the reactor complex—which we have provided (at least approximately) above, and second, an estimate of the inventory of spent fuel in the reactor and in storage at the time of the assumed incident, and an estimate of how much of certain key radioactive species are present in the fuel at that time. In order to estimate these quantities, we assume, for the sake of the radiological risk assessment calculation that:

The reactor has operated for 1, 3, 5, 15, and 20 years as of the time of this radiological risk calculation. Assuming that the reactor had operated for less time yields a lower inventory of radioactive products overall, as shown in Figure 2-40.

- The reactor operates at an average capacity factor of 80 percent. This is somewhat less than the typical capacity factor for many LWRs worldwide, though in fact not so different than that experienced in Japan during most of the pre-Fukushima years. It is still likely to be an over-estimate of actual performance for the DPRK LWR.
- Approximately one-third of the reactor's core is replaced every 1.5 years, consistent with designs of PWRs (and BWRs) in general.[60]
- The spent fuel storage pool is assumed to be located, as in other PWR designs, near the reactor containment building.
- By 15 years after the first operation of the spent fuel pool inventory would be 12 tonnes HM. Note that this assumes that all of the spent fuel produced is not only placed in but stays in the spent fuel pool.
- We assume that the spent fuel pool capacity (packed at low or standard, not high, density) is approximately five times the core size, or sufficient to accommodate 20 tonnes HM of spent fuel assemblies.[61]

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[57] L. Baker, Jr. (1983), "Hydrogen-Generating Reactions in LWR Severe Accidents", prepared for International meeting on light-water reactor severe accident evaluation; Cambridge, MA (USA); 28 Aug - 1 Sep 1983, and available as http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/15/003/15003080.pdf.

[58] Zircaloy has advantages as a cladding material over stainless steel in terms of its in-reactor performance, leading to reactor fuel cost advantages, but the authors and experts we have asked are unaware of studies that fully document the tradeoffs between the two cladding materials.

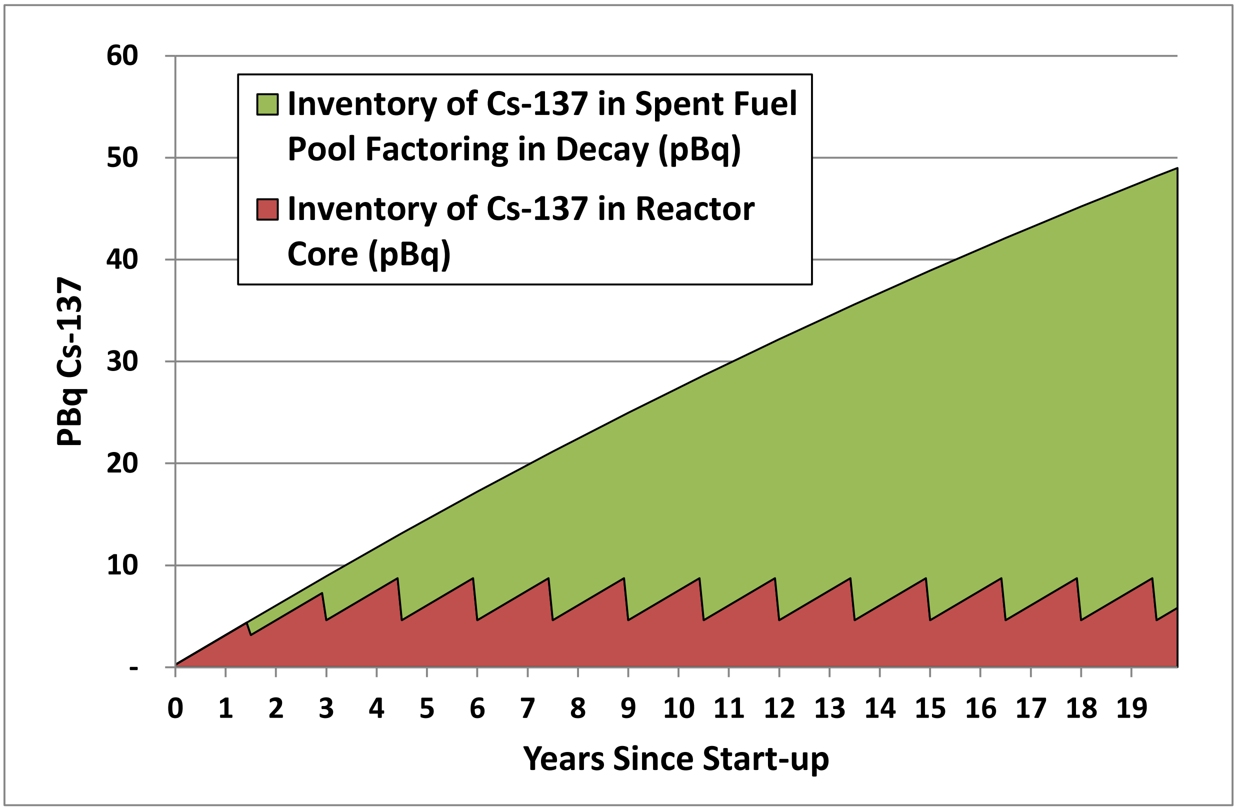
[59] United States Nuclear Regulatory Commission (NRC, 2013), *Waste Confidence Generic Environmental Impact Statement: Draft Report for Comment*, Report # NUREG-2157, dated August 2013, and available as http://pbadupws.nrc.gov/docs/ML1315/ML13150A347.pdf.

[60] See, for example, Nuclear Energy Institute, "Costs: Fuel, Operation, Waste Disposal & Life Cycle", undated, but probably 2013, available as http://www.nei.org/Knowledge-Center/Nuclear-Statistics/Costs-Fuel,-Operation,-Waste-Disposal-Life-Cycle.

- We assume that the *design* fuel burn-up at the DPRK plant was intended to average somewhat approximately the representative level of 32 GW-days/tHM, cited by Gordon Thompson for PWRs with enrichment of 3.2 percent U-235, which adjusted for the higher assumed enrichment in the DPRK reactor fuel yields 35.0 GW-days/tHM, We assume somewhat actual average burn-up is lower than this design level, however, because it will take DPRK technicians some time to become proficient in fuel fabrication and handling. As a consequence, we assume an average burn-up of 28 GW-days/tHM over the reactor lifetime, which implies that the average full-load thermal output is about 85 MWth, rather than 100 MWth, if we continue to assume that the mass of the reactor core is at the as-reported level of 4 tHM. Average burn-up is thus assumed to be 28 GW-days/tHM for spent fuel added to the spent fuel pool during and after the third refueling of the reactor (that is, from 4.5 years after start-up on).
- The average age (after discharge) of spent fuel in the spent fuel pool is 6.75 years (calculated) after the reactor has been operating for 15 years.
- We assume that the DPRK converts to dense racking when or if the amount of spent fuel in the pool plus the amount of fuel in one core plus the amount require for one refueling of the reactor would exceed the capacity (at standard packing density) of the reactor pool. Based on the assumptions above, this would occur after about 17 years of reactor operation.

[61] See, for example, R. Alavarez (2011), *Spent Nuclear Fuel Pools in the U.S.: Reducing the Deadly Risks of Storage*, Institute for Policy Studies, released May 24, 2011, and available as http://www.ips-dc.org/reports/spent_nuclear_fuel_pools_in_the_us_reducing_the_deadly_risks_of_storage.

Figure 2-40: Estimated Cesium-137 Inventory in DPRK LWR versus Years since Reactor Start-up



In order to estimate the radiological outcome of an accident at or attack on a reactor and/or spent fuel storage complex, it is necessary to make assumptions about the degree to which each of the source of radioactivity (specifically, for this estimate, Cs-137) "participate in" (that is, are affected by to the extent that radioactivity is released) the event. For those fuel containing facilities of the reactor complex (reactor core, spent fuel pools, transport casks, and dry casks) that are involved in the event, it is further necessary to estimate a release fraction for the Cs-137 present.

We made the following assumptions in applying step 3 of the methodology developed by Gordon Thompson:

- Unlike larger LWRs, including the Fukushima BWRs, the core of the DPRK LWR will be sufficiently small that virtually no plausible accident scenarios related to, for example, technical malfunctions, inadvertent operator error, seismic damage, or industrial accidents can be devised that would lead to significant releases of Cs-137 to the atmosphere. The reason for this is that the core is sufficiently small that in the event of loss of coolant the reactor core would be self-cooling, and releases of Cs-137 would be small, if any. As a result, we assume that the reactor core has a "participation fraction" of

zero in the event of an accident. In the event of an attack, however, including through the use of explosives or via sabotage (whether carried out by those inside or outside the plants), the reactor core could be breached, thus for an attack scenario, we assume a participation fraction of one. This implies for an incident affecting the Yongbyon LWR, the reactor core is damaged such that a pathway for emissions of radioactive gases is created. An attack on the facility, in this case, is assumed to be a general one by a non-state actor using devices designed to cripple or destroy the facility, or carried out via sabotage, but is not specifically designed to maximize release of radioactive materials.

- The "Participation Fraction" for the spent fuel pool in an accident or attack was assumed to be zero until dense racking is needed. Thereafter, its participation fraction depends on the mode of the accident or attack, as described below.
- If, as has been reported, the DPRK LWR is a PWR, its spent fuel pool will likely be located outside of the reactor containment in an adjacent building, and at or below grade level (as opposed, for example, to the spent fuel pool location at a level above the reactor core used in the Fukushima BWRs). As such, its potential exposure to conditions that would cause it to release radioactivity to the atmosphere in the event of a reactor *accident*, for example, through a technical failure, operator error, or seismic event,[62] are likely more limited than would be the case for a BWR design.
- It is beyond the scope of this analysis to explore all of the possible accident or attack scenarios that could befall the DPRK LWR. Given the technical considerations above, we assume that the range of true *accident* scenarios that would involve a participation fraction significantly above zero for the spent fuel pool is very limited. Such an accident would have to apply to a spent fuel pool using dense packing of spent fuel. We do, however, consider as a worst-case scenario, an event in which the participation fraction in the event of an accident is one—due, for example, to a failure causing a large leak in the spent fuel pool under conditions where auxiliary cooling cannot be implemented in a timely fashion. The consequences of this worst-case accident scenario, for modeling purposes, are the same as for a scenario involving an attack designed to breach the spent-fuel pool while crippling the LWR itself.
- Under an *attack* scenario, the "Release Fraction"—that is, the fraction of Cs-137 released to the atmosphere—is assumed to be 0.3 for Cs-137 in the reactor core.
- For the spent fuel pool, though as noted above, given the period in operation assumed before an incident, the spent fuel pool is assumed not to be involved in releases of radioactivity until it is dense-packed. At that point, in a worst-case accident scenario or an attack scenario, the release fraction for Cs-137 becomes limited by our assumption of the use of stainless steel cladding for the reactors fuel assemblies. As an alternative

[62] Yongbyon is located in an area of relatively low historical seismic activity. See, for example, Wenjie Zhai et al., "Research in historical earthquakes in the Korean peninsula and its circumferential regions", *Acta Seismologica Sinica*, Vol.17, No.3, p.366-371, May 2004, as cited in Jungmin KANG (2010), *An Initial Exploration of the Potent ial for Deep Borehole Disposal of Nuclear Wastes in South Korea*, dated December 13, 2010, and available as http://nautilus.org/wp-content/uploads/2011/12/JMK_DBD_in_ROK_Final_with_Exec_Summ_12-14-102.pdf.

scenario, also in case of a worst-case accident or attack, we calculate releases of Cs-137 if the DPRK *does* use Zircaloy cladding. In this variant, the release fraction for the spent fuel pool is assumed to be 0.3 for the entire spent fuel pool once dense-racking has begun.

- No dry casks or transport casks are present at the time of the modeled accident, because spent fuel inventories have not yet accrued to the point that they are needed. If such casks were present, their participation fraction would be assumed to be zero.

In order to estimate the behavior of a radioactive plume rising from the Yongbyon LWR after an accident or attack (step 4 in the methodology), we make the following assumptions:

- The average wind speed at Yongbyon at the time of the accident or attack is 7 meters per second,[63] and prevailing winds at the time of the incident are out of the North or Northwest. As the prevailing winds on the Korean peninsula are typically from the North (that is, blowing toward the Republic of Korea) in the winter, and from the South (that is, blowing toward China and Russia) in the summer, this assumption is quite important in defining downwind assets.
- We used a 1 cm per second deposition velocity for particles released in the accident or attack. This is assumption is commonly used in the application of the wedge model, and is consistent with typical winter weather and windspeeds in the region of the Yongbyon site.

As noted, the fourth step in Thompson's methodology involves modeling the behavior of the plume of radioactive material released by the accident or attack and through subsequent damage at to the reactor and spent fuel stored at the site. A simple "wedge" model is used to carry out this modeling[64] Some of the assumptions made in applying the wedge model for a release of radioactivity from the LWR at Yongbyon include:

- A "Mixing Height" of 1000 meters, representing the height above the ground through which the plume of released materials is assumed to be mixed.
- A "Wedge Angle" of 0.25 radians (about 14 degrees), representing the spread of the plume of material as it travels downwind.
- A "Shield Factor" of 0.33, representing the average degree to which humans in the area of the plume are shielded from radiation.
- An exposure time of 5 years, though this parameter was varied in our application of the model for the purposes of sensitivity analysis.

[63] No direct weather data was immediately available for the Yongbyon area. As an approximate value, we assume 7 meters per second based very roughly on estimated values for the area around Yongbyon from a map developed by 3TIER (2011), "Global Mean Wind Speed at 80m", available as http://www.3tier.com/static/ttcms/us/images/support/maps/3tier_5km_global_wind_speed.pdf.

[64] Thompson (2013, ibid) refers to the source of the wedge model as Lewis et al (1975), H. W. Lewis (chairman) and eleven other members of the APS Study Group, "Report to the American Physical Society by the study group on light-water reactor safety", *Reviews of Modern Physics,* Volume 47, Supplement Number 1, Summer 1975.

- Distances for ground contamination and individual dose calculation were varied from 5 to 350 km from Yongbyon (see below).
- Calculations of collective dose were made at four locations, ranging from the immediate area near Yongbyon outward and southward to Seoul (see below).

Based on our assumption of a wintertime event (accident or attack) triggering releases of radioactivity from the LWR at Yongbyon, we reviewed the downwind assets that the plume would encounter. These include (but are by no means limited to):

- The plutonium separation complex at the Yongbyon site and other elements of the Yongbyon research area; this complex is located 1 to 2 km due South of the reactor site.
- The Chongchon River, which is 10-to15 km South of the reactor site, and to which the river flowing past the reactor site (within tens of meters of the reactor) is a tributary.
- A tributary of the Taedong river (which flows through Pyongyang), located about 30 km South of Yongbyon.
- The Pukchang power plant (the largest in the DPRK, with a nominal capacity of 1600 MW, and, probably, a functional capacity of 500 MW or so) about 35 km southeast of Yonbyon.
- The coal mining area of Anju, about 50 to 60 km to the Southwest of the reactor site. The Anju coal area is the site of one of the major mines in the DPRK.
- A number of cities with populations of 100,000 or greater, and located between 15 and 100 km from Yongbyon, as well as, further afield, the major cities of Pyongyang and Seoul. Table 2-10 provides a summary of the larger cities downwind of the reactor in winter.

Table 2-10: Major Cities Downwind from Yongbyon in Wintertime[65]

	Population (as of 2008)
Kaechon, 15 km South/Southeast	320,000
Anju, 30 km South/Southwest, an imporant coal-mining region	240,000
Sunchon, 50 km south, 10 km east	297,000
Sukchon, 60 km south, 10 km west (rough estimate)	100,000
Pyongsong, 80 km south	284,000
Pyongyang, 130 km south	3,255,000
Kaesong, 250 km south, 70 km east	308,000
Seoul (ROK), 310 km south, 100 km east (metro area)	16,000,000
Seoul (ROK), 310 km south, 100 km east	10,582,000

2.5.2 Results

As described in section 2.5.1, above, we quantitatively explored three different incident scenarios involving the DPRK LWRs. These scenarios can be summarized as follows:

- In the first scenario, which we characterize as "Worst-case Accident" (referred to also as "S1" below), the reactor itself is assumed to be highly unlikely to suffer a meltdown due to its small size. The spent fuel pool is assumed to suffer a loss of coolant, likely by suffering a major rupture.
- For the second scenario, which we characterized as "Worst-case Attack" (or "S2"), we assume that as a result of sabotage of reactor controls/components and/or an explosion that breaches the containment dome and reactor vessel, sufficient damage is caused that the cladding in the fuel in the reactor fails, and the cesium in the spent fuel is heated to the point that a portion of it is released to the atmosphere. In this scenario, the spent fuel pool cooling system also fails and/or there is a major rupture in the pool (the pool is also targeted by the attackers), leaving it vulnerable to overheating and eventual rupture of the cladding in the most radioactive fuel elements.
- For the final scenario, which we call "Worst-case Attack/Zircaloy cladding" (or "S3"), again, as a result of sabotage of reactor controls/components and/or an explosion that breaches the containment dome and reactor vessel, sufficient damage is caused that the cladding in the fuel in the reactor fails, and cesium is released to the atmosphere. In addition, in this scenario, the spent fuel pool cooling system also fails (it is also targeted by the attackers) but, different from S2, in this case the use of Zircaloy cladding is

[65] Source: *Wikipedia*, "List of cities in North Korea ", based on DPRK Census, available http://en.wikipedia.org/wiki/List_of_cities_in_North_Korea. Distances are approximate, based on measurements by the authors using Google Maps.

assumed to have been used by the DPRK, meaning that coolant loss results in a cladding fire if the pool is dense-packed.

These three scenarios, of course, do not begin to exhaust the universe of possible scenarios of damage and subsequent release of radioactivity that could result from different types of accidents or attacks on the DPRK LWR. Knowing as little as we do about the ultimate technologies to be used on the LWR, and with a wide range of different modes possible for a terrorist attack on the plant, we have chosen what we view to be illustrative "worst-case" scenarios in order to provide an upper bound possible emissions (the lower bound being zero).

Table 2-11 presents estimated atmospheric emissions of Cs-137 for each of these three scenarios for incidents occurring at different times after reactor start-up. An accident scenario—and again, there are many possible scenarios that could be devised—would likely not result in significant emissions until after the spent fuel pool began to be dense-packed, at a minimum 17 or so years into the future, and at that point, the assumption of stainless steel cladding would limit emissions of Cs-137 to about 0.1 PBq, a fraction of a percent of estimated emissions from Fukushima. In the other two scenarios, an attack on the LWR yields Cs-137 emissions to the atmosphere of about 2 PBq, or about 5-10 percent of total Fukushima emissions, with the exception being an attack on the reactor and spent fuel pool when the spent fuel pool is dense-racked **and** if Zircaloy is used as the cladding material for the reactor fuel. In this worst of worst cases we have explored, emissions would rise to about 15 PBq, on the order of half of atmospheric emissions from Fukushima as estimated to date.

Table 2-11: Estimated Cs-137 Emissions to the Atmosphere by Incident Scenario[66]

	Atmospheric Emissions of Cs-137 (PBq) for an Incident Occuring				
Scenario	1 year after start-up	3 years after start-up	5 years after start-up	15 years after start-up	20 years after start-up
S1: Worst-case Accident	-	-	-	-	0.1
S2: Worst-case Attack/Stainless Steel Cladding	0.9	2.2	1.7	2.6	1.9
S3: Worst-case Attack/Zircaloy Cladding	0.9	2.2	1.7	2.6	14.7

Figure 2-41 presents our estimates of ground contamination, at a range of distances from the reactor site, following the release of radiation from the Yongbyon LWR under the modeling assumptions presented above, for releases occurring 1, 3, 5, and 15 years after reactor start-up for scenarios 2 and 3. No significant emissions are likely during this period for Scenario 1, again because it involves only the reactor. Note that the results for years 3, 5, and 15 are quite similar as all involve releases only from the reactor core, and thus vary only based on the timing of the refueling cycle (with releases in year 3, in fact, being greater than in year 5). Figure 2-42 shows the same result for scenario 3 for a release occurring 20 years after reactor start up, at a time when the spent fuel pool is assumed to be dense-packed, and thus vulnerable to releases of

[66] Note that in this table, as for other results below, although results are sometimes presented, for convenience, with two or three significant figures, the many unknowns and uncertainties involved in the calculations that underlie these estimates mean that the actual precision of the calculations is likely to be no more than one significant figure.

radioactivity through failure or, when Zircaloy cladding is used, ignition of the cladding and fuel. Again, however, the assumption that the spent fuel pool would be dense-packed due to rising inventories of spent fuel may prove incorrect if, as is certainly at this point conceivable, the DPRK decides to attempt to reprocess some of the spent fuel from the LWR, and/or if some of the spent fuel is removed for storage elsewhere. Note that the scale on Figure 2-42 is different from that in Figure 2-41. Figure 2-43 presents estimates of the external dose after deposition for the attack scenarios 2 and 3 for an incident occurring one to 15 years after reactor start-up, again at a range of distances from the site of release. The accident scenario (scenario 1) is assumed to yield no significant emissions, and thus no dose, for an accident occurring up to 15 years after reactor start-up.

Assuming, based on USEPA recommendations, at 20 mSv (millisievert) threshold for the first year dose that would trigger abandonment of lands[67], the radius of land area contaminated to a dose threshold of 20 mSv would be about 3 kilometers, encompassing at least some of the Pu production facility and related areas at Yongbyon. Under attack scenarios 2 and 3, for a release after 3 to 15 years of operation (and after 20 years of operation in scenario 2), the area contaminated to the 20 mSv dose threshold would be on the order of 1 square km; a release after one year of operation would contaminate a slightly smaller area. In scenario 3, increasing the reactor's time in operation to 20 years increases the contaminated radius under scenario 3 to approximately 20 km, and the contaminated area to about 40 square km, making the consequences of the release much more serious both near to and far from the reactor site. The reason for this significant increase in risk is the assumed requirement to move to dense racking in the spent fuel pool used by the LWR could put the spent fuel, which is assumed in this scenario to have Zircaloy cladding, at risk.

As shown in Figure 2-43, the first-year radiological dose received in the vicinity of the nearest medium-sized city south of Yonbyon, the city of Anju, would be about 3 mSv per year for releases occurring 15 years or less after start-up, well below the EPA's guideline dose for abandonment of contaminated lands.

[67] Gordon Thompson (2013, ibid) describes the EPA's threshold value as follows: "In its guidance manual for nuclear incidents, the US Environmental Protection Agency (EPA) recommends that the general population be relocated if the cumulative 1st-year dose to an individual at a radioactively-contaminated location is projected to exceed 0.02 Sv. EPA states that the projected dose should account for external gamma radiation and inhalation of re-suspended material during the 1st year, but should not account for shielding from structures or the application of dose reduction techniques." (Note (f) for Table II.6-6.) The description refers to the US Environmental Protection Agency document, *Manual of Protective Action Guides and Protective Actions for Nuclear Incidents* (Washington, DC: EPA, Revised 1991, Second printing May 1992).

Figure 2-41: Ground Contamination Results for Attack Scenarios (2 and 3)

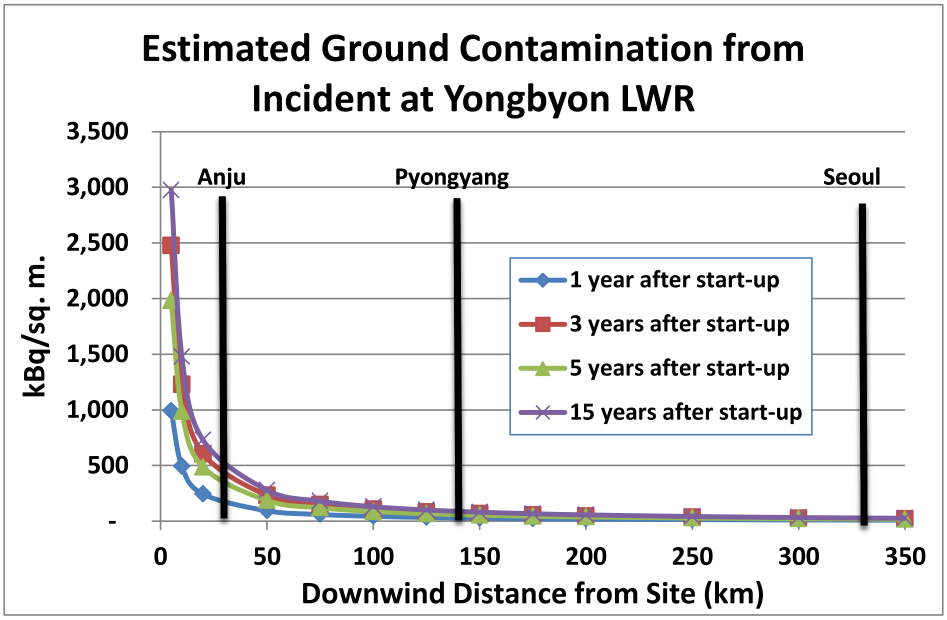


Figure 2-42: Ground Contamination Results for Attack Scenario 3 for an Incident 20 Years after Reactor Start-up

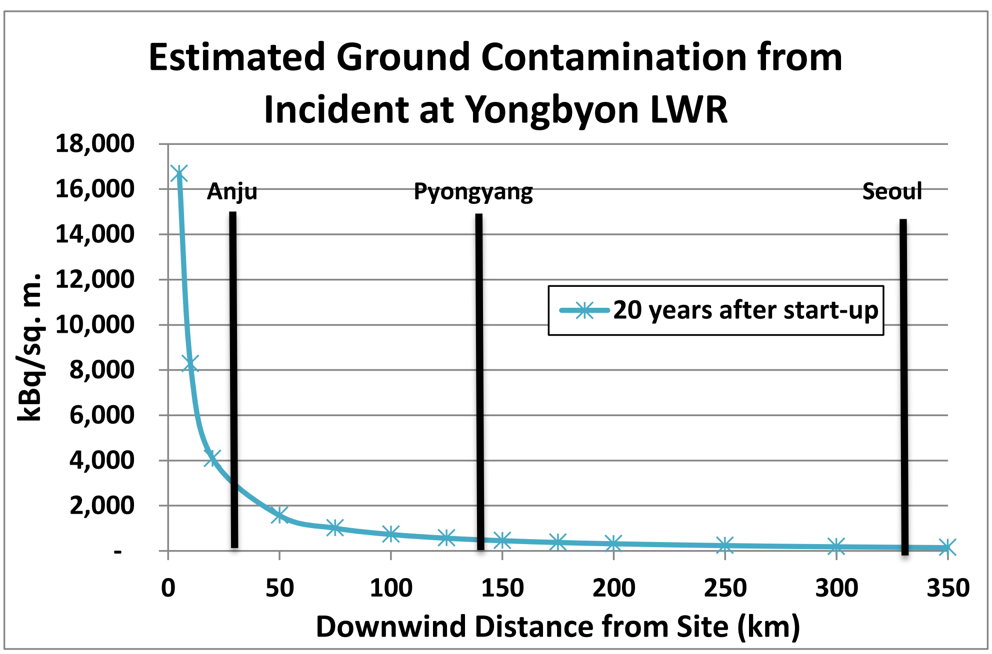


Figure 2-43: Estimated External Dose, Scenarios 2 and 3

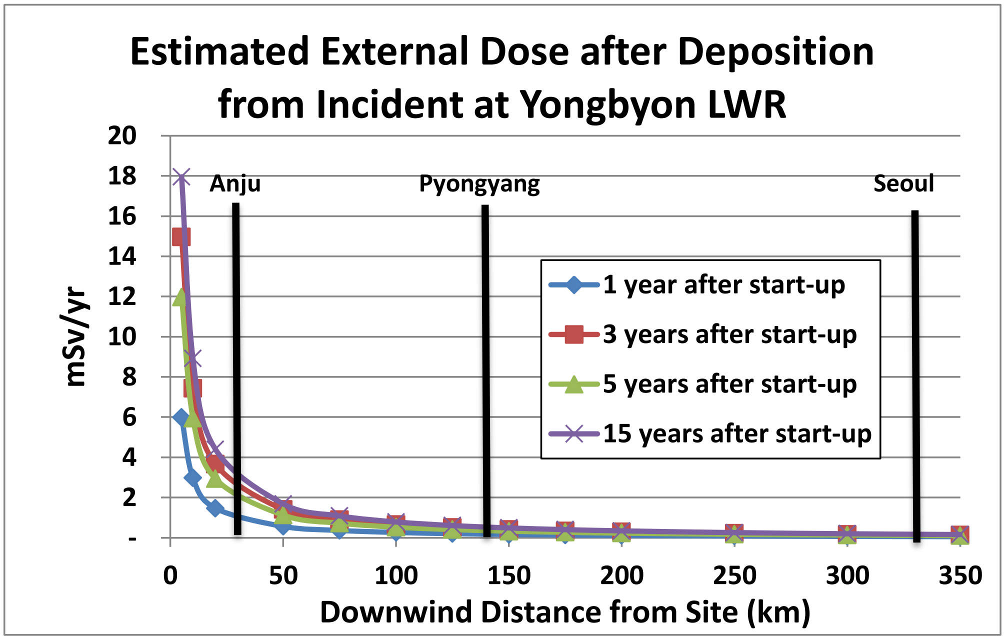


Figure 2-44 presents the estimated cumulative external dose from radiation release at Yongbyon under scenarios 2 and 3 at a range of downwind distances from the site, and over time periods ranging from 1 to 50 years, for a release occurring after 15 years of reactor operation. Assuming the USEPA's guideline that the cumulative 50-year dose to an exposed individual should not exceed 50 mSv[68], no medium or large cities in the DPRK would be within the cumulative exposure threshold area for a release not involving the spent fuel pool, though contamination at some smaller cities closer to Yongbyon could cross the long-term exposure threshold.

[68] As described by Gordon Thompson (2013, ibid).

Figure 2-44: Estimated Cumulative Dose, Scenarios 2 and 3

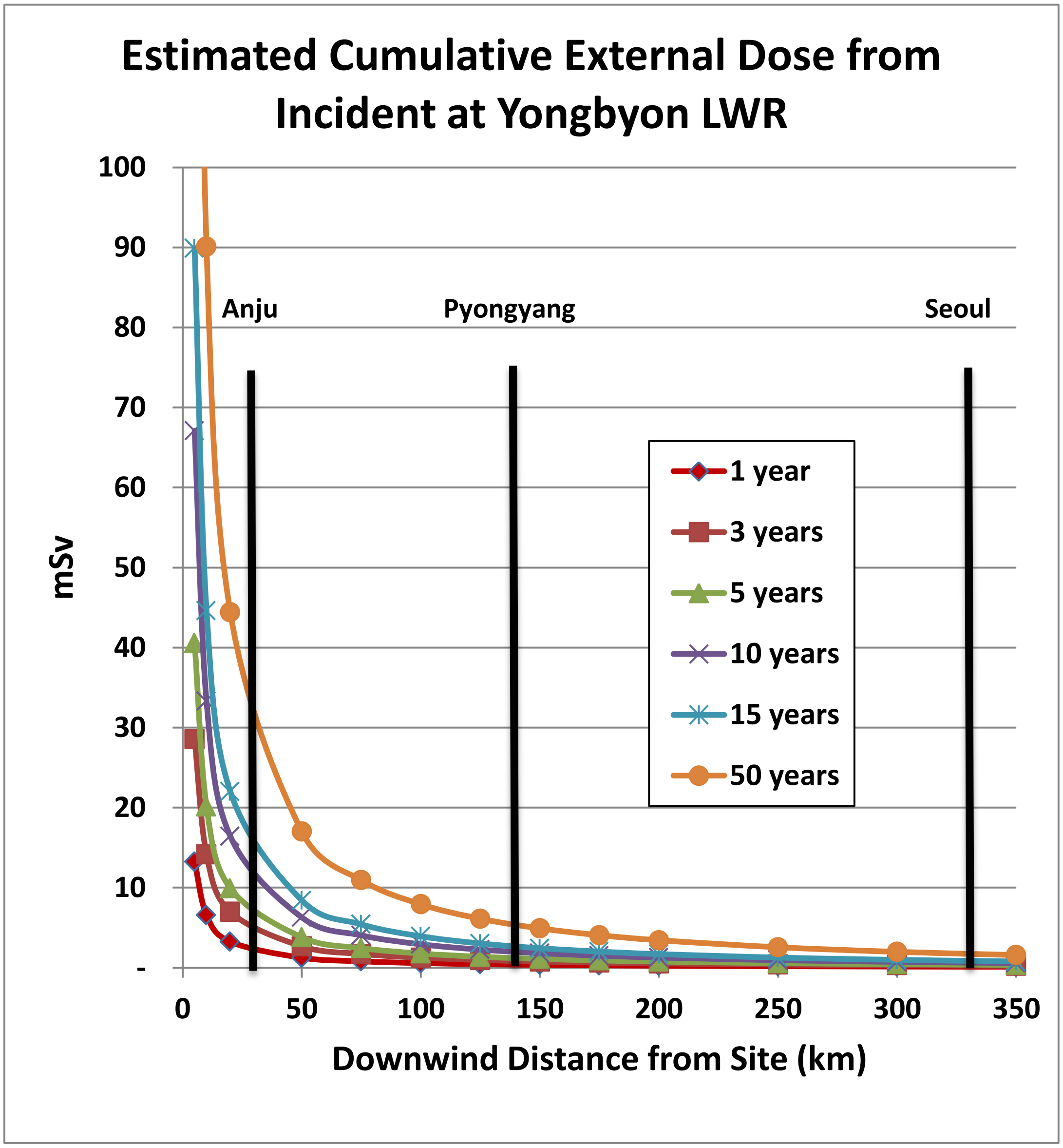


Table 2-12 presents estimates of the excess deaths implied in each of four locations, at varying distances from the release of radioactivity, for releases after 15, and 20 years of LWR operation, respectively, and assuming an exposure time of 10 years. These cities are examples of locations along potential southward downwind emission paths, and thus in interpreting the results in these tables, three issues must be kept in mind. First, using the wedge angle that we applied, the cloud of emissions would not, without a very discrete mid-incident shift in the wind, pass over both Pyongyang and Seoul. As a consequence, the rows in these tables cannot be summed to an overall value. A larger wedge angle could be used in the analysis, implying southerly winds that shift back and forth over time, but using a wedge angle that was, for instance, doubled (implying radioactivity would be dispersed over a wider area) would imply Cs-137 deposition and related results one-quarter of those shown. Second, the example cities listed are only some of the possible population centers along any given southerly downwind path, thus the sum of the impacts of listed cities that *are* within a given wedge angle from the Yongbyon source is not the sum of all of the affected individuals or impacts within the arc modeled. Third, though some general wind directions at specific times of year are more probable than others, many wind directions are possible at the specific time of an incident, meaning that the probability of any given city, particularly one far from Yongbyon, being affected may be small. Each calculation assumes an exposure time of ten years. As noted above, this calculation assumes that a linear dose-response relationship between excess deaths from solid cancers and radiation dose can be extrapolated linearly to zero for both dose and effect. As we have explicitly included only selected population centers between Yonbyon and Seoul (and beyond), our results indicate that on the order of several hundred early cancer deaths might arise as a result of the radiation released from an accident at or non-state attack on Yongbyon for releases occurring between 3 and 15 years after start-up, rising to on the order of perhaps a few thousand for a release 20 years after start-up. It should be stressed that in this context "early" may mean death occurs just minutes earlier than it might have in the absence of the additional radiation, and thus essentially indiscernible from deaths caused by background radiation. If, rather than using a no-threshold dose-response relationship, we count those individuals receiving a dose greater than approximately the USEPA's guideline (that a cumulative 50-year dose to an exposed individual should not exceed 50 mSv), the number of early cancer deaths falls to a few hundred for radiation releases between 3 and 15 years after start-up, with the number of people exposed to doses of that level on the order of a few hundred thousand.[69] In the very worst case, for a radiation release at 20 years after start-up and for scenario 3, which includes substantial emissions from the spent fuel pool because it assumes a Zircaloy cladding fire, neglecting those exposed to a dose less than 50 mSv suggests early cancer deaths numbering in perhaps the low thousands out of a population of a million or so exposed beyond the EPA's guidelines. In both cases, all of those individuals would be in the DPRK.

[69] The USEPA has recently drafted new guidelines for protecting the public in the event of a radiological emergency. See, for example, World Nuclear News (2013) "Update to US emergency guidelines", dated 16 April 2013, and available as http://www.world-nuclear-news.org/RS_Update_to_US_emergency_guidelines_1604121.html.

Table 2-12: Calculation of Collective Dose at Selected Locations along the Southward Deposition Path from Yongbyon for Release 15 years after Reactor Start-up, Attack Scenarios 2 and 3

	Diameter (km)		Population Density	Initial Collective Radiation Dose
Location	Inner	Outer	persons/km^2	person-Sv/yr
Yongbyon	0	2	2,000	100
Kaechon	13	17	20,000	1,800
Pyongyang	120	140	5,008	1,900
Seoul	315	335	4,185	1,200

	Cumulative Collective Radiation Dose	Exposed Population	Percent Excess Deaths	Implied Number of Excess Deaths
Location	person-Sv	People	%	
Yongbyon	300	1,000	1.700	17
Kaechon	6,600	300,000	0.110	330
Pyongyang	7,000	3,255,000	0.010	330
Seoul	4,400	6,800,000	0.003	200

In addition to the impacts on cancer deaths noted above, several types of economic damages could arise due to the release of radioactivity following an accident or attack on a LWR. These include:

- Economic damages related to premature human deaths due to the effects of radiation exposure.
- Direct economic impacts related to the loss of generating capacity in the DPRK due to the impacts of the accident or attack on the reactor (that is, to the loss of the reactor as a functional asset).
- Direct economic impacts related to the need to clean up the reactor site following an accident or attack.
- Economic damages related to the loss of use of areas (including the farms, homes, mines, and other assets in those areas) downwind of the reactor that are contaminated past a threshold of tolerance by radioactive materials as a result of the accident or attack, and/or the costs of decontaminating those areas sufficiently that they can be used again.

We prepared rough estimates of damages related to premature human deaths based on two estimates of the “value of a statistical life” compiled in a review of a number of studies, one of which is for the United States (about $10 million per person in 2012 dollars) and one of which is for the ROK (about $1.1 million per person).[70] Applying these estimates—and remembering that these calculations include both the extrapolation of the calculation of excess deaths to very low doses of radioactivity *and* the application of the value of a statistical life, each of which involves assumptions about which there is considerable debate—yields values in the range of $1 to perhaps $15 to 20 billion for events before 16 years after reactor start-up, and perhaps $10 to $100 billion for events after that point, for loss of life caused by a radiological release from the Yongbyon LWR, in both cases roughly factoring in population areas that the plume of material released will encounter that are not included in Table 2-12. Note, however, that the range of values per excess death that has been used here is adopted with no attempt to adapt it to DPRK conditions or practices, although the bulk of early cancer deaths would occur in the DPRK. It is important for readers to keep in mind that the range of excess deaths and value thereof is enormous in this sensitivity analysis due to the combination in the calculations of high-low dose response assumptions with high-low estimated values of excess deaths.

2.5.3 Conclusions

Our conclusions from the examination of the radiological risks associated with accident at or attack on the DPRK LWR are four-fold.

First, the radiological risk arising from the DPRK's small LWR should not be overstated, but it also should not be neglected. Should an accident (as opposed to an attack) occur at this LWR, the consequences would not be zero, but due to the technical characteristics of the reactor, they would likely be modest in scale and in scope. If the accident affected only the reactor, and not the spent fuel pool, it seems likely that radiological releases could be very small. The radiological consequences of a concerted terrorist attack on the reactor and associated facilities, however, could be more substantial, in terms of health impacts and damages to property. These impacts, however, are highly uncertain, and will remain so even after such an event due to the unresolved issue of dose-response threshold assumptions made to determine the excess deaths resulting from low-level radiation exposure. Thus, the primary predictable impacts of a radiological release from the DPRK's LWR will be psychological in terms of downwind perceptions and anxiety on the part of exposed or potentially exposed populations, and political, in terms of the policies adopted in anticipation or as a result of such an event.

Second, our appraisal is that the DPRK undertook this project at least in part in order to offset the loss of the KEDO (Korean Peninsula Energy Development Organization) LWRs that were to have been built under the original 1994 Agreed Framework between the US (and its allies) and the DPRK. The completion and operation of the KEDO LWRs would have, in the eyes of the DPRK leadership, brought the DPRK to co-equal status with other regional powers in terms of a complete nuclear fuel cycle—that is, the DPRK's small LWR is a symbolic project

[70] ROK value from p. 27 of W. Kip Viscusi and Joseph E. Aldy (2003), "The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World", *The Journal of Risk and Uncertainty*, 27:1; 5–76, 2003, one version of which is available as http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0483-09.pdf/$file/EE-0483-09.pdf. The US value roughly of $10 million per premature death from solid cancer corresponds to the high end of a range cited in Gordon R. Thompson (2013), Handbook to Support Assessment of Radiological Risk Arising from Management of Spent Nuclear Fuel, and is used in the Methodology set out in the Handbook.

aimed at embodying the perceived prestige of the DPRK state in the eyes of its own population and third parties, in accordance with the *juche* principle of self-reliance, and in response to the slight of the United States in cancelling the KEDO project, as well as to fulfill the leadership's long-standing commitment to build a nuclear power reactor, a commitment dating back to the early 1980s. Following the suspension of the KEDO project, the DPRK leadership sees this small reactor as a first step in gaining the experience needed to construct a reactor fleet based on domestic technologies. Nonetheless, the potential utility of the small LWR as a negotiating item, should the parties to the Korean conflict return to talks, cannot have escaped the attention of the DPRK's leadership.

Third, on balance and in light of our net assessment of the stakes involved with a potential incident at the DPRK small LWR leading to release of radiation, we conclude that it is timely for the ROK, the United States, China, Japan, and Russia—all potentially affected states—to engage the DPRK on the issue of nuclear reactor safety, irrespective of the nuclear weapons issue. Although it is difficult to bring the DPRK into the trilateral Cooperative Nuclear Safety Initiative while it remains completely isolated due to its nuclear weapons program, the earlier it is engaged on fuel cycle safety issues, the better, and this area is one in which confidence building measures with the DPRK should be undertaken.

Fourth, this analysis should lay to rest any argument that the DPRK's small LWR avails it of a way to lever the United States and its partners to engage it due to the radiological risks posed by the small LWR. Left to itself, radiological release due to technological failure, natural disasters, operating error, or malevolent state or non-state attack on the DPRK's small LWR poses a risk only to North Koreans, and because it is so small, even then it poses only a relatively small risk to North Korean public health due to the high levels of existing risk from disease, malnutrition, and other health risks in the DPRK. This conclusion arises from a careful consideration of the plausible pathways for release of radiation from the DPRK's small LWR and its spent fuel pond, over time, under a wide range of event specification and analytic assumptions, and in no way suggests a low valuation of North Korean lives that would be put at risk irrespective of the initial cause of the release. Rather, it is a statement of fact about the risk posed on populations outside the DPRK, whose welfare is the direct responsibility of external governments.

The only way we can envision a large-scale release of radiation, benchmarked against the release that occurred at Fukushima disaster for example, is deliberate, malevolent attack on the DPRK's small LWR and/or its spent fuel pond. In principle, the power grid connecting to the LWR also could be subject to attacks intended to cut off its power supply to adjacent areas, or to stop it operating for safety or other reasons, which could compound difficulties of maintaining control of the small LWR in the lead up to, during, or after a direct attack. Due to the risk of reciprocal attack, in which case, the ROK is disproportionately vulnerable, readers should note that we are *not* suggesting that US and ROK forces currently target the Yongbyon reactors or grid. Whether such attacks would be legal under international law in any circumstances remains controversial given reactor targeting during the Cold War, Israel's attacks on Iraqi and Syrian reactors under construction, and the International Atomic Energy Agency's 1990 resolution 510 on the "Prohibition Of All Armed Attacks Against Nuclear Installations Devoted To Peaceful

Purposes Whether Under Construction Or In Operation".[71] In 1994, US military planners did examine closely the feasibility of attacking the Yongbyon thermal graphite-moderated reactor to disable it, before it could accumulate large quantities of plutonium.[72] Such attacks therefore cannot be discounted.

Of course, the probability of such attack from a state-based actor is controlled by the DPRK's adversaries, not the DPRK itself (except to the extent it attempts to defend the small LWR against external attack—mostly likely with the surface-to-air missiles that defend the entire Yongbyon complex, and their associated radar systems). Today, the United States has low flying stealth aircraft (and in the future, drones) and air-launched cruise missiles able to exploit corridors that evade these radars and would be able to deliver precisely conventional warheads that would disable and destroy the small LWR. In this scenario, significant radiological release could occur, and we have addressed radiological releases roughly consistent with this scenario in our analysis.

The possibility of a reciprocal, retaliatory attack on the ROK's much larger LWRs or spent fuel storage sites, however, is likely to give the United States and its allies pause when considering this option, because the risks to populations and economic losses arising from successful North Korean missile bombardment of ROK LWRs or spent fuel sites are much greater to the ROK (including not only radiological exposure, but prospective loss of large fractions of the ROK's power supply) than the consequences of a successful attack on the DPRK's reactor. In short, the United States and its allies control most of the variables that would result in substantial radiological release from the DPRK's small LWR, but any leverage arising from that dominance is offset by the reciprocal threat posed by DPRK retaliation to ROK LWRs, neutralizing the US-ROK threat from the DPRK's perspective.

Finally, some would ignore the risk *of non-state* attack on the DPRK's LWR on the grounds that nuclear security in the DPRK is extremely tight—possibly more so than any other reactor site on Earth. In our view, any assumption that non-state actors are not present or unable to attack radiological facilities in the DPRK is just that—an assumption. Transnational criminal networks operate across borders and reach into the DPRK,[73] as do politically and ideologically motivated networks opposed to the regime. For all these reasons, it is appropriate at a purely analytical level to include state and non-state attacks on the reactor and its supporting

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[71] For discussion of the legal dimensions of attacking nuclear facilities, see D. Joyner, "Can the U.S. or Israel Lawfully Attack Iran's Nuclear Facilities?" Arms Control Law (blog), August 7, 2012, at: http://armscontrollaw.com/2012/08/07/can-the-u-s-or-israel-lawfully-attack-irans-nuclear-facilities/ and, International Atomic Energy Agency, "Prohibition Of All Armed Attacks Against Nuclear Installations Devoted To Peaceful Purposes Whether Under Construction Or In Operation," Governing Council resolution 533, GC(XXXIV)/RES/533, October 1990, at: https://www.google.com/url?q=http://www.iaea.org/About/Policy/GC/GC34/GC34Resolutions/English/gc34res-533_en.pdf&sa=U&ei=hhF3UuXFK-SujALfkIH4BQ&ved=0CAcQFjAA&client=internal-uds-cse&usg=AFQjCNFr4CI35gSvcCEZFdsOki4vHS0pWQ

[72] As recounted by A. Carter, W. Perry, *Preventive Defense, A New Security Strategy for America*, Brookings Institution, 1999, Washington DC, p. 129.

[73] J. Hastings, "The economic geography of North Korean drug trafficking networks," University of Sydney, January 2014, at: http://jvhastings.files.wordpress.com/2014/01/ripe-article-north-korea-release.pdf

infrastructure as possible reason for a reactor accident and radiological release, not only technological failures within the reactor itself.

The prevailing assumption is that the chance of non-state malevolent attack on the DPRK's nuclear facilities, including its small LWR, is non-existent, due in part to the related belief that there are no autonomous, non-state actors in the DPRK social system. Based on our experience of working in the DPRK as well as decades of close observation of DPRK decision-making at many levels, we believe that these assumptions and beliefs are wrong, both empirically, and in the underlying theoretical frameworks that shape these external perceptions of the social reality of the DPRK. This essay is not the place to engage in this debate. We admit that the DPRK has many cross-cutting surveillance and control apparati that provide the leadership with unparalleled means of control over the population.[74] We suggest, however, that fealty and ideological commitment are at the core of compliant individual and group behavior in the DPRK, not surveillance and terror. This issue is hotly contested among scholars of the DPRK's political culture. We believe that there *are* plausible scenarios of collapse and disorder in which insurgent individuals and networks could pose a threat to the regime, albeit of indeterminate probability.[75] In some scenarios in which the regime unravels from the top down, potential insurgent elements could find it useful to create spectacular threats in order to invoke US and ROK intervention. We stress that there is no empirical data on which to make such judgments at this point.

Relatedly, the DPRK was characterized in 2012 as having the worst nuclear security of the thirty states that have access to weapons-usable nuclear materials (based on an index ranking of five material quantity, security and control measures, global norms, domestic commitments and capacity, and societal factors).[76] If, as we suggest above, scenarios of non-state malevolent attack are plausible, then it is prudent for external powers party to the DPRK nuclear conflict to persuade the DPRK to implement its national obligations to control non-state actors in relation to weapons of mass destruction imposed on all states by UNSC Resolution 1540, including reporting to the 1540 Expert Committee. Participation in this regime may enable the DPRK to build confidence that the small LWR and DPRK spent fuel ponds are not vulnerable to non-state-actor malevolent attacks, and it is hoped that that by building control systems that meet international standards and are transparent to external actors, the DPRK can be induced to participate in the international nuclear security regime in a responsible manner.

2.6 <u>Potential Next Steps on the Radiological Risk Issue in NE Asia</u>

Reducing spent fuel density at existing and future reactors would require changes in design and operation, especially in BWRs (boiling water reactors). The resulting incremental cost of these

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[74] Oh Jae-hwan, "Security Agencies of North Korea under the Kim Jong Un Regime," *The Korean Journal of Defense Analysis,* 26:1, March 2014, pp. 117–131

[75] Peter Hayes, "Thinking About The Thinkable: DPRK Collapse Scenarios Redux", NAPSNet Policy Forum, September 24, 2013, http://nautilus.org/napsnet/napsnet-policy-forum/thinking-about-the-thinkable-dprk-collapse-scenarios-redux/

[76] Nuclear Threat Initiative, *NTI Nuclear Materials Security Index, Building a Framework for Assurance, Accountability, and Action,* January 2012, pp. 7, 14, at: www.ntiindex.org/static/pdfs/nti_index_final.pdf

changes per unit of electricity is highly likely to be tiny, but the benefits in terms of avoided risk of radiological emissions and damage could be huge, as could the benefits of avoided public anxiety. Conversely, the risks of not changing spent fuel pool practices could be catastrophic. Moreover, reducing pool density implies choices with regard to dry cask storage versus surface or underground spent fuel pools outside existing secure reactor containment buildings, posing different and new risks of technological accident and/or malevolent attack (in the ROK, DPRK missile or bomb attack; in the PRC, of non-state actor attack, in particular).

It is clear that further work is needed to identify technical means of reducing the risks associated with current common practices of spent fuel storage, to more rigorously estimate the relative costs and benefits of adopting risk-reduction approaches, to communicate the results of those assessments to decision-makers, and to work with decision-makers to develop policies that work toward risk reduction. One approach to accomplishing these tasks might be to convene an expert group on spent fuel management that includes both advocates of changed spent fuel management and critics and skeptics of the case that spent fuel pool density should be reduced. This might start in one country, probably Japan. Subsequently, the expert group could be broadened by convening a regional workshop involving representatives from the ROK, Taiwan, and China, as well as US and Japanese experts to address this issue, and ways to mitigate the different hazard events (natural disasters, aerial bombardment, non-state attack). In addition to expert meetings, synthesis, analysis, and summarizing of findings for policy input would be carried out.

In Japan, there is now a strong civil society and business constituency, as well as a well-informed nuclear-expert community, able and willing to address this issue in policy contexts, as part of the overall battle to reform the "nuclear village", and to reconstitute the social pact that sustains the LWR-reprocessing-breeder reactor strategy in Japan. These have been noted, and the need to confront them has been identified, in a recent International Panel on Fissile Materials publication.[77] In Korea, there is less public interest, but keen political and bureaucratic interest given the issue's salience of the US-ROK 123 negotiation. There are key political and social constraints on fuel storage options in both nations that need further exploration in light of recent events. Policy options are less constrained and therefore more open in China, and we believe that Chinese experts and policymakers will respond to new data and analysis.

In short, it is critical to nuclear security to clarify whether reducing spent fuel pool density is justified to reduce the possible risk of inadvertent or malevolent radiological release from spent fuel pools and reactor sites.

[77] Masafumi Takubo and Frank von Hippel (2013), *Ending reprocessing in Japan: An alternative approach to managing Japan's spent nuclear fuel and separated plutonium*. International Panel on Fissile Materials Research Report No. 12, dated November 2013, available as http://fissilematerials.org/library/rr12.pdf.

3 Nuclear Energy and Nuclear Spent Fuel Management in East Asia

Closely related to the issue of radiological risk from spent fuel management practices are nuclear energy and nuclear spent fuel management policies. In this chapter of this Final Report, we provide summaries and excerpts of papers and presentations commissioned by the Project from Country Team members in China, Japan, and the ROK, and briefly discuss nuclear energy policy and spent fuel management in the DPRK.

3.1 Nuclear Sector and Spent Fuel Policy in China

Though the decision to develop civilian nuclear energy in China dates back to the 1970s, concrete efforts to construct nuclear power plants (NPPs) began only in the late 1980s. The first commercial nuclear reactors in China came into operation in 1994. All of China's nuclear power units have been installed and started operation since that time, thus the history of civilian nuclear development in China spans less than twenty years.

The development of China's nuclear power was slow in its first decade, which is described as the period of "moderate development" for nuclear power. By the end of 2003, only eight units were in operation with 6.1 GWe of total installed capacity. China's development of nuclear power accelerated from 2004, when the so-called "nuclear renaissance" became a topic of worldwide discussion. Between 2004 and 2011, five new nuclear units were commissioned in China, with total capacity of 4.2 GWe. More importantly, China's national nuclear policy was changed from "moderate development" to "positive development", which resulted in construction starting for a large number of NPPs, with planning for many more underway. By the end of 2010, twenty six nuclear units with total rated capacity of approximately 26.2 GWe were under construction, and thirty two further units had been approved. The different planning authorities with jurisdiction over the nuclear sector announced their nuclear programs, with expectations ranging from 40 to 86 GWe of installed capacity in by 2020.

The 2011 nuclear accident at the Fukushima Daiichi nuclear power plant in Japan brought a sudden halt to the worldwide enthusiasm for nuclear power. On March 16, 2011, five days after the accident, the State Council of China announced the suspension of approvals of new nuclear projects, and started comprehensive safety inspections of all existing nuclear projects, including those in operation and under construction as well as all research reactors and fuel cycle facilities. The State Council also suspended construction of four approved units on which work was to begin in 2011. The HTR-PM project in Rongcheng, Shandong province, though ready for the first concrete to be poured for its foundations, was also delayed.

In June 2012, after gaining approval of the State Council in principle, the National Nuclear Safety Administration (NNSA) released drafts of "Report on safety inspection of national civilian nuclear facilities" (hereafter referred to as "Safety Inspection Report") and "The 12th Five-Year Plan for Nuclear Safety and Prevention and Control of Radioactive Pollution and the Long-term Vision by 2020" (hereafter referred to as "Nuclear Safety Plan").[78]

- The Safety Inspection Report covered 11 nuclear safety areas, including site selection and

[78] http://english.mep.gov.cn/News_service/news_release/201206/t20120621_231995.htm

external event evaluation; flood and earthquake resistance; extreme disaster prevention and protection; electricity blackouts and emergency plans; severe accident prevention and mitigation; environmental monitor systems; and emergency response system effectiveness.

- As concluded in the Safety Inspection Report, the operating reactors "basically fulfill" China's nuclear safety laws and regulations and the International Atomic Energy Agency's latest standards; The nation's reactors are capable of responding to basic accidents and severe accidents as designed, and safety risks are found to be under control.
- The Safety Inspection Report also pointed out four major safety problems, including the lack of severe accident alleviation rules, the use of an improper design basis for flood, tsunami and earthquake protection, and the use of an insufficient safety margin in planning.[79]
- The Nuclear Safety Plan laid out short-, mid- and long-term tasks to strengthen safety for NPPs, research reactors and fuel cycle facilities. For example, short-term tasks for operating reactors included inspecting and waterproofing all openings, electric cable lines, etc.; and ensuring cooling functions are maintained for the reactor core and spent fuel in the event of a blackout through the use of mobile generators and pumps.

In October 2012, according to an official statement, the Executive Meeting of the State Council approved the "Nuclear Power Safety Plan (2011-20)" and "Mid- and Long-term Development Plan for Nuclear Power (2011-2020)".[80] The statement said:

- China will also apply the world's highest safety requirements to new nuclear power projects and adhere to third-generation nuclear safety standards in constructing new projects.
- During the 2011-2015 period no nuclear projects would be constructed in inland regions, with construction allowed on only a few projects in coastal areas that have gone through adequate justification processes.
- China should constantly carry out safety upgrades on currently operating reactors and use the most advanced mature technologies.

On the same day, China also issued the 2012 edition of its Energy Policy White Paper, elaborating on its energy development policies, energy conservation and the promotion of renewable power sources. The white paper emphasizes that China will develop nuclear power in a safe and highly efficient way. China's installed nuclear power capacity is expected to reach 40 GWe by 2015. Soon after the publication of the White Paper, China restarted the nuclear projects suspended after the Fukushima accident.

In March 2013, *China Daily* news reports indicated:[81]

- Nuclear power totaling 3.24 gigawatts (GWe) will be added in China in 2013.
- 30 units were under construction in China with a total capacity of 32.81 GWe.

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[79] http://www.dynabondpowertech.com/en/nuclear-power-news/topic-of-the-month/30-topic-of-the-month/5935-problems-found-during-the-safety-inspection-of-civilian-nuclear-power-facilities
[80] http://news.xinhuanet.com/english/china/2012-10/24/c_131927898.htm
[81] http://usa.chinadaily.com.cn/china/2013-03/12/content_16301751.htm

- Installed nuclear capacity will total 58 GWe by 2020, accounting for less than 4 percent of China's total power-generating capacity.
- An additional 30 GWe of nuclear units will be under construction as of 2020.[82]

In terms of nuclear power capacity, four new units (3.6 GWe) had been brought into operation in China in the two years following the Fukushima nuclear accident, making the total nuclear capacity reach 13.9 GWe (17 units total) by mid-2013.

Regulation of the Nuclear Power Sector in China

Formally, three organizations are in charge of governing nuclear energy development in China.

The National Energy Agency (NEA) is under the National Development and Reform Commission. As the governmental department for Nuclear Energy, NEA is responsible for promoting the development of nuclear energy, drafting corresponding development plans, and organizing nuclear energy research.

The China Atomic Energy Agency (CAEA) is under the Ministry of Industry and Information Technology (MIIT). As the government department for nuclear industry, CAEA has the responsibility for development of China's nuclear industry (except for NPPs), coordinating nuclear emergency management, and being the main contact with the IAEA on behalf of the Chinese government.

The National Nuclear Safety Administration (NNSA) of the Ministry of Environmental Protection (MEP) is the central government agency responsible for regulating nuclear safety, and for supervision of all civilian nuclear infrastructure in China. The NNSA also reviews nuclear safety activities and regulates the approval mechanism for those activities.

In general, China develops its nuclear safety regulations to be based on the IAEA nuclear safety standards, while also including consideration of national conditions and regulatory practice. The technical goals, safety requirements and methods described in the regulations are consistent with the international safety standards. After the Fukushima accident, China initiated the preparation of the Atomic Energy Act and the Nuclear Safety Act in order to refine the general requirements for nuclear safety as described by law.

Licensing of nuclear facilities is at the core of regulation. In China, the NNSA is responsible for issuing licenses for design, installation, and construction of nuclear energy facilities, as well as licensing of radioactive waste management (from transportation to final disposal) facilities and other elements of the nuclear sector. As a regulator, the NNSA issues licenses to companies and individuals and undertakes the duty of conducting inspections.

While public opinion in Western countries has generally had a chilling effect on the development of nuclear power, the Chinese public seems to accept and embrace nuclear technologies for several reasons. Nuclear power plant development, for instance, provides thousands of local jobs. Local Chinese governments have been scrambling to build nuclear power plants, in part because they believe that nuclear power projects will significantly benefit the local economy, increase

[82] Hua LIU, presentation in ICONE 13, July 30, 2013. Chengdu, China.

local tax revenues, and resolve persistent electricity shortfalls. In addition, since China's nuclear power industry is relatively young, spent fuel and nuclear waste management issues have not become sufficiently urgent as to have become public concerns yet.

Spent Fuel Storage in China

Dating from the start of operations of China's first nuclear power plant, the total operational experience with nuclear power in China had reached only about 130 reactor years by 2012. The total discharged spent nuclear fuel in China as of the end of 2012 is estimated at around 2000 tHM, excluding the spent fuel from CANDU reactors.

Most spent PWR fuel is stored in pools on reactor sites. Generally, the on-site spent fuel storage capacity at operational nuclear power plants can accommodate 10 years of spent fuel. Taking into account ongoing trends in nuclear fuel management, such as increasingly high rates burnup, extensions of reload cycles, and high-dense pack storage in spent fuel pools into consideration, the storage capacity of present facilities can be enlarged to hold approximately 20 years' worth of spent fuel. Currently, all PWR spent fuel is in fact stored at NPP sites except for part of the spent fuel from the Daya Bay NPP, the first NPP in commercial operation in China. Since 2003, loads of spent fuel from Daya Bay have been transported approximately twice annually to the centralized interim storage facility in Gansu province. For detailed information on spent fuel in China's NPPs, please see the analysis by Yun ZHOU.[83] Zhou's analysis indicates that there is no urgent worry about the storage capacity in most China's NPPs. However, the storage capacity in the spent fuel pools at Daya Bay and Tianwan might approach their limits within the next few years.

China's nuclear fleet currently consists and will consist of multiple nuclear models from different manufacturers and of different designs. Models used in China include PWR units such as the M310, CPR, CANDU, and AP1000 designs, as well as high temperature gas reactors (HTR) and other reactor types. This variety of models in use makes for a large diversity of storage specifications for spent fuel at reactor sites.

Following the Fukushima accident, in addition to the above engineering research and development for storage for different types of spent fuel, some preliminary research activities on the safety of spent fuel storage have been conducted by different organizations in China.

The China Nuclear Power Engineering Co., Ltd. (CNPE) studied the safety features of Spent Fuel Pool (SFP) in GW-sized PWRs using Probabilistic Safety Analysis (PSA) methods. Eight groups of reactor events, including loss of coolant accidents (LOCA), loss of off-site power, loss of plant thermal cycling, and other events were taken into consideration. The summary conclusions of the research include an estimated frequency of spent fuel damage of $2.17*10^{-7}$ per reactor-year, which is quite low compared to the frequency of core damage[84].

[83] Zhou Yun (2012), An Initial Exploration of the Potential for Deep Borehole Disposal of Nuclear Wastes in China, Nautilus Institute Special Report dated October 23, 2012, and available as http://nautilus.org/napsnet/napsnet-special-reports/an-initial-exploration-of-the-potential-for-deep-borehole-disposal-of-nuclear-wastes-in-china/#axzz2UNmkAn6g.
[84] Presentation of CNPE, Oct. 2012, available as: http://ishare.sina.cn/dintro.php?id=35130415

Using a 1000 MWe PWR as an example, Zhen assessed the consequence of attack on a spent fuel pool by terrorists. The radii of areas in which under different levels of radiological risk were calculated using the MELCOR Accident Consequence Code System (MACCS).[85] The results show that in the three accidental cases in which 1) a Zircaloy fire propagates throughout all of the spent fuel in the pool, 2) a Zircaloy fire involves only the batches of spent fuel last removed from the reactor, and 3) radioactive substance releases occur only from the gaps among the last three discharged fuel batches, the radii of the areas in which there is danger of acute death are about 6 km, 3 km and 0 km respectively; the radii of areas in which the effective dose is larger than 50 mSv are about 80 km, 34 km and 9 km respectively; and the radii of the areas in which the avertable dose[86] if those exposed take shelter is larger than 10 mSv are about 100 km, 48 km and 11 km respectively.

Conclusions

With China's large population and rapid economic growth, electricity demand continues to grow at a high rate. Nuclear energy will play a more and more important role in China's energy mix. After the shock of the Fukushima nuclear accident, the development of China's nuclear sector has slowed somewhat but still continues at a steady pace, and with planned levels of new development in the nuclear sector that exceed those of any other nation. Nuclear installed capacity in China is projected to be 58 GWe in 2020.

Due to the present relatively small quantity of spent fuel currently in storage, it appears that there will be no critical pressure to reduce the quantities of spent fuel stored on-site at Chinese reactors in the near-term. In fact, except for Daya Bay, all of the existing nuclear plants in China are storing spent fuel exclusively in at-reactor storage. Wet pool storage of PWR spent fuel is a mature technology, and is widely implemented in all operational nuclear plants in China. Based on the technical details of the spent fuel pool technologies described in this paper, it seems that there are no serious risks associated with wet pool storage in China. Based on still-evolving enhanced safety regulations, there is no doubt that the safety standards for spent fuel storage will be strengthened further over time.

Dry storage is currently only used for CANDU reactors in China, and will be implemented for HTR spent fuel. These two reactor models account for only a minor portion of the whole Chinese nuclear fleet. But the utilization of dry storage and its performance will have a great impact on future decision-making for the sector. Though some experts consider that the pool capacity at reactors in China is large enough to accommodate spent fuel for the next 5 to 10 years, there are strong voices supporting the building of a large-scale centralized spent fuel storage facility soon. In part, it is argued, the current practice of pool storage for spent fuel in highly dense packed arrays has been subject to criticism following the Fukushima accident. In case dense-racking is ultimately not chosen as a means of spent fuel storage in China, the decrease in potential spent fuel storage density will result in a lack of storage space at Chinese reactors relatively soon. For

[85] Q. Y. Zheng, et al. "Consequence Assessment of Attacking Nuclear Spent Fuel Pool By Terrorist". *Radiation Protection* (in Chinese), Jan. 2005. (Note that Nautilus has available a partially translated version of this article.)
[86] The IAEA defines "avertable dose as "[t]he dose that could be averted if a countermeasure or set of countermeasures were to be applied". See http://www.iaea.org/ns/tutorials/regcontrol/intro/glossaryd.htm. .

at-reactor storage, it is difficult to build new pools to store spent fuel due to the complexity of the pool systems. Dry storage is very promising in those cases. For centralized storage away from reactors, dry storage is still a strong competitor to pool-type storage due to advantages such as low investment, modular design, and easy maintenance. As a result, though dry storage has not been adopted for PWR spent fuel storage in China, the utilization of dry storage facilities is a strong possibility in the short or medium-term.[87]

Facilitating China's nuclear energy development plans will require a higher degree of sustained support among the general public. In the past, the Chinese public was not an integral part of nuclear energy decision-making, but this situation is changing. The MEP has released a tentative measure that outlines increased public involvement in the environmental impact assessment (EIA) process.[88] As part of the measure, local governments are required to release EIA reports and allow public feedback before the construction of large-scale projects can commence. Despite these positive developments, this process has not been effective or efficient as, for example, the public review period is presently 10 days long—an insufficient time to understand an assessment of a nuclear energy project. Additionally, the public is generally unaware of how to participate in these consultative processes. For example, according to the first national environmental protection and livelihood index released in 2006, 80 percent of respondents were unaware of the existence of China's free phone hotline for reporting environmental problems. In the nuclear field, the level of public participation and involvement in the licensing process is very limited in comparison with public involvement in nuclear issues in other major nuclear energy states.

As a consequence of the Fukushima accident, the public's awareness of China's nuclear energy development and related safety issues has increased. For example, internet bloggers started the internal Chinese debate on safety issues related to nuclear energy. In July 2013, the local government in Jiangmen, in southern China, had to cancel plans for a nuclear fuel cycle complex project due to public protests, which really showed the importance of public acceptance on nuclear projects, and serves as an indicator of the type of difficulties that might ultimately be experienced in HLW repository siting.[89] In the near future, the Chinese government will have to improve public participation during the processes of discussing and deciding upon nuclear energy projects so as to make the decision making process more transparent and enforce the regulatory system more effectively.

3.2 <u>Nuclear Sector and Spent Fuel Policy in Japan</u>

Subsequent to the Fukushima accident, Japan is now deeply divided over the role of nuclear power in its energy mix. The number of active nuclear plants in Japan dropped to zero in May of

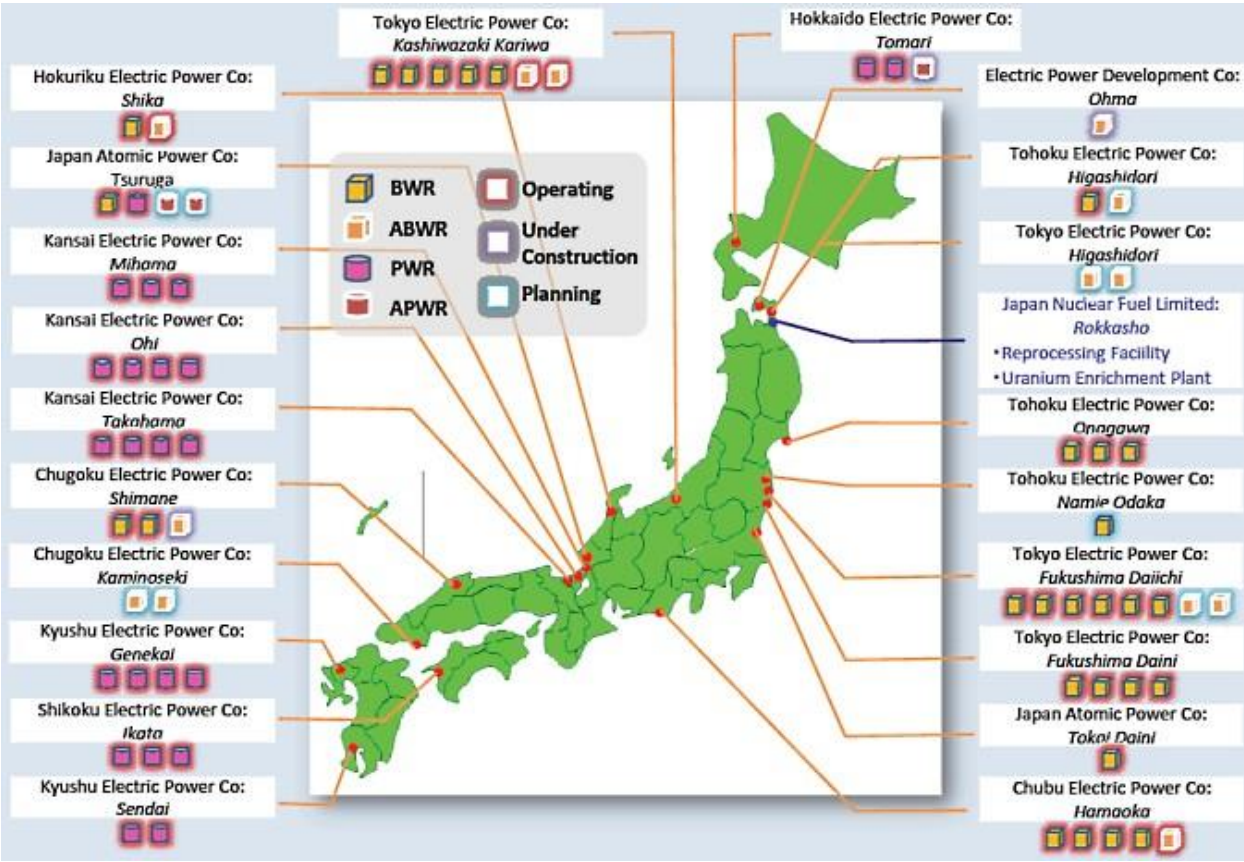
[87] This discussion notwithstanding, we note that Professor Liu Xuegang, a China Country Team member and the author of one of the papers on which this section is based, believes that safety concerns regarding wet storage are not a sufficient motive to develop or deploy dry storage technology in the near future.
[88] Liu, Y.L., 2006. *SEPA releases new measure on public participation in environmental impact assessment process*. Worldwatch Institute Available at: /http://www.worldwatch.org/node/3886S.
[89] The Jiangmen government cancelled the Heshan nuclear fuel cycle project. July 15th 2013. Available at: http://politics.people.com.cn/n/2013/0715/c14562-22194186.html

2012, and is back at zero as of this writing. A review commission was set up to recommend how many, if any, plants will be restarted is divided between groups seeking zero nuclear energy (no restart of nuclear power plants), market oriented groups, and pro-nuclear power advocates (seeking a share of between 35 and 50% of Japan's energy supply). The group's results led to a plan to phase out nuclear power in Japan by 2030, but with the change in administration, the phase-out plan is being reconsidered and will likely be overturned. Until an updated nuclear energy plan is provided, and perhaps even then, the role of renewables, the future of reprocessing, and the impact on greenhouse gas emissions in Japan will remain uncertain. It also seems likely that individual communities serving as hosts to nuclear facilities will have their own say as to whether those facilities will resume operation.

Nuclear Sector Background

The first commercial nuclear power plants in Japan, Tsuruga unit #1 and Mihama unit #1, started operation in 1970, followed by the Fukushima Daiichi #1 plant in 1971. In all, during the 1970s, 20 nuclear power plants started operation in Japan. Figure 3-1 provides a map of the locations of the nuclear power plants and units in Japan. At present there are 50 nuclear reactor units at power plant sites in Japan, excluding Fukushima Daiichi units #1 to #4, which were damaged seriously following the March 11, 2011 Sendai earthquake.

Figure 3-1: Japan's Nuclear Power Plant Fleet[90]

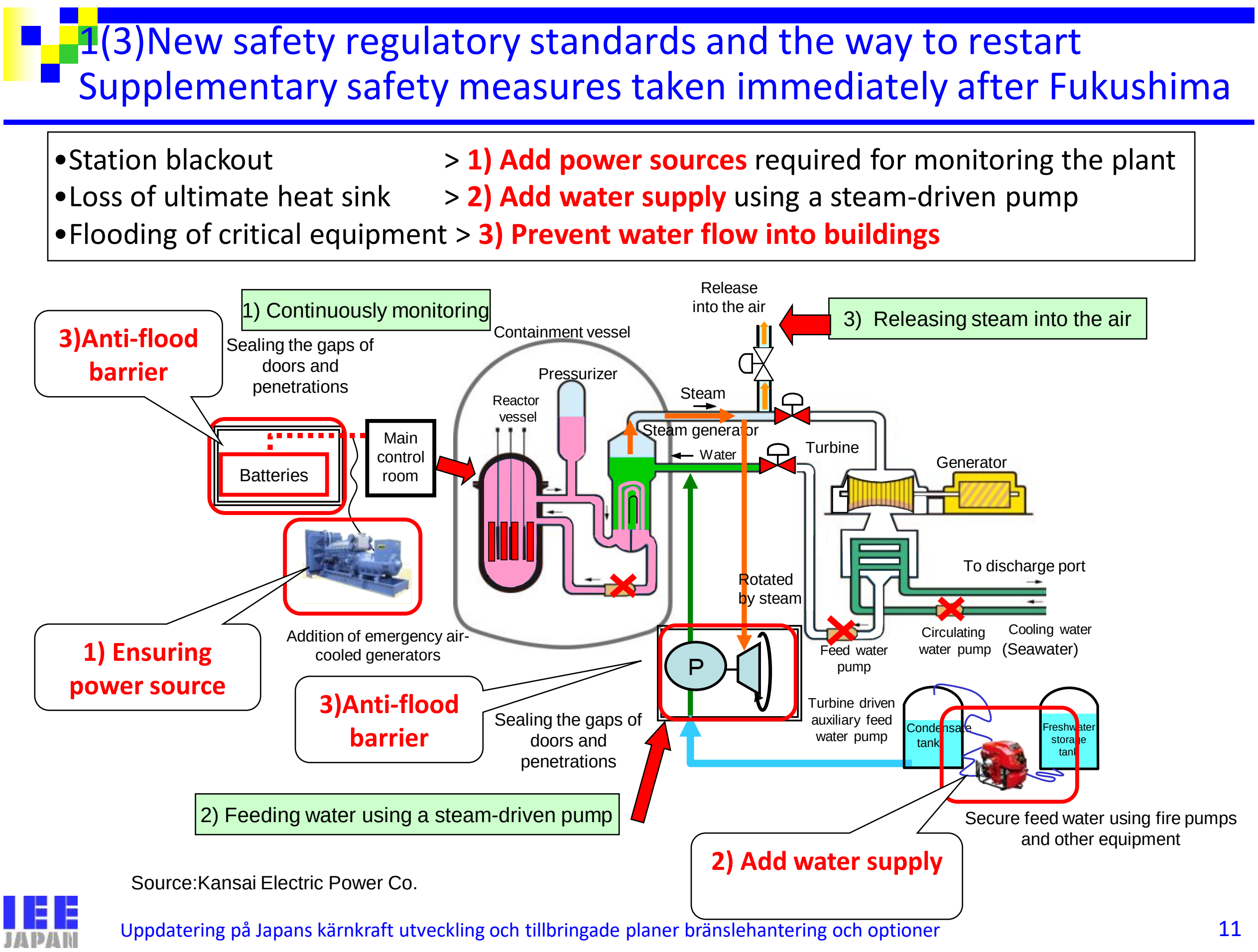


After the Fukushima accident, the number of nuclear power plants under operation decreased very rapidly. Many of the nuclear plants operating at the time of the accident automatically stopped operating at the time of the earthquake as safety systems were engaged, but after the accident, all of the remaining reactors were shut down for safety inspections. In practice, in Japan, nuclear power plants cannot be restarted, even if shut down for routine inspections, without the local government's permission to restart the plant. This is not a legal regulation, but is conventional rule followed by nuclear plant owners and their local hosts. In the aftermath of Fukushima, local governments were reluctant to give permission to allow reactors to restart. As a result, by May, 2012 no nuclear power units were operating due to the difficulty of receiving permission to proceed with restart following inspections. In July and August, 2012, two units at the Ohi power station were restarted, but were shut down again when the time came for their next scheduled regular inspection, in September 2013.

[90] Source: World Nuclear Association, "Nuclear Power in Japan" (Updated April 2014), http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/Japan/.

Japan's Nuclear Regulation Authority, launched in September 2012, was established to absorb and learn the lessons of the Fukushima Daiichi nuclear accident, with a goal of rebuilding the nuclear safety system and management on a solid basis, placing the highest priority on public safety and development of a genuine safety culture. The guiding principles for the NRS's activities are independence and transparency, independent decision making, effective actions, and open and transparent organization, ongoing improvement and commitment, and establishing emergency response preparedness. Figure 3-2 summarizes the supplementary safety measures implemented after the Fukushima accident.

Figure 3-2: Safety Measures Taken After Fukushima



The NRA released draft safety standards in April 2013. Following a public comment and revision period, the new safety standards expected to be enforced starting in July 2013. Safety standards in three areas were prepared:[91]

[91] Source: NRA, http://www.nsr.go.jp/english/data/new_safety_standards.pdf.

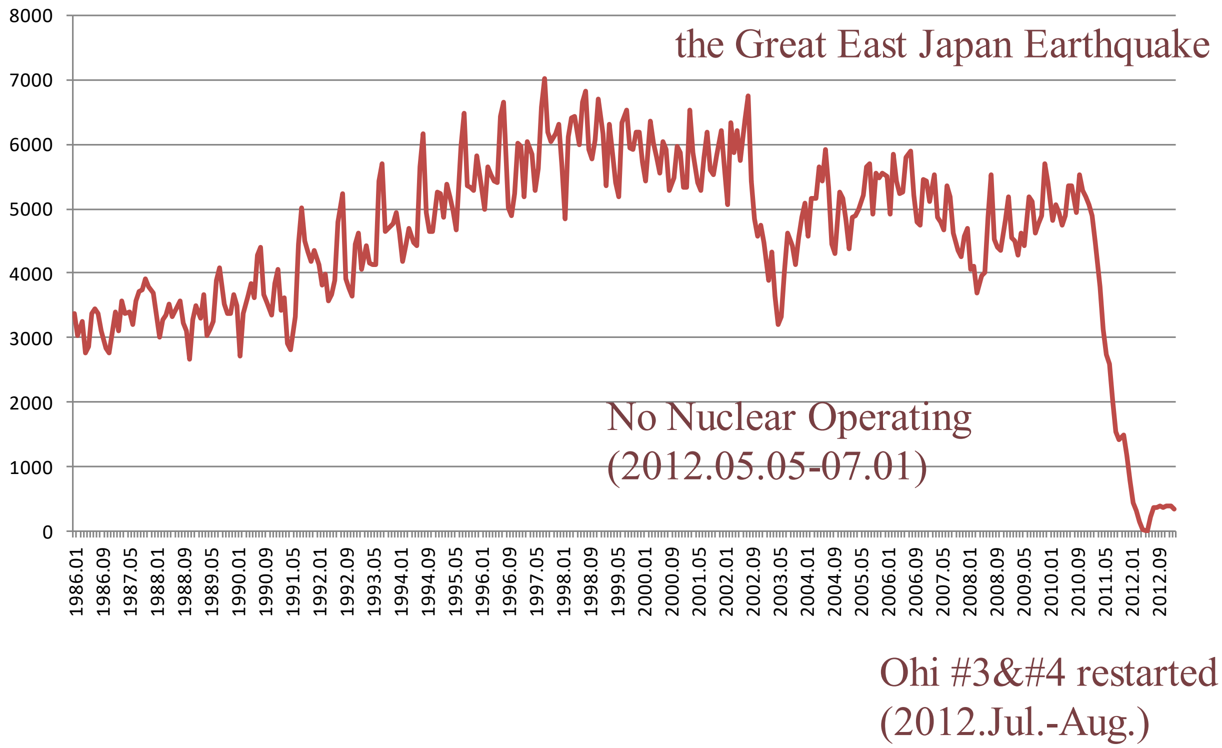
- Safety Standard for Design Basis, including safety measures against natural phenomena (e.g., tornados, forest fires) and external man-made hazards (e.g., an aircraft crash), on the reliability of off-site power supply, the availability of ultimate heat sinks and the functions of SSCs, as well as fire protection measures.
- Safety Standards for Severe Accidents, including equipping plants with filtered containment vessel venting systems, permanent and portable coolant injection equipment, portable alternate coolant injection equipment for spent fuel pools, power generation vehicles with facilities for connecting on-vehicle generators to plant equipment and Specific Safety Facilities (SSFs).
- Safety Standard for Earthquakes and Tsunamis, including protective measures such as sea walls against tsunamis, anti-inundation measures, and a prohibition of construction of Class S nuclear facilities in areas exposed to active faults.

Nuclear plant operators and other experts in the Japanese nuclear industry have not been universally positive about the NRAs new standards. Opinions voiced with regard to the standards include the following. The new Safety Standards should be: based on defense-in-depth, and evaluate plant management under beyond-design conditions. The Standards should be discussed and determined based on scientific and technically reasonable evidence. The current draft Safety Standards fail to meet these criteria because they are not founded in performance-based regulation, rather in specification of hardware with little scope for application of alternative measures. Examples of hardware specifications include diversified emergency power sources, containment venting systems, alternative control centers, and others. The Standards also have been criticized as violating the defense-in-depth concept, not helping nuclear plant operators to be any more prepared for unexpected events, and inadequately considering the relative risks of nuclear events when the Standards were formulated. The Standards were also seen as excessively severe relative to those in other countries around the world, and beyond the scope of international standards. Nuclear industry representatives have also suggested that the NRA jumped to conclusions in its May 2013 evaluations of the seismic safety of the Tsuruga and Higashidori nuclear plants.

The NRA released its new regulatory guidelines for nuclear power plants in July, 2013, and as of late 2013 electric utilities were applying to restart reactors under those guidelines, and hoping for faster restarts. The approval process under the new guidelines, however, was likely to take one half to one year to complete, thus rapid restarts seemed unlikely.

Operation of the Rokkasho reprocessing plant, which has been temporarily stopped due to various operational difficulties, is expected to eventually resume, in large part, because the governor of Aomori prefecture has protested and asked that all of the spent fuel now in storage at Rokkasho be moved out of Rokkasho if reprocessing should stop. Since Japan lacks the facilities to store the 3000 tonnes of spent fuel currently, complying with the request of governor's request implies either restarting Rokkasho or embarking on an immediate program of building additional storage facilities, which is unlikely to be a rapid process, based on recent experience of difficulties in siting nuclear facilities in Japan.

Figure 3-3: Historical Trends of Nuclear Power Monthly Output in Japan, 1986 through late 2012 (10^{10} kcal)[92]



Spent Fuel Accumulation Scenarios

During the Nautilus Working Group Meeting in May, 2013, held in Beijing, the Japan Team assembled several spent fuel accumulation scenarios. These do not correspond exactly to the range of nuclear power scenarios described in section 5.3 of this Final Report, but represent a range of different possible outcomes for spent fuel accumulation in Japan.[93]

Four scenarios of future nuclear generation capacity were developed. Scenario 1 is an example case, prepared for comparison purposes, that projects what might have happened had there not been a Fukushima accident. In this case, 14 additional nuclear power plants[94] would have been added, it is assumed, and life extension is applied to all plants such that each operates for 60

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[92] Source: METI (2013), "“Monthly report on electric power statistics”, available as http://www.enecho.meti.go.jp/info/statistics/denryoku.

[93] The Japan team consisted of Professor Tomochika Tokunaga of the University of Tokyo, Ms. Tomoko Murakami of the Institute of Energy Economics, Japan (IEEJ), and Kae Takase (the author of this paper).most of the information and basic data regarding nuclear power and spent fuel that was used in generating and evaluating these scenarios was provided by Ms. Tomoko Murakami (IEEJ), but the calculations of spent fuel arisings and accumulation described below were done by Kae Takase, and thus should not be interpreted as indicative of Ms. Murakami’s or IEEJ’s view of nuclear power and spent fuel futures in Japan.

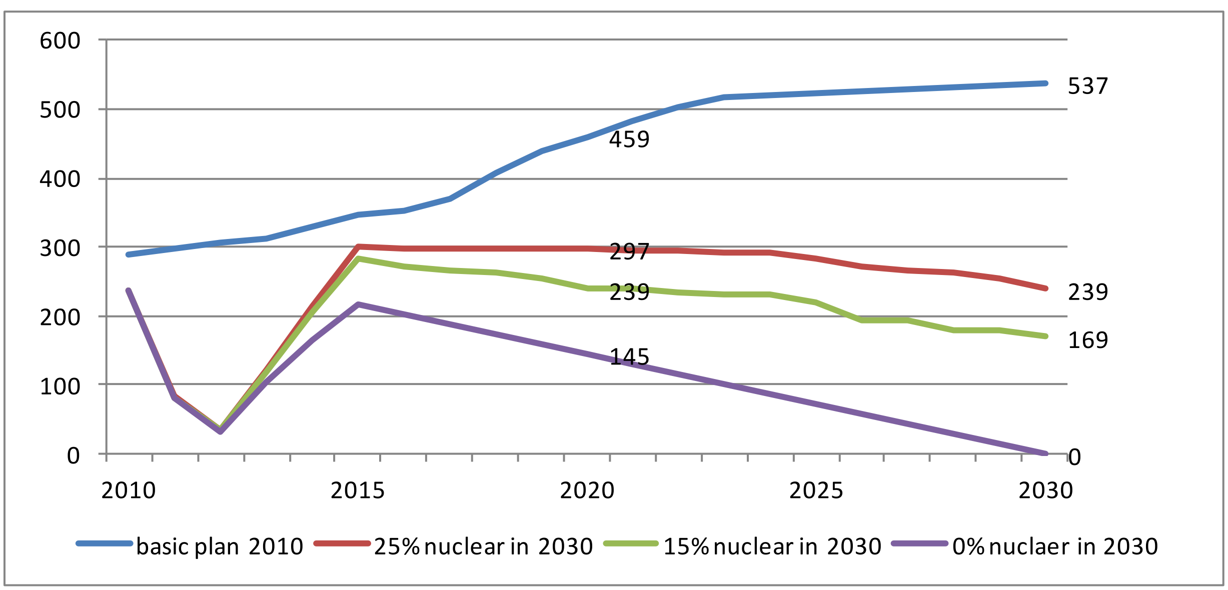
[94] Additional plants are shown in Table 5. 2 plants are under construction, namely Shimane 3 and Ohma1, 9 are planned and 3 are proposed.

years. In this case, the Fukushima plants all also continue to operate. In Scenario 2 to 4, all 10 units at the two Fukushima plants (6 plants in Fukushima Daiichi (#1), 4 plants in Fukushima Daini (#2)) are assumed to be shut down permanently following the accident in March, 2011. In Scenario 2 and 3, two units are added: those under construction at the Shimane plant (unit #3) and at Ohma. Shimane #3 is assumed to start operating in 2014, with Ohma starting in 2015. In Scenario 2, all plants are assumed to operate for 50 years. In Scenario 3, all plants will operate for 40 years. In Scenario 4, nuclear plants will be phased out such that no plants will remain in operation in 2030.

Different assumed annual average capacity factor (the fraction of the time the plants generate electricity at full capacity) trends for the reactor fleets were assumed under the four different spent fuel scenarios. In Scenario 1, to approximate the previous energy basic plan (2010), the average capacity factor is assumed to increase to 90% in 2030. In the other scenarios, capacity factors decreases to 10% in 2012, consistent with actual experience post-Fukushima, then increase to reach 80% in 2015, maintaining that level until 2030. In reality, the actual capacity factor in 2013 was significantly lower than the 30% used to model these scenarios.

Based on the capacity and capacity factor assumptions as described above, electricity generation from nuclear power under the four spent fuel scenarios is calculated as shown in Figure 3-4, below. Electricity generated in 2011 FY was 1108 TWh. Assuming the level will be remain roughly constant, the nuclear ratio would have reached about 50% in Scenario 1 (2030).

Figure 3-4: Electricity Generation from Nuclear Power in Four Spent Fuel Scenarios (TWh)

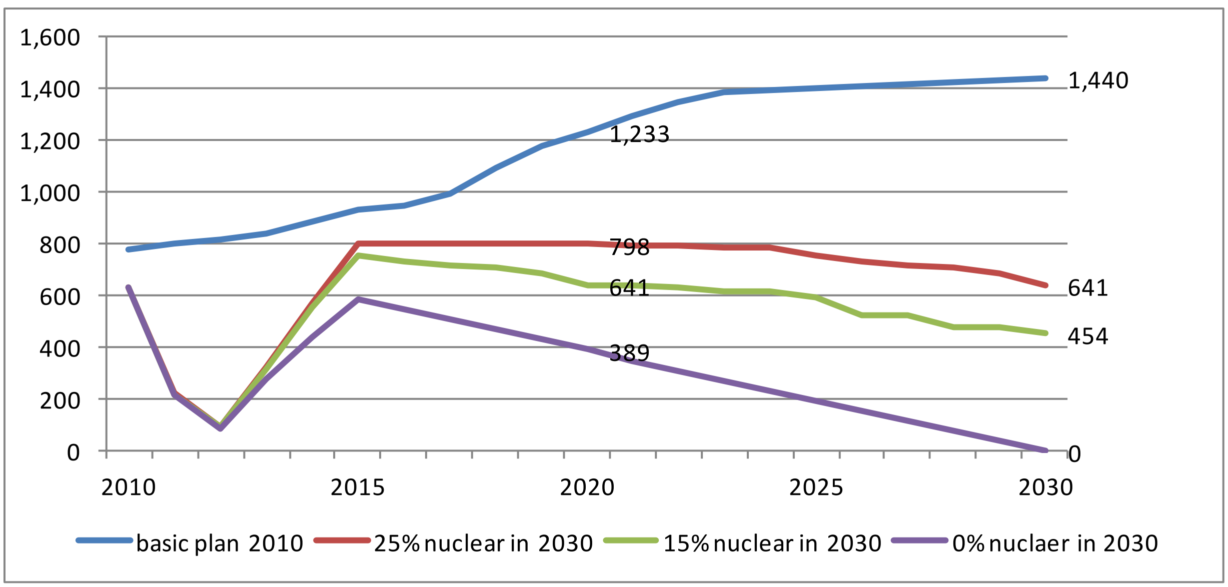


The total accumulated amount of spent fuel in Japan, including spent fuel in store on-site at power plants site storage and at the Rokkasho reprocessing plant as of April 2013 was about

17,770 tHM (tonnes of heavy metal) That is, 14,200+120+(3,362-20)=17662. According to the Atomic Energy Commission of Japan, the spent fuel stockpile located at the generation plants sites as of September 2011 was 14,200 tHM[95]. According to JNFL (Japan Nuclear Fuel Limited), which operates the reprocessing plant at Rokkasho, the accumulated received spent fuel in April 2013 amounts for 3,362 tHM[96]. Nuclear power generation between September 2011 and March 2013 amounted to 44.658 TWh, which would have produce about another 120 tHM of spent fuel, with newly discharged spent fuel received into storage during the fiscal year 2012 (April 2012 through March 2013) is about 20 tHM.

Based on estimates of future annual spent fuel generation and the initial amounts in storage as of the end of 2012, the total spent fuel generated and accumulated can be calculated. A burn-up factor of 2.684 tHM/TWh is used to calculated spent fuel generation from nuclear power generation. Figure 3-5 shows annual spent fuel generation under each of the four spent fuel scenarios.

Figure 3-5: Annual Spent Fuel Generation in Japan under Four Scenarios (tHM/year)



Based on these calculations, as shown in Figure 3-6, the accumulated spent fuel in Japan will be will be 40,000 tHM in Scenario1 by 2030, but will be much less in the other three scenarios. Even with nuclear phase out by 2030 (Scenario 4), however, the accumulated spent fuel will total 23,000 tHM in 2030.

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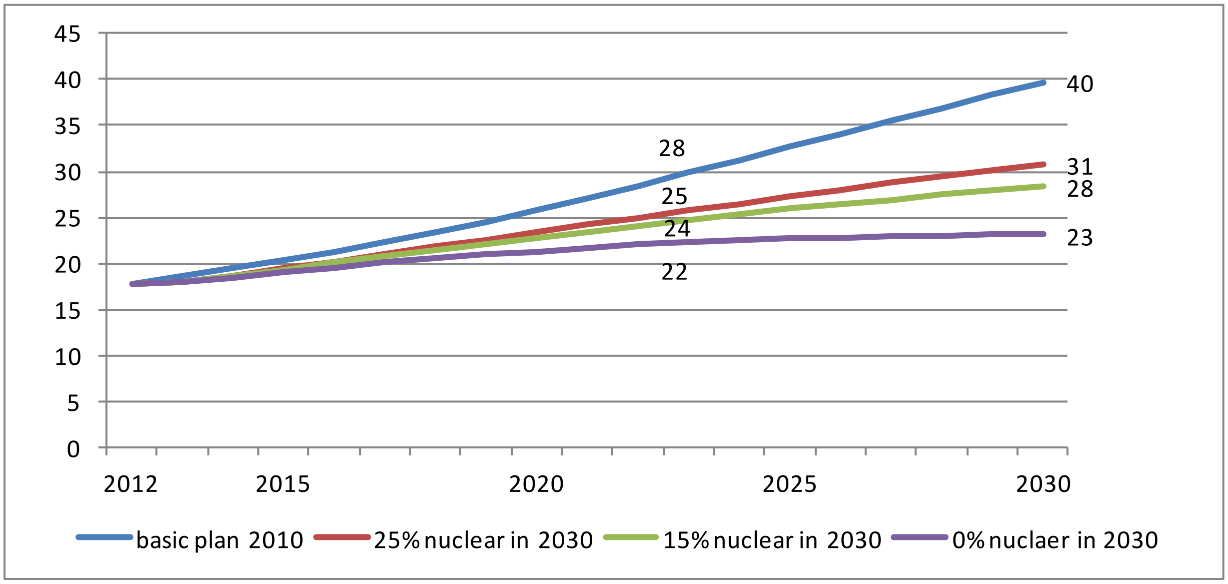
[95] Cabinet Office, Government of Japan, "Major Issue for Discussing Energy Policy Alternatives, Spent Fuel Management in Japan", http://www.aec.go.jp/jicst/NC/tyoki/hatukaku/siryo/siryo8/siryo3-2.pdf

[96] Japan Nuclear Fuel Limited, Plan and Record of Spent Fuel Transportation during Fiscal Year 2012, http://www.jnfl.co.jp/transport-schedule/execution/recycle/2012.html.

Figure 3-6: Accumulated spent fuel in Japan (10^3 tHM)



Spent Fuel Management Scenarios

Three paths for future spent fuel management in Japan were developed by the Japan Team.

- A. Reprocessing with re-use of reprocessed plutonium in mixed-oxide fuel (spent MOX fuel is disposed of, not reprocessed)
- A-2. Reprocessing with re-use of reprocessed plutonium in mixed-oxide fuel (spent MOX fuel is reprocessed)
- B. Direct disposal of all spent fuel

Nuclear power generation will produce spent fuel at a rate of 0.27 tHM spent fuel per 10^8 kWh. In the "B" path, spent fuel will be directly disposed of. When the spent fuel is to be reprocessed, the chemical structure of the spent fuel (Pu 1%, U 94%, fissile Products 5%) dictates the amount of plutonium produced, as well as the amount of vitrified waste exiting the process. 1 ton of spent fuel will produce 50 kg of high-level fission products, which will be disposed of in the form of vitrified canisters. 1 ton of spent fuel will produce 1 unit (500kg) of high-level vitrified waste.

Plutonium and uranium separated from spent fuel will be mixed to produce MOX fuel for use in light water reactors. Plutonium will be enriched to account for 6% of the mass of MOX fuel, the rest of which will be uranium. 1 ton of spent fuel will produce 1/8 ton of MOX fuel

Also uncertain at present are Japan's policies for pluthermal power plants, that is, using mixed-oxide fuel in light water reactors to help to reduce the inventory of plutonium-bearing, but non-irradiated, MOx fuel that Japan has built up through its domestic reprocessing activities and through reprocessing done under contract for Japanese utilities in Europe. Based on the analysis described above, however, the use of pluthermal reactors will have at best relatively little impact on the current inventory of plutonium-bearing MOX fuel, and at worst could substantially increase the inventory of MOX fuel. The use of MOX fuel in pluthermal reactors will also have relatively little impact on Japan's inventory of spent fuel, in scenarios with or without reprocessing.

Overall, it seems clear that reprocessing and the use of MOX fuel in pluthermal reactors will do little to address Japan's spent nuclear fuel problem, which therefore will have to be addressed through other means that will necessarily incorporate both political and technical dimensions.

Pluthermal in Japan

The pluthermal concept involves the use of reprocessed plutonium in MOX fuel in conventional light water reactors, sometimes in combination with standard fuel elements using enriched uranium. Pluthermal power production is considered a means to stretch uranium resources, and a "bridge" to a future in which plutonium is produced and used in fast neutron reactors. A history of the pluthermal process in Japan is provided below.

During the late 1980s and early 1990s, proving tests were done at the Mihama and Tsuruga nuclear power plants of the "pluthermal" concept. In the "Long-term Nuclear plan" published in 1994, commercial operation of pluthermal plants in the late 1990s was planned, and the Nuclear Safety Commission reviewed the safety of the MOX fuel during 1990-1995. In 1997, given cabinet approval to suggest earliest implementation of pluthermal plants, electric utilities published their plans to implement pluthermal in 16-18 nuclear power reactors by 2015. In August 1999, the Ohma power plants, which were to be MOX-ABWR (advanced boiling water reactor)-type plants, which were designed to use fully MOX fuel, were added to the list of the new nuclear plants to be built in governments electric capacity development plan.[97]

Since the pluthermal plan was published, however, there have been many incidents that have caused the implementation of pluthermal to be delayed. In 1999, falsification of MOX fuel data by BNFL occurred. In 2001, a local referendum in Kariwa, Nigata (close to Kashiwazaki-Kariwa) requested that the local nuclear plant not use pluthermal fueling[98]. Then, in 2002, TEPCO was found to have done voluntary inspection of pluthermal-related facilities inappropriately. Following these setbacks, many efforts to increase the public acceptance were carried out by the Japanese government and the electric utilities operating nuclear plants. In December of 2003, the Federation of Electric Power Companies (FEPC) reconfirmed that pluthermal would be start to be used in selected reactors where possible, with a target of using pluthermal in 16 to 18 reactors plants by 2015. In May 2009, three electric utilities (Chubu Electric, Shikoku Electric, and Kyushu Electric) finished MOX fuel transportation arrangements, and also several other electric utilities agreed to contracts with fuel processing companies, or approached local municipalities for permission to use MOX fuel in reactors. In April 2009, Japan

[97] The Federation of Electric Power Companies of Japan, "Current Situation and History of Pluthermal in Japan", http://www.fepc.or.jp/nuclear/cycle/pluthermal/genjou/.
[98] The All-Japan Prefectural and Municipal Workers Union (JICHIRO), "Report on Local Referendum on Pluthermal Operation in Kashiwazaki-Kariwa Nuclear Power #3 plants", http://www.jichiro.gr.jp/jichiken_kako/report/rep_tokushima29/jichiken/5/5_2_02.htm.

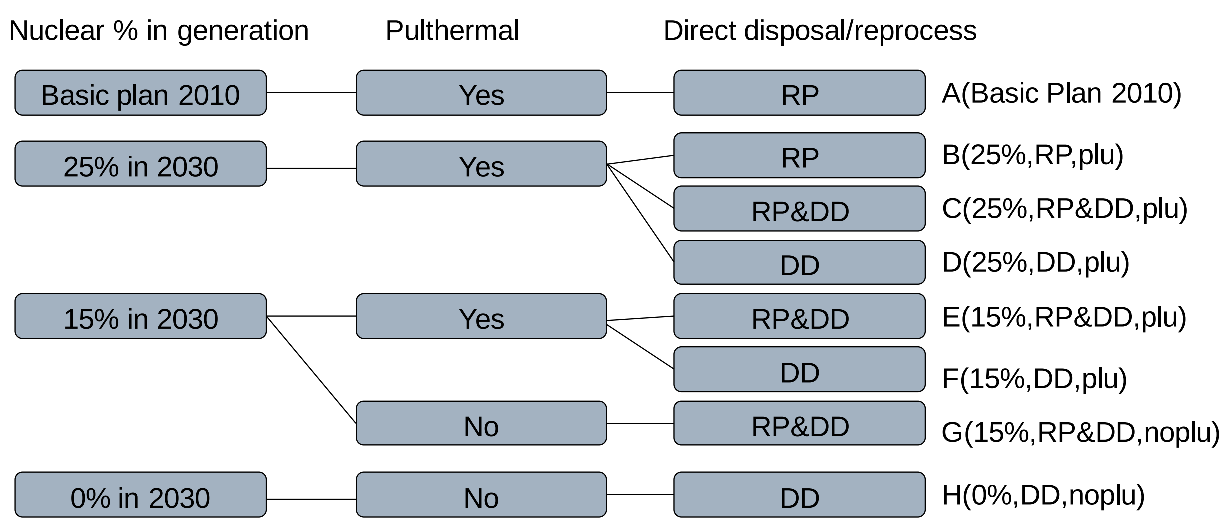
Nuclear Fuel Ltd. (JNFL) changed the planned start date of their MOX fuel processing plant. In June 12th, 2009, FEPC reviewed its pluthermal plan, but reconfirmed the target of starting 16-18 pluthermal units by the 2015 fiscal year, when JNFL was to have started pluthermal fuel fabrication operations.

As a result, 3 pluthermal nuclear power units have started using MOX fuel. These are Genkai #3, operated by Kyushu Electric, in December, 2009; Ikata #3, operated by Shikoku Electric, in March, 2010; and Fukushima Daiichi #3, operated by TEPCO, in January, 2011 (two months before the Fukushima accident).

<u>Scenarios for "Back-end" Spent Fuel Management: Direct Disposal/Reprocessing of Uranium Spent Fuel, and for MOX Fuel Reprocessing</u>

The Japan team established seven scenarios for Japan's future activities in the areas of direct disposal of spent fuel, reprocessing of enriched uranium-based spent fuel, and reprocessing of MOX fuel, based on the combination of whether reprocessing or directly disposal or both were to be pursued, and on the target percentage of generation made up by nuclear power. Scenarios A through F include pluthermal nuclear power to consume MOX fuel, so that there will be less clean MOX fuel in Japan's inventory, and thus less of a nuclear weapons proliferation risk, since it is relatively straightforward to separate plutonium from clean (fresh, or not yet irradiated) MOX fuel. Figure 3-7 shows the assumptions used in these scenarios.

Figure 3-7: Back-end Spent Fuel Management Scenarios A-H, and Their Features



Based on the back-end scenarios above, the Japan Team calculated: 1) the amount of spent fuel produced, and 2) the amount of MOX fuel (which is equal to the amount of spent MOX fuel). As we described above, the amount of MOX fuel and spent MOX fuel is 1/8 ton per ton of original spent fuel.

The 100% reprocessing scenario (RP) assumes full operation of the Rokkasho reprocessing plant. In that scenario, in which 100% of spent fuel from light water reactors is sent to reprocessing, 800 tHM of spent fuel will be reprocessed to MOx fuel annually starting from 2015, resulting in a decrease in Japan's spent fuel stockpile. In the half reprocessing/half direct disposal (denoted as RP&DD) scenarios, 400 tHM of spent fuel will be reprocessed each year after 2015. In the DD scenarios, spent fuel will not be reprocessed to MOx fuel, but will be disposed of directly.

Direct disposal requires sites in which canisters of spent fuel and other nuclear wastes can be buried (or stored over the very long term). In scenarios including DD and RP&DD elements, we assume construction of a final disposal site will start in 2015, and start operating in 2035, so that there will be no influence on the amount of spent fuel stockpiled above ground before 2035.

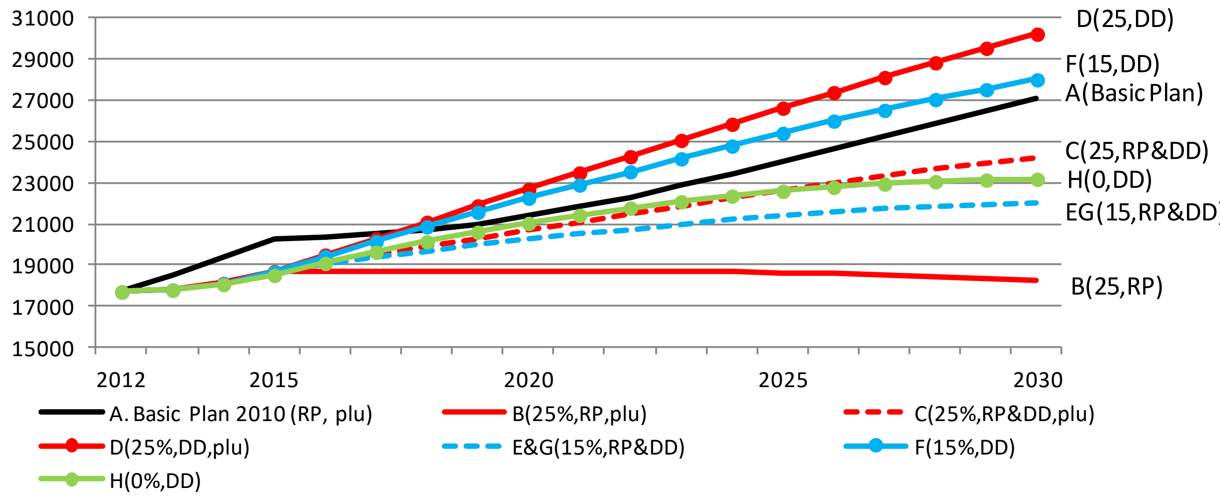
A fraction of the reactor cores made up of MOx fuel in each pluthermal reactor was assigned as follows. The Ohma power plant is designed to use 100% MOx fuel, but the other plants where MOx fuel is to be used were originally designed for enriched uranium fuel, and are thus assumed to have a maximum fraction of MOx in their cores of 30%. Also, it was assumed that mixture ratio for the pluthermal reactors other than Ohma is 10% MOx for the first year of operation with MOx fuel.

The per-unit enriched uranium and MOX fuel use in pluthermal plants is assumed to be 2.684 tHM/TWh produced, with the same mass of spent MOX fuel produced per TWh of electricity as the fuel input. In the scenarios that assume MOX fuel will be used in pluthermal plants, 107-121 tHM of MOx fuel will be used annually, with production of an equivalent amount of spent MOx fuel each year.

Based on the inputs and assumptions above, the amounts of spent fuel, directly disposed spent fuel, separated plutonium in MOX fuel, and spent MOX fuel were calculated. The cumulative total spent fuel produced is shown in Figure 3-8 for the various back-end scenarios.

Under all of the back-end fuel cycle scenarios explored, spent fuel is produced in proportion to the electricity production from nuclear power plants. Spent fuel is reprocessed in the RP and RP&DD scenario branches, which reduces the amount of spent fuel accumulated, relative to branches without reprocessing, though under all of the scenarios explored 2030 spent fuel inventories are higher than inventories as they stood in 2012. The amount of accumulated spent fuel would be 27 thousand tons of HM in 2030 in the case where Japan was assumed to follow the previous energy basic plan starting from 2010 (Scenario A). If the fraction of electricity generation supplied by nuclear power in surpasses 15%, and reprocessing is not used in the future, the amount of spent fuel accumulated by 2030 will somewhat exceed the total in scenario A. By 2030, total accumulated spent fuel is about 28,000 and 30,000 tHM in scenarios D and F, respectively. If the reprocessing plant (Rokkasho plant) successfully starts commercial operation in 2015, the spent fuel stockpile by 2030 will be less than in scenario A in all other scenarios (Scenario B, C, E, G, and H).

Figure 3-8: Accumulated "spent fuel" (not including spent MOX fuel)



MOX fuels are produced primarily at the reprocessing plant in Rokkasho. In the RP scenarios, 800 tHM of spent fuel will be reprocessed annually[99] to produce 800*1/8 tHM of MOX fuel, for a cumulative total of 2250 tHM by 2030. In the RP&DD scenario, 400 tHM of spent fuel will be reprocessed annually to produce 400*1/8 tHM of MOX fuel, yielding 1500 tHM of MOX fuel by 2030. In the DD scenario, the accumulated MOX fuel stockpile, at 750 tHM does not change.

Figure 3-9 shows the amount of accumulated plutonium in MOX fuel in Japan under the different back-end fuel cycle scenarios considered. The accumulated amount of plutonium in MOX fuel will not increase from the initial value of 45 tons in 2011 in scenario H, which assumes no reprocessing, and no use of pluthermal fueling in reactors. In the scenario D and F, where no reprocessing is operating but in which it is assumed that pluthermal power plants will operate, the amount of plutonium in accumulated MOx fuel will decrease slightly over time, to 39 tons in 2030. In scenarios A and B, even though there will be pluthermal plants operating, the amount of plutonium in MOx fuel will increase to reach almost 130 tons in 2030. In Scenario G, where the reprocessing plants operates at half of its capacity, but there is no use of pluthermal power production, the amount of plutonium in MOx fuel will increase to reach 90 tons of plutonium in 2030. If pluthermal power operates, the plutonium stockpile will decrease by 6 tons of plutonium (equivalent to 107 tHM of MOx fuel) to reach 84 tons of plutonium in 2030. Scenarios D and F, focusing on direct disposal, result in the smallest plutonium stockpiles by 2030 among all of the scenarios. Scenarios D and F assume no reprocessing, but with pluthermal operation. In scenarios D and F, the resulting plutonium in MOX fuel by 2030 is slightly lower than in Japan's current MOX fuel inventory (2011-2014).

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[99] Japan Nuclear Fuel Limited, "Reprocessing Plant", http://www.jnfl.co.jp/english/business/reprocessing.html.

Figure 3-9: Accumulated MOX Fuel Considering Usage in Pluthermal Plants (tons of plutonium in MOX fuel)

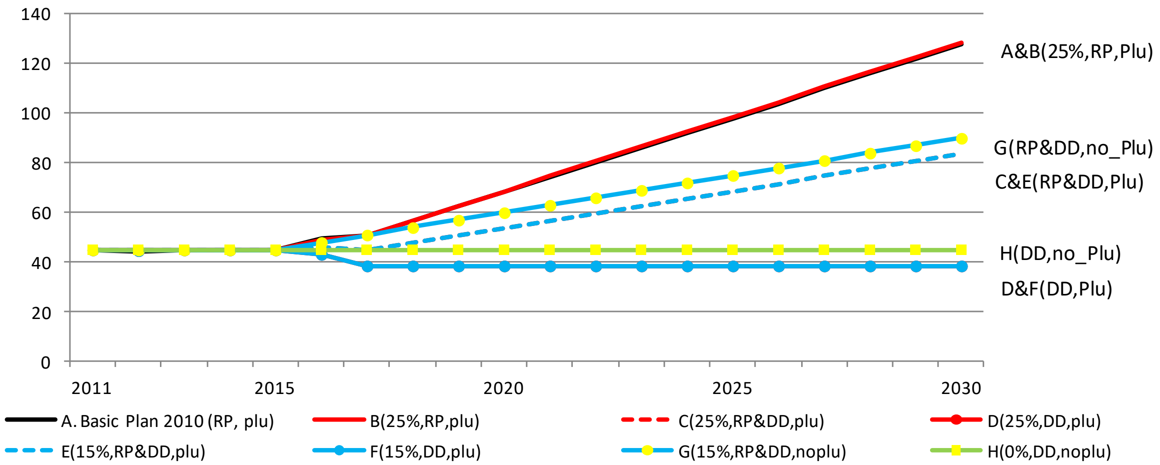
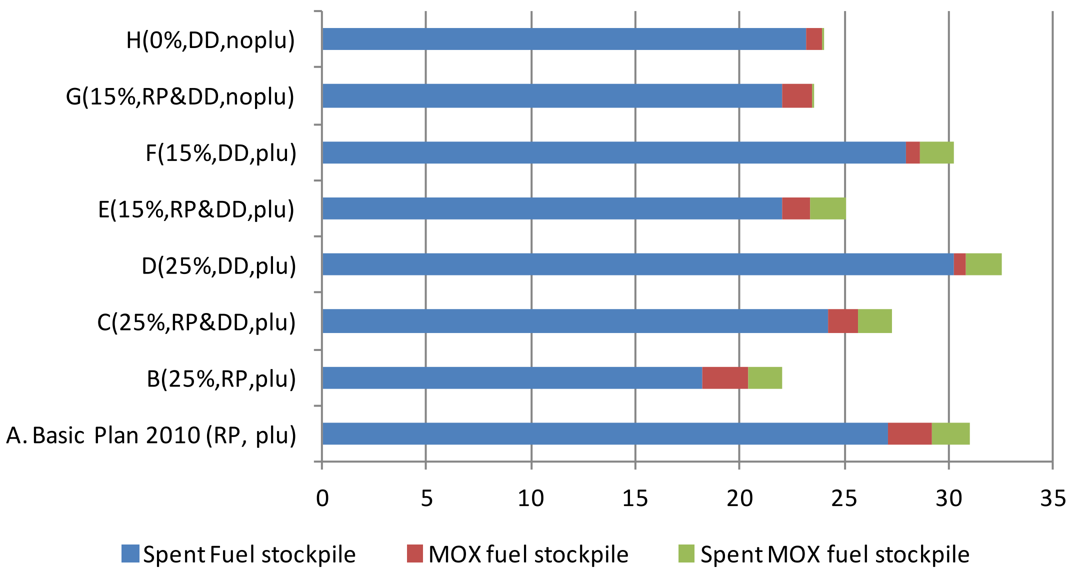


Figure 3-10 compares the estimated year 2030 stockpiles of spent fuel, spent MOx fuel, and fresh MOx fuel under the back-end fuel cycle scenarios evaluated. These results indicate that a reprocessing capacity of 800 tHM/year is not sufficient to decrease spent fuel stockpiles in Japan. Moreover, the existing MOx fuel stockpile, which contains plutonium separated from spent fuel, will remain quite large amount in all scenarios that assumes reprocessing. On the other hand, the amount of spent MOx fuel will not be that large, even assuming the current plans for pluthermal capacity of 15 plants (of which 14 plants can use a core containing nom more than 30% MOx). This is of significance because spent MOX fuel requires different handling than spent enriched uranium fuel because of its different radiological properties.

Figure 3-10: Accumulated Spent (enriched uranium) Fuel, MOX fuel, and Spent MOX fuel in 2030 (10^3 tHM)



Nuclear Waste Disposal Policies in Japan

The Japanese implementing organization for high-level waste and the transuranic waste disposal, that is, the Nuclear Waste Management Organization of Japan (NUMO), was established in October 2000, and an open solicitation for accepting literature surveys for evaluating the suitability for radioactive waste disposal was initiated in December 2002. The documents distributed by NUMO for the open solicitation stated that all municipalities have a right to apply to the open solicitation, for which no application deadline was set at the time. The solicitation is still open and a final deadline has not yet been set even to this day. Please see Tokunaga (2013) for the events with respect to the open solicitation in between year 2002 to early 2007. The major activities related to the siting process that occurred from 2007 to the present (2014) in Japan are summarized below.

In the year 2007, since the official response to the initial solicitation by municipalities was extremely limited, a new option for initiating discussions was added, which focused on asking communities to accept a literature survey as a first step in the siting process. The open solicitation offer remained in place as well. The proposal acceptance scheme was explained as follows: "The opinions of the people in the regions will be fully respected and the government can take the step of proposing to municipalities that a literature survey be carried out". This essentially means that rather than waiting for municipalities to volunteer, the government could ask municipalities to be the focus of a literature survey to explore the suitability of the area for hosting disposal facilities if the municipalities are willing to accept the activities.

In addition, in year 2007, NUMO was identified as the implementing organization for the disposal of transuranic wastes, with the Japan Atomic Energy Agency (JAEA) declared to be the organization responsible for the disposal of radioactive wastes produced through research activities.

In year 2010, the Japan Atomic Energy Commission (JAEC) sent a request to the Science Council of Japan (SCJ) to consider recommendations for activities to disclose literature and information on the disposal of high-level radioactive wastes to the public. While this topic was under discussion in the SCJ, the Tohoku Earthquake and tsunami hit the Pacific coast of the northeast Japan, on March 11, 2011, and the disaster of the Fukushima Daiichi nuclear plant occurred following the inundation of the power plant site by the huge tsunami.

On September 11, 2012, SCJ sent a document entitled "Issues concerning high-level radioactive waste disposal (Reply)" back to JAEC (SCJ, 2012). The main messages conveyed in this document were summarized by JAEC (2012) as follows:

"The Reply from SCJ pointed out that seeking a consensus on an individual issue of selecting the final HLW disposal site before reaching a consensus on broader policies concerning nuclear power generation was procedurally inverted and thus inappropriate. Moreover, it suggested the requirements for a fundamental review of policies concerning HLW disposal, restructuring of the policy framework focusing on identifying the limits of scientific and technical viability, ensuring scientific autonomy, temporal storage and total volume control, and streamlining of procedures for determining reasonable policies in terms of fair burden sharing, and making multistage agreements by providing a venue for discussion. It recommended continuing tenacious negotiations from a long-term perspective to solve the problem."

Responding to the document from SCJ, JAEC reconsidered and issued the necessary approaches for the high-level nuclear waste disposal program (JAEC, 2012). JAEC (2012) summarized their resulting findings and direction as follows:

1: Clarify the amount and nature of the high-level radioactive waste for disposal in association with nuclear energy and fuel cycle policies, 2: Apply the latest earth science knowledge to a viability study of geological disposal, and share the result with the public, 3: Improve the operation according to the discussions on the need and significance of interim storage, 4: Provide a system of sharing disposal techniques and the site selection process with the public, and 5: The government leads policy reconstructing.

The Agency for Natural Resources and Energy, in the Ministry of Economy, Trade and Industry (METI), has been convening meetings of two subcommittees (working groups) related to the nuclear waste disposal since 2013. One committee (working group) has focused on summarizing the current status and issues related to the final disposal of high-level radioactive waste, discussing how the current generation should tackle issues related to final disposal, proposing possible improvements for the site selection process, and proposing improvements in the implementation structures for handling the high-level radioactive waste disposal program. The other subcommittee (working group) has re-evaluated the geological disposal of high-level radioactive waste from the viewpoint of the up-to-date scientific knowledge, and has focused mainly on the long-term stability of the geological environment. Both subcommittees (working groups) are now in the process of soliciting public comments on their draft mid-term reports, and the mid-term reports will be finalized after receiving public comments and discussing the possible revision of the present versions of the reports. Details of the discussion undertaken by both subcommittees (working groups) can be found on the METI website at http://www.meti.go.jp/committee/gizi_8/21.html.

Conclusions

How Japan's nuclear sector will evolve is at the moment very unclear, and depends substantially on how the government chooses to move forward, or not, with the nuclear power sector. Likewise, several scenarios for spent fuel management in Japan remain possible, but cover a wide range of technical options, from continuing with pre-Fukushima policies including reprocessing and pluthermal use, to ceasing reprocessing entirely. In any of these scenarios, however, Japan is left with a substantial amount of spent fuel that must be managed, and a substantial inventory of separated plutonium and plutonium in MOX fuel that must likewise be carefully administered. Arguably the greatest impediment to implementing spent fuel management options in Japan, however, is obtaining consensus on what approaches to take, and then obtaining approval, especially from local jurisdictions, for the siting of spent fuel facilities. The lengthy and, thus far, unsuccessful process of seeking a host for a nuclear waste disposal facility in Japan, as described above, is a specific case in point. Even more modest modifications to current practices, however, such as storing spent fuel in dry casks at reactor or interim storage sites, face significant legal and local political hurdles.

Also uncertain at present are Japan's policies for pluthermal power plants, that is, using mixed-oxide fuel in light water reactors to help to reduce the inventory of plutonium-bearing, but non-irradiated, MOx fuel that Japan has built up through its domestic reprocessing activities and through reprocessing done under contract for Japanese utilities in Europe. Based on the analysis described above, however, the use of pluthermal reactors will have at best relatively little impact on the current inventory of plutonium-bearing MOx fuel, and at worst could substantially increase the inventory of MOX fuel. The use of MOX fuel in pluthermal reactors will also have relatively little impact on Japan's inventory of spent fuel, in scenarios with or without reprocessing.

Overall, it seems clear that reprocessing and the use of MOX fuel in pluthermal reactors will do little to address Japan's spent nuclear fuel problem, which therefore will have to be addressed through other means that will necessarily incorporate both political and technical dimensions.

3.3 Nuclear Sector and Spent Fuel Policy in the ROK

South Korea (the ROK) has been increasingly reliant on nuclear power since 1978, when it started its first commercial nuclear power plant. The ROK imported 96.0% of its primary energy resources (at a cost of 184.8 billion US dollars) from abroad in 2012, to compensate for its lack of domestic reserves.[100] This high level of imports has been the energy supply security consideration driving the ROK's reliance on nuclear power. As of February 2, 2014, the ROK had 23 power reactors in operation, with a total capacity of 20.7 GWe. The ROK reactor fleet as

[100] Korea Energy Economics Institute, *2013 Energy Info. Korea*, December 2013.

of August 2013 consisted of 19 pressurized water reactors (PWRs) and four CANDU heavy water reactors (HWRs), the latter with a combined capacity of 2.8 GWe,[101] An additional 6.6 GWe of PWRs were under construction,[102] and additional PWRs capacity was planned that would bring South Korea's total nuclear generating capacity up to 43 GWe by 2035.[103]

All of the nuclear power plants in The ROK are located along the coast of the peninsula, as shown in Figure 3-11: Locations of the ROK's Nuclear Power Plants. On September 14, 2012, Ministry of Trade, Industry and Energy (MOTIE) announced that Yeongdeok and Samcheok both located on the East coast, have been identified as new sites for nuclear power plants.

Table 3-1 shows the generating capacities and expected initial operating dates of the ROK's power reactors through 2027.[104]

All of the nuclear power plants in The ROK are located along the coast of the peninsula, as shown in Figure 3-11: Locations of the ROK's Nuclear Power Plants.[105] On September 14, 2012, Ministry of Trade, Industry and Energy (MOTIE) announced that Yeongdeok and Samcheok both located on the East coast, have been identified as new sites for nuclear power plants.[106]

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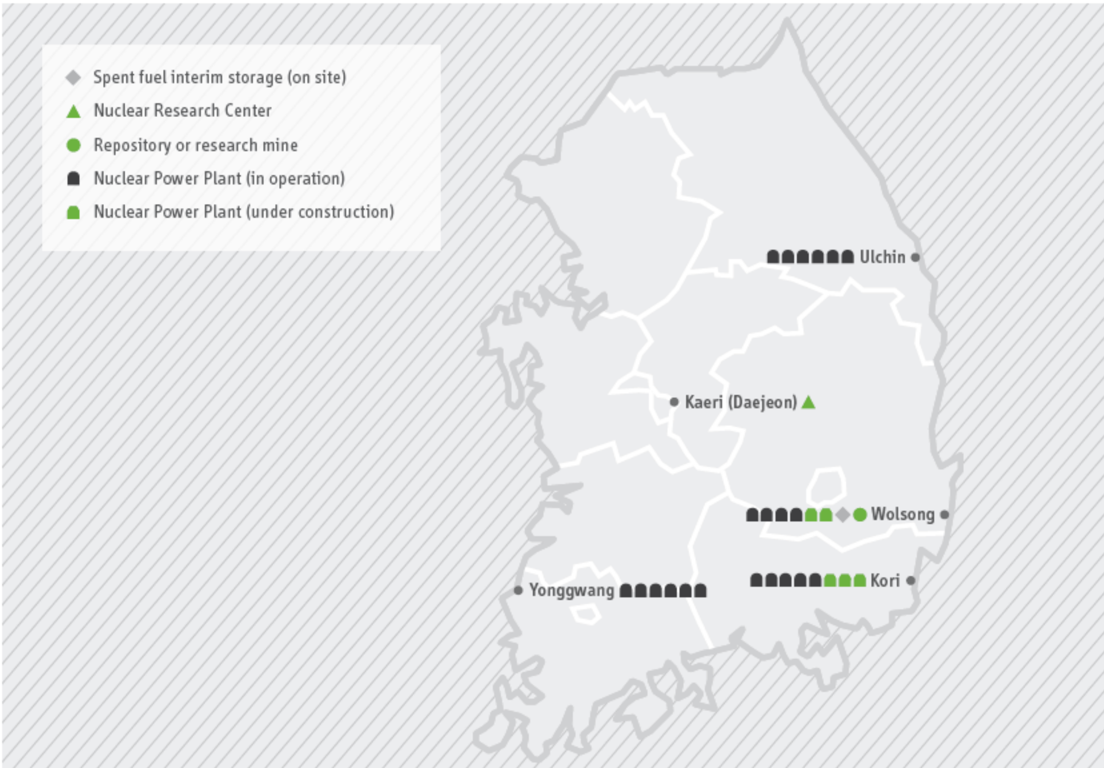
[101] Retrieved February 2, 2014 from website: http://www.nppinfo.co.kr/action?cmd=NOPA01.
[102] Retrieved February 2, 2014 from website: http://www.khnp.co.kr.
[103] Ministry of Trade, Industry and Energy, *The 2nd National Energy Basic Plan*, January 2014 (Korean).
[104] Ministry of Trade, Industry and Energy (previously Ministry of Knowledge Economy), *The 6th Basic Plan for Long-Term Electricity Supply and Demand (2013 ~ 2027)*, January 2013 (Korean).
[105] International Panel on Fissile Materials, *Managing Spent Fuel from Nuclear Power Reactors: Experience and Lessons from Around the World*, September 2011, p.62.
[106] http://www.ytn.co.kr/_ln/0102_201209140905445385

Table 3-1: Current and Planned Nuclear Power Capacity in the ROK through 2027

Site	Unit	Type	Capacity (MWe)	Initial Operation
Kori	Kori-1 Kori-2 Kori-3 Kori-4 Shin-Kori-1 Shin-Kori-2	PWR PWR PWR PWR PWR PWR	587 650 950 950 1000 1000	Apr. 1978 Jul. 1983 Sept. 1985 Apr. 1986 Dec. 2010 Dec. 2011
Shin-Kori	Shin-Kori-3 Shin-Kori-4 Shin-Kori-5 Shin-Kori-6 Shin-Kori-7 Shin-Kori-8	PWR PWR PWR PWR PWR PWR	1400 1400 1400 1400 1500 1500	Dec. 2013 Sept. 2014 Dec. 2019 Dec. 2020 Dec. 2023 Dec. 2024
Yonggwang	Yonggwang-1 Yonggwang-2 Yonggwang-3 Yonggwang-4 Yonggwang-5 Yonggwang-6	PWR PWR PWR PWR PWR PWR	950 950 1000 1000 1000 1000	Aug. 1986 Jun. 1987 Mar. 1995 Jan. 1996 Apr. 2002 Oct. 2002
Ulchin	Ulchin-1 Ulchin-2 Ulchin-3 Ulchin-4 Ulchin-5 Ulchin-6 Shin-Ulchin-1 Shin-Ulchin-2 Shin-Ulchin-3 Shin-Ulchin-4	PWR PWR PWR PWR PWR PWR PWR PWR PWR PWR	950 950 1000 1000 1000 1000 1400 1400 1400 1400	Sept. 1988 Sept. 1989 Aug. 1998 Dec. 1999 Jul. 2004 Jun. 2005 Apr. 2017 Apr. 2018 Jun. 2021 Jun. 2022
Wolsong	Wolsong-1 Wolsong-2 Wolsong-3 Wolsong-4	CANDU CANDU CANDU CANDU	679 700 700 700	Apr. 1983 Jul. 1997 Jul. 1998 Oct. 1999
Wolsong	Shin-Wolsong-1 Shin-Wolsong-2	PWR PWR	1000 1000	Mar. 2012 Oct. 2013

Figure 3-11: Locations of the ROK's Nuclear Power Plants

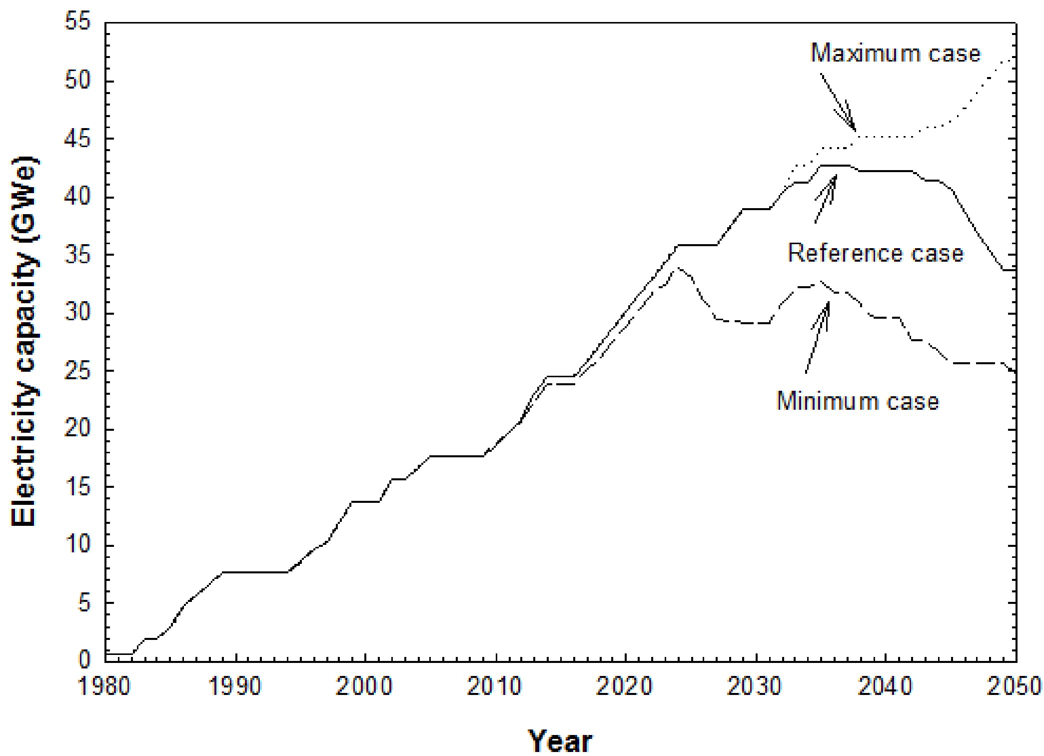


Considering the uncertainty with regard to the future of the nuclear power sector, this study assumes maximum case and minimum case scenarios for the projection of NPPs deployment in the ROK. Projections of nuclear power capacity through 2035 as planned by the ROK government (at least as most recently published) serves as the reference case for this study. Table 3-2: Assumed NPPs Deployment Scenarios in the ROK shows the assumptions associated with the three NPPs deployment scenario analyzed. Figure 3-12 shows the resulting projected nuclear generation capacity in the ROK under each scenario through 2050. These projections are used to estimate spent fuel arisings and storage needs, and are also used in the LEAP nuclear scenarios presented in section 5.4 of this Final Report.

Table 3-2: Assumed NPPs Deployment Scenarios in the ROK

Case	Assumptions
Ref. Case	- Based on the ROK government plan - Considering life-time extension of NPPs (to 60 years for PWRs/APWRs and 50 years for CANDUs) - No replacement of shutdown NPPs
Max. Case	- Based on the ROK government plan - Considering life-time extension of NPPs (to 60 years for PWRs/APWRs and 50 years for CANDUs) - Replacement of shutdown NPPs with 1.5 GWe PWRs by 2050
Min. Case	- Based on the ROK government plan, except of - No life-time extension of NPPs (to 40 years for PWRs, 60 years for APWR and 30 years for CANDUs) - No replacement of shutdown NPPs

Figure 3-12: Projected Nuclear Generation Capacity in the ROK for Each Scenario (1980-2050)



Status of and Prospects for Spent Fuel Generation

As of the end of 2012, 5,829 tHM (tons heavy metal) of spent PWR fuel and 6,878 tHM of spent HWR fuel were stored in the spent fuel storage facilities at The ROK's four NPP sites.[107]

Projections of spent fuel generation depend on the capacity factors of the reactors (that is, what fraction of the time they operate and at what average fraction of their nominal capacities), and the burnup of spent fuel (that is, the number of megawatt-days of heat that can be generated from a unit of fuel before it is discharged from the reactor, or "spent"). The average discharged burnup level for spent PWR fuel is around 50,000 MWd/tHM in today's reactors. Heavy-water reactors are fueled with natural uranium, and the burnup rate is about 7,100 MWd/tHM. Assuming that all NPPs have thermal efficiencies of 33% and capacity factors of 90 percent, projections through the year 2050 of cumulative spent fuel generation in the ROK from reactors were

[107] Ministry of Trade, Industry and Energy (MOTIE), "Status of Spent Fuel Management and Plan for Public Consultation Process," May 2013 (Korean).

calculated for PWR and CANDU spent fuels.[108] Even by 2050, the difference between the minimum and reference cases for PWR spent fuel is only on the order of 11 percent, while the maximum case produces a 2050 inventory of PWR spent fuel 7 percent higher than the reference case. For CANDU spent fuel, the reference case is about one third higher than the minimum case, which foresees decommissioning of the ROK's existing CANDU units by around 2020, without replacing them. There is no difference between CANDU spent fuel generation in the reference and maximum cases.

The ROK started to research and designed a central interim spent-fuel storage facility and repository for low and intermediate level waste (LILW) in 1986. The implementing organizations for this effort were KAERI and then-Ministry of Science and Technology. In July 1988, the Korean Atomic Energy Commission (AEC) announced that a centralized away from reactor (AFR) facility would be constructed by December 1997. In December 1988, the AEC announced the intention to construct a wet-type AFR with a capacity of 3,000 t of spent fuel. Due to strong opposition from local potential host communities that have developed in the wake of these announcements, all attempts to acquired AFR sites have failed since 1987. In 1996, the responsibility for radioactive waste management was transferred first to the then-Ministry of Commerce, Industry and Energy, then on to KEPCO (the Korea Electric Power Corporation). In September 1998, the AEC announced that a LILW disposal facility would be built by 2008 and an interim spent-fuel storage facility would be built nearby by 2016. The AEC also announced the intent to acquire 2,000 t of spent fuel storage capacity at a dry facility AFR site by 2016. Due to continuing difficulties in securing sites since 1996, the AEC decided to pursue separate sites for the LILW repository and the central spent-fuel storage facility. The AEC recently announced that it would adopt a public and stakeholder engagement process to help to reach agreement on a site for an AFR spent fuel storage facility.[109]

In the ROK, the Ministry of Trade, Industry and Energy (MOTIE, previously the Ministry of the Knowledge Economy) is primarily responsible for making and approving plans regarding nuclear reactor deployment. Although there has been some limited public concern about reactor deployment and other nuclear energy plans in the ROK, the role that the public has in terms of input to nuclear energy-related decisions is extremely limited. As of this writing, it does not seem that the Fukushima accident has significantly affected thinking on the part of nuclear policymakers regarding reactor deployment in the ROK.

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[108] Calculations by Jungmin Kang (2013) in support of his report *The ROK's Nuclear Energy Development and Spent Fuel Management Plans and Options*, available as http://nautilus.org/napsnet/napsnet-special-reports/the-roks-nuclear-energy-development-and-spent-fuel-management-plans-and-options/.

[109] South Korea chapter of *Managing Spent Fuel from Nuclear Power Reactors,: Experience and Lessons from Around the World*, International Panel on Fissile Materials, September 2011; Seong-Won Park, "Pyroprocessing Technology for Sustainable Nuclear Energy," Presentation given at a workshop on Status of Reprocessing Worldwide and Pyroprocessing in South Korea, Seoul, South Korea, October 26, 2012.

Shortage of Sites' Storage Capacities for Spent Fuel

The ROK maintains its inventory of spent reactor fuel in wet storage spent fuel pools at each of the four reactor sites, and at a dry storage facility at Wolsong.[110]

Dry storage facilities are only used for CANDU spent fuel at the Wolsong site, partly because of the much lower burnup of CANDU spent fuel than that of PWR spent fuel (and thus the higher volume and lower radioactivity of CANDU spent fuel). CANDU spent fuel is transported to the dry storage facilities via a road on the reactor site; the dry storage site is adjacent to the reactor site.

Multi-reactor nuclear plant sites in the ROK do not use centralized spent-fuel pools accepting fuel from multiple reactors. Rather, for each reactor, the spent fuel pool is located in the fuel building next to the domed reactor containment building at ground level. The spent fuel pools at the ROK reactors are typically 40 or more feet (12 meters) deep. The sizes of the spent fuel pools in use vary among the ROK reactors.

According to an analysis by the operator, Korea Hydro & Nuclear Power Co., Ltd, the saturation dates for the current spent fuel storage at the Kori, Yonggwang and Ulchin sites for spent PWR fuel, and at the Wolsong site for spent HWR fuel, will be 2016, 2021, 2018 and 2017 respectively.[111] KHNP did not fully consider the potential for dense racking arrangement of spent fuel assemblies in pools in its assessment—"re-racking" was assumed in the spent fuel pools of some reactors but not in others.

However, when KHNP stated that the spent fuel pools at Kori will be full in 2016, it had considered only intra-site transshipment of spent fuel among the pools of the four older Kori reactors. That is, for example, KHNP considered only transfers such as from the Kori unit 1 to unit 4 on the same site. The old spent fuel in the pools of the older (pre-2010) 4 reactors at the Kori site could in practice be shifted to the pools built for the newer 2 reactors, that is, the Shin-kori units 1 and 2 that went into operation in 2010 and 2011, respectively, on the same site. If this intra-site transshipment of spent fuel is implemented, it extends the saturation year for spent fuel pools from 2016 to 2023.

At the Ulchin site, similarly, KHNP considered only intra-site transshipment of spent fuel among the pools of the old 6 reactors, that is, between Ulchin units 1 to 6 on the site. The old spent fuel in the pools of the older 6 reactors could in practice be shifted to the pools of the newer 4 reactors, that is, to Shin-ulchin units 1 to unit 4, which are to be put in operation on the same site from 2015 through 2021. If implemented, this extends the saturation year for spent fuel pools at the Ulchin site from 2018 to 2028.

With regard to the reactors on the Yonggwang site, KHNP's assessment of the date of saturation might be accurate, considering that there are no plans for new deployment of NPPs at the site

[110] International Panel on Fissile Materials, *Managing Spent Fuel from Nuclear Power Reactors: Experience and Lessons from Around the World*, September 2011, p.69.
[111] Ki-Chul Park, "Status and Prospect of Spent Fuel Management in South Korea," *Nuclear Industry*, August 2008 (in Korean)

until 2022 at the earliest, and thus no adjacent new spent fuel pools to which to move existing inventories,

The situation of storage of spent fuel at Wolsong is somewhat complex, compared with that at the other PWR sites. According to a law entitled “Special Act on Support for Areas Hosting Low and Intermediate Level Radioactive Waste (LILW) Disposal Facility”, dated 2005, spent fuel-related facilities cannot be built in the local area that hosts the LILW site, which includes the Wolsong site. Some South Korean nuclear experts argue that the law means that no more dry storage facilities are to be built after 2017 when current dry storage will be full. However, the Korea Radioactive Waste Agency (KORAD, then- KRMC) argues that those dry storage facilities at Wolsong are “tentative” ones, not the types of “interim” storage that are banned by the 2005 Special Act of LILW. “Tentative” storage means storage of spent fuel on site under the control of KHNP, whereas “interim” storage means storage of spent fuel on site or at an AFR site under the control of KORAD, though this is an administrative difference only, as there is no physical difference between “tentative storage” and “interim storage”.

KHNP has expanded the capacities of dry storage at Wolsong by 680 tHM in 1990, 907 tHM in 1998, 680 tHM in 2002, 1134 tHM in 2006 and 3528 tHM in February 2010 for a total of 6,929 tHM dry storage capacity and 3,053 tHM pool capacity as of August, 2012. Whether or not dry storage facilities at Wolsong violate the special Act of LILW is still controversial and needs to be clarified by the ROK government.

According to a recent study performed by an expert group composed of members of the ROK’s nuclear establishment, the storage pools at the ROK’s four reactor sites, Kori, Ulchin Yonggwang, and Wolsong are projected to be full by 2028, 2028, 2024 and 2025, even considering re-racking and intra-site transshipment between NPPs at individual PWRs sites, as well as the installation of two additional MACSTOR/KN-400 modules at Wolsong.[112]

National Policy on Spent Fuel Management

At its 253rd meeting in 2004, the AEC announced that national policy for spent fuel management would be decided later in consideration of progress of domestic and international technology development, and that spent fuel would be stored at a reactor sites through 2016 under KHNP’s responsibility.[113] Since The ROK has not decided whether to directly dispose of or recycle spent fuel, it currently has no national plan on geologic disposal of spent fuel.

A KORAD report assumes operation of AR and/or AFR interim dry storage of spent fuel in around early 2020s, operation of geologic disposal site for CANDU spent fuel in around 2050,

[112] Korea Radioactive Waste Management Corporation, "Alternatives and Roadmap of Spent Fuel Management in South Korea," Final report prepared by Korean Nuclear Society, Korean Radioactive Waste Society and Green Korea 21, August 2011 (Korean)

[113] 253rd meeting of Korea AEC in 2004. See, for example, Ministry of Education, Science & Technology, *Korean Third National Report under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*, dated October, 2008, and available as www.kins.re.kr/pdf/Korean%20Third%20National%20Report%202008.pdf.

and operation of geologic disposal site for PWR spent fuel and/or HLW from pyroprocessing in around 2070.[114]

Legal and Institutional Issues in the Radioactive Waste Management

Key ROK National laws related to spent fuel and radioactive waste management are the Atomic Energy Act (AEA) and the Radioactive Waste Management Act (RWMA). The AEA provides for matters concerning safety regulations, including permission for construction and operation of radioactive waste disposal facilities. The RWMA, which determines all aspects of managing radioactive waste, was enacted on March 31, 2008. Based on the RWMA, the KORAD and the Radioactive Waste Management Fund were established in January 2009. According to the RWMA, KHNP, the utility company, should annually deposit to the Fund payments toward the cost of decommissioning of nuclear power plants, disposal of low and intermediate level waste (LILW), and spent fuel management.[115] Funds for these activities are collected from electricity consumers via tariffs; data how these funds are collected and disbursed for nuclear sector activities in the ROK are not yet public information.

With regard to the governmental organizations concerned with radioactive waste, the main administrative authorities in the ROK are the Ministry of Trade, Industry and Energy (MOTIE, previously the Ministry of the Knowledge Economy), which supervises the nuclear power program, and a newly founded Nuclear Safety and Security Commission (NSSC) under the jurisdiction of the Prime Minister, which is responsible for nuclear safety regulations including the licensing of nuclear facilities as well as nuclear security.[116] The Atomic Energy Committee (AEC) under the jurisdiction of the Prime Minister is the supreme organization for decision-making on national nuclear policies. The NSSC is responsible for matters concerning the safety of nuclear facilities and radioactive waste management. NSSC is also responsible for developing licensing criteria for the construction and operation of radioactive waste disposal facilities, for developing technical standards for operational safety measures, and for assuring safe management of radioactive waste at every stage of the life cycle of waste disposal facilities, including the site selection, design, construction, operation, closure and post-closure phases. MKE also develops and implements management policies regarding radioactive waste treatment, storage and disposal. These policies are prepared by MOTIE and deliberated by the AEC before implementation.

KAERI's Plans for Pyroprocessing and Fast Reactors

The ROK's debate regarding spent fuel management has been focused on "pyroprocessing," driven by the Korean Atomic Energy Research Institute (KAERI). KAERI has been developing pyroprocessing technologies, in which plutonium and other transuranics are electrochemically separated from uranium and fission products in spent fuel after the dissolution of spent fuel in molten salt. Pyroprocessing is thus different from typical aqueous reprocessing, which separates

[114] Korea Radioactive Waste Management Corporation, "Alternatives and Roadmap of Spent Fuel Management in South Korea," Final report prepared by Korean Nuclear Society, Korean Radioactive Waste Society and Green Korea 21, August 2011 (Korean)
[115] Ibid.
[116] Retrieved August 16, 2012 from website: http://www.nssc.go.kr/nssc/english/introduction/purpose.html.

pure plutonium from other spent fuel components. KAERI argues that with pyroprocessing, less spent fuel waste would need to be disposed of, in that the transuranics, after being separated and fabricated into reactor fuel, can eventually be fissioned in fast neutron reactors.[117] The push for pyroprocessing in the ROK is happening partially because Japan has established its own spent fuel reprocessing capacity, and the ROK wishes to have a similar capability, and because, although a reprocessing plant could not be put into operation by the time that the PWR spent fuel pools begin to fill up in the 2020s, the expectation is that reprocessing spent fuel could provide a justification for establishing an additional central storage site for spent fuel waiting to be reprocessed that would be located near the site where the reprocessing plant would be built. KAERI insists that pyroprocessing and recycling of spent fuel is the best alternative for reducing the future burden of geologic disposal of spent fuel, a view supported by the Ministry of Science, ICT and Future Planning (previously the Ministry of Education, Science and Technology). A 10-year US-ROK joint study on pyroprocessing has been underway since 2011. No plans as to the location of potential pyroprocessing or fast reactor facilities in the ROK have been announced to date.

Conclusion

The ROK's current nuclear capacity of 20.7 GWe will, under current plans, be approximately doubled by 2030. Given the current lack of pool storage capacity for PWR spent fuel, the problem of PWR spent fuel storage in the ROK will become worse in the near future. Decisions regarding the interim storage of spent fuel will play key roles in shaping nuclear fuel cycle activities and development in the ROK in the coming years because interim storage would provide flexibility in nuclear sector decision-making—whether or not the ROK moves toward pyroprocessing—by delaying, possibly for decades, the day when final decisions regarding spent fuel management must be made.

The 10-year US-ROK joint study on pyroprocessing, begun in 2011, will likely also affect future nuclear fuel cycle activities and development in the ROK. If the joint study reaches a positive conclusion regarding pyroprocessing, it could affect the ROK government's consideration of deployment of pyroprocessing as a means to resolve the ROK's spent fuel storage problems.

In terms of the potential impact of the Fukushima accident on ROK policy, the ROK public might, after seeing the Fukushima accident play out, be more accepting in the future of dry storage facilities if the public is more fully educated about the relative safety aspects of different spent fuel storage options. The deployment of dry storage facilities for spent fuel will likely be a key factor affecting nuclear fuel cycle activities and development in the ROK in the coming years.

A government-supported committee tasked with carrying out a public consultation process on spent fuel management in Korea was established in October 2013. The 13 committee members are from academia, local communities and non-governmental organizations. The committee plans to provide recommendations to the South Korean government on spent fuel management

[117] Jungmin Kang, "South Korea in focus: The Politics of Spent Fuel Storage and Disposal," *Bulletin of the Atomic Scientists*, May/June 2011.

by the end of 2014, following a public consultation process including meetings, seminars, fora, surveys, and other events and activities.[118]

3.4 Nuclear Sector and Spent Fuel Policy in the DPRK

The DPRK's nuclear energy ambitions date back to at least the 1950s, but its domestic reactor program is inextricably entwined with its nuclear weapons program. The DPRK's first reactor was (and is) an IRT-2000 pool-type unit obtained from the Soviet Union, which began operations in 1965. The DPRK's first non-research reactor, a graphite-moderated, gas-cooled unit with a nominal capacity of 5 MWe, based on the design of the United Kingdom's Calder Hall reactor,[119] began operating in the late 1980s. Despite being justified as a step in the DPRK's program to produce electricity for civilian use, this reactor has never actually produced electricity, though it probably produced heat and steam for use elsewhere in the Yongbyon nuclear complex. The 5 MWe reactor was, however, used to produce plutonium for the DPRK's nuclear weapons program, in conjunction with a reprocessing plant co-located at Yongbyon. The operation of the 5 MWe reactor has been stopped and restarted several times since 1990 in response to agreements, and broken agreements, related to the DPRK nuclear weapons program. As of early 2014, satellite evidence suggests that the 5 MWe reactor is operating again, or at least undergoing testing.[120] The DPRK announced and began to build a nominal 50 MWe (at Yongbyon) and 200 MWe (at Taechon) reactors using similar technology gas-cooled, though neither was completed, and little progress was made on the 200 MWe reactor.[121]

After the 1994 Agreed Framework was signed, the DPRK suspended operation of the 5 MWe reactor and construction on the larger reactors in exchange for a promise by a consortium of nations operating as the Korean Peninsula Energy Development Organization (KEDO) to build two modern 1000 MWe light-water reactors at Simpo. Construction of those reactors began in 1999 and continued into the early 2000s, but was suspended in 2003, and the KEDO board voted to terminate the LWR project in 2006.[122]

Following the termination of the Simpo LWR project, the DPRK decided to embark upon a centrifuge enrichment program and the construction of an experimental LWR, as described in section 2.6 of this Report. Understanding, apparently, a point that we have made on many occasions, namely that the Simpo reactors could never have operated safely within the DPRK

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[118] A public consultation committee on spent fuel, "Action Plan for Public Consultation Process on Spent Fuel," January 29, 2014 (Korean).
[119] See, for example, Nuclear Threat Initiative (2014), "Yongbyon 5MWe Reactor", last modified March 19, 2014, and available as http://www.nti.org/facilities/766/.
[120] See, for example David Albright and Serena Kelleher-Vergantini (2014), *Monitoring Activity at Yongbyon Nuclear Site*, Institute for Science and International Security Imagery Brief, dated April 23, 2014, and available as http://isis-online.org/uploads/isis-reports/documents/Yongbyon_April2014.pdf.
[121] See, for example, GlobalSecurity.org (2013), "Weapons of Mass Destruction (WMD): Yongbyon [Nyongbyon]", available as http://www.globalsecurity.org/wmd/world/dprk/yongbyon-50.htm.
[122] See, for example, http://www.kedo.org/index.asp and Korean Peninsula Energy Development Organization Annual Report 2003, available as http://www.kedo.org/pdfs/KEDO_AR_2003.pdf.

electricity transmission and distribution grid, the DPRK has indicated its intention to build a fleet of smaller LWRs to help to provide electricity to its population.[123]

It is unclear what the DPRK's plans are for spent fuel management for either the fuel from the experimental LWR or from a future fleet of small LWRs. The DPRK's current reprocessing plant is not built to handle fuel from the LWRs, but could conceivably, albeit with some difficulty, be modified to do so. Beyond the inclusion of a spent fuel pool in the experimental LWR design, no particular indication has been provided by the DPRK of how spent fuel coming from LWRs will be managed in the medium or long term.

4 Prospects for deep borehole disposal of nuclear waste

4.1 Summary of Concept

Deep borehole disposal of nuclear waste (DBD) is a possible technological strategy that could help to avoid security and sustainability dilemmas associated with the management of the rapidly growing quantities of nuclear spent fuel in the East Asia region. As noted in Chapter 3 of this Final Report, the region's spent fuel inventories from nuclear power are growing rapidly. The standard approach is to store spent fuel in retrievable surface storage or relatively shallow (tens to hundreds of meters) geologic repositories. In this Chapter we summarize the potential applications of an alternative disposal strategy, the emplacement spent fuel directly into very deep boreholes after a once-through cycle (that is, without separating spent fuel into its radioactive components via reprocessing). Deep boreholes could also, however, be used to dispose of high level wastes (HLW) from reprocessing, and potentially for other radioactive materials.

The deep borehole disposal approach would avoid many of the proliferation-prone steps involved with reprocessing and recycling fissile material from spent fuel. It also could prove to be more acceptable socially and politically, more economic in the short and long run, and less hazardous with respect to the technological and ecological risks arising from the disposition of large amounts of radioactive material. To date, no systematic investigation into the deep borehole disposal option has been done in the major nuclear power states in East Asia, nor has a detailed assessment been made of the regional cooperation potential from its implementation in lieu of various proposed regional spent fuel storage and reprocessing schemes. The summaries presented below, and the papers prepared for this project from which the summaries have been

[123] Nautilus has presented ideas related to cooperation with the DPRK on its LWR program in several publications, including David von Hippel and Peter Hayes (2010), *Engaging The DPRK Enrichment And Small LWR Program: What Would It Take?*, Nautilus Institute Special Report, dated December 23, 2010, and available as http://nautilus.org/wp-content/uploads/2011/12/vonHippelHayesLWR2.pdf. In these publications we have made the argument that that it may be possible to slow and even reverse the DPRK's nuclear breakout by collaboration that assists it to develop small light water reactors (LWRs) that are safe, reliable, and above all, safeguarded, and that integrates its enrichment capacity into a regional enrichment consortium, possibly as part of a Northeast Asian Nuclear Weapon Free Zone.

derived, therefore represent an initial effort at compiling what is known about deep borehole disposal in East Asia, and evaluating its potential.

Deep borehole technology is advancing rapidly through advances in petroleum and natural gas exploration technologies. There are many opportunities for regional cooperation to explore the potential for deep borehole disposal, to compare it with other regional cooperation schemes to manage spent fuel, and to avoid safeguards and security dilemmas associated with accumulating large amounts of separated fissile material from spent fuel. This issue is especially salient in the Korean Peninsula and Japan (as well as in Taiwan, though the latter has not been included in this study to date), where spent fuel storage is already in scarce supply. It could also play a role in the eventual resolution of the North Korean nuclear weapons issue if a regional nuclear weapon free zone is adopted that includes collaboration between national nuclear fuel cycles.

Deep borehole disposal of nuclear materials is not a new concept, but has attracted a resurgence of interest in recent years. In this concept, boreholes of 0.5 to 0.8 meters in diameter would be drilled on the order of 5 km deep into stable, crystalline basement rocks. DBD would have potential advantages over normal geologic disposal, as it would place waste canisters at greater depths, where the hydro-geological conditions are less dynamic, than in conventional mined repositories. This greater depth increases confidence that eventual impacts on the biosphere by the radioactive waste can be avoided or substantially reduced. Low permeability in the deep crystalline basement rocks and the high salinity in the deep aquifers found there suggest that the chances of interaction of wastes with groundwater that could interact with the biosphere should be minimal. Crystalline basement rocks are relatively common at depths of 2 km to 5 km in many countries, leading to wider availability of suitable sites for DBD than for nearer-surface repositories. Along with greater safety through better isolation of wastes from the biosphere, greater security against terrorist diversion of wastes disposed of in DBD and better cost-effectiveness would be additional potential benefits.[124] Figure 4-1 presents a schematic of deep borehole disposal and waste package emplacement. Nuclear materials to be permanently and (essentially) irretrievably disposed of—potentially including spent nuclear reactor fuel, high level nuclear waste from spent fuel reprocessing and similar processes, and separated or partially-separated plutonium—would be placed in canisters and buried in a disposal zone at depths of 3 to 5 km in the borehole, which would be capped.

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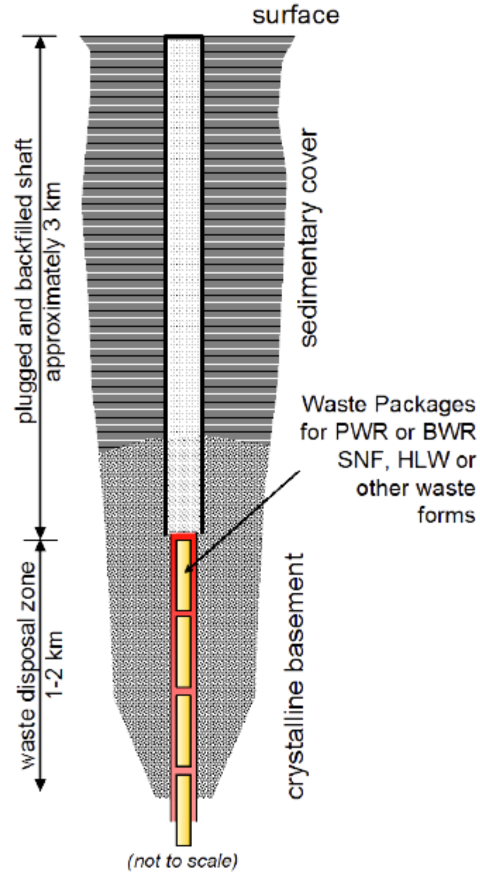
[124] Bill W. Arnold et al., "Into the deep," *Nuclear Engineering International*, 25 March 2010; Gibb, F.G.F., Taylor, K.J. and Burakov, B.E. "The 'granite encapsulation' route to the safe disposal of Pu and other actinide," *Journal of Nuclear Materials*, Volume 374 (3), p.364 – 369 (2008). As shown in Figure 4-1, the waste at the bottom of the borehole would be protected by 3-4 km of clay and concrete plugs and backfill, requiring a major drilling operation to penetrate to where the wastes have been buried, and making it highly unlikely that a terrorist group could access the wastes undetected.

Figure 4-1: Schematic of Deep Borehole Disposal



This approach presents potential technical simplicity and cost implications, relative to other approaches to nuclear materials, as well as for its promise of permanent disposal. It is also attractive for its potential to offer more robust safeguards against diversion of nuclear materials, reduction of nuclear materials stocks and transport, reduction in spent fuel handling, and other considerations, relative to some of the other fuel cycle options.

Possible institutional configurations for deep borehole disposal in East Asia include the use of the technology for nuclear materials disposal by each nation going it alone, by some nations contracting for disposal with a few service supplying nations, or through the coordinated development and operation of one or a few central deep borehole facilities used and governed by all of the key nuclear user (present and future) nations of the region.

4.2 Summary of Prospects/challenges for Deep Borehole Disposal in NE Asia

At the May 2013 Nautilus meeting in Beijing, updates on work or policy considerations of DBD were presented for each country. These updates are summarized in sections 4.3 through 4.5 of this Chapter. Yun Zhou (Harvard University, USA) explained that, in China, deep borehole disposal was not considered as an option for HLW management and has not been studied closely. China has a reprocessing policy for spent fuel and the resulting high-level waste will likely be disposed next to the reprocessing site. An agreement is being pursued with Areva (France) for the development of a large-scale (800 tHM/a) reprocessing plant. Commercial drilling capabilities in China currently extend to 4 km deep holes and mainly focus on mining exploration. In 2005, China's national drilling R&D project completed a 5 km deep borehole. At present there is an incomplete regulatory system to regulate all nuclear activities and China needs an Atomic Energy Law and regulations to cover nuclear waste management, disposal and a possible spent fuel disposal fund. Additional funding is required for radwaste R&D, which has so far not attracted a high priority. Future developments would be enhanced and facilitated by increased international co-operation.

The situation in Japan was presented by Tomochika Tokunaga (University of Tokyo). Although NUMO (the Nuclear Waste Management Organization of Japan) identified DBD as an option in 2004, there has been little interest in the approach and no work has been carried out by NUMO. Japan has several very deep holes, constructed by METI (the Ministry of Economy, Trade and Industry) in the 1990s, e.g.: Shin-Takenomachi (1993) to 6,310 m, with a cased diameter of ~17.8 cm OD and a bottom temperature of 197 C; Mishima (1992) to 6,300 m with a bottom temperature of 226 C; Higashi-kubiki (1989-1990) to 6,001 m, cased to 5000 m at about 24.4 cm OD and uncased below that. The stability of deep (especially geothermal) boreholes has been an issue, with casing collapse problems reported. In addition, certain areas of Japan are characterized by upwelling deep crustal fluids and may be unsuitable for geological disposal. These examples of test drilling in Japan are all slimmer holes than would be needed for emplacing radioactive materials, for example, a vitrified HLW package of 43 cm diameter. With 40,000 HLW packages, around 100 holes could be required. The difficulty of retrieval is seen as an issue, if such a requirement would be placed on the disposer. Nevertheless, because DBD is an option that can be considered for any small volume waste, there has been a reawakening of interest recently with respect to several waste-streams:

- Debris inside the partially-melted core of several units of the Fukushima-daiichi NPP;
- Damaged fuel/spent fuel from the pool at Fukushima-daiichi;
- Radioactive wastes from research institutions;
- ^{129}I (^{14}C) in TRU waste.

Advantages being discussed are that it may not be necessary to separate wastes, small volumes can be accommodated by smaller diameter boreholes and might allow a retrievability option, the characterization of the site and monitoring can be achieved by side-track holes and, in particular, this option might contribute to overcoming the difficulties of handling some wastes at the Fukushima-daiichi NPP. If any of these options were to be pursued further, it is recognized that both the engineering and the safety case development would need major efforts and that finding a site will continue to present problems, as with a conventional geologic disposal facility.

An update on the situation in the Republic of Korea was given by Jungmin Kang (Korea Advanced Institute of Science and Technology, or KAIST), who pointed out the over-arching consideration that, since ROK has not decided whether to directly dispose of or recycle spent fuel, it currently has no national plan on geological disposal of spent fuel either, although it has a long-standing R&D program in this area. Geologically, much of the ROK, indeed the whole Korean Peninsula, may be suitable for consideration for DBD. By 2050, ROK will have between 40,000 and 50,000 tHM of PWR and CANDU spent fuel that will require management. IF DBD were to be implemented, then it is estimated that a program disposing of between 300-500 tHM/a between 2030 and 2050 (with a start-up disposal of over 2000 tHM) would cost between 3 to 6 billion USD. A borehole is assumed to accommodate 200-400 canisters containing a total of about 100-200 tHM of spent PWR fuel, or about 1,600-3,200 canisters containing about 32-64 tHM spent HWR fuel. Cost estimation is based on a cost of about 20 million USD for construction of each 5 km-depth borehole. Whether or not local communities in the ROK would oppose the siting of a DBD facility for spent fuel/HLW remains to be seen, but there are no current legal issues that might affect the practicality of deep borehole disposal of spent fuel in the ROK. Considering its potential safety superiority when compared with conventional geological disposal, DBD could be more acceptable to local communities. A public consultation process on spent fuel management will start soon, which will critically affect nuclear fuel cycle activities and development, including deep borehole disposal, in the ROK in the coming years.

There are several DBD issues that are specific to its use to dispose of spent fuel. Unlike vitrified HLW, unmodified spent fuel in standard fuel assemblies is a less stable material to handle, owing to the presence of readily mobilized fractions of several radionuclides in fuel assembly gaps and in fuel grain boundaries. If a package containing spent fuel assemblies is breached, then this ‘instant release fraction’ has the potential to contaminate the fluid in a deep borehole in the event of a serious accident or jam that destroys the container integrity. This may indicate that more robust packages (as in a geologic disposal facility) may be required. Questions that arise are whether it would be possible to recover the situation (recover the compromised container, and clear the borehole), whether the radiological consequences at the surface (during recovery or afterwards) would actually be significant if the borehole were to be sealed and abandoned, and whether it would matter economically to lose a single hole.

A second question is more fundamental to the concept of using DBD to enhance regional safety and nuclear security. In principle, such an aspiration would seem best to be met by moving spent fuel quickly from the NPP to a point of final, inaccessible disposal. This could be achieved, for example, by moving spent fuel from at-reactor pools to interim dry storage as soon as practicable (e.g. 5 to 10 years), using a centralized, hardened (e.g. underground cavern) dry store that could be protected from natural events and from human attack, and then moving the spent fuel to disposal as soon as it is cool enough to match the design requirements of the disposal facility. Conventional geologic disposal facilities typically require 50 to 100 years of cooling of spent fuel after it is discharged from the reactor and before disposal. The low-temperature DBD concepts discussed above and which are attracting most interest (compared to high-temperature, rock melting concepts) could be designed to accept SF earlier: the current US studies are, for example, considering about 25 years as the target for after-discharge cooling before disposal. Nevertheless, it is clear that DBD does not offer an 'instant solution' to security issues, as it would still require some decades of interim storage – implying that a security focus should rather be placed on storage facilities and strategies.

A third issue concerns retrievability and resources. The fissile material in spent fuel (uranium and Pu) is certainly a potential resource, whose significance will attract more or less attention depending on the mood of global and national policies on reprocessing and advanced reactor technologies. Despite attempts to build retrievability into DBD design, it must be accepted that DBD is a practically irretrievable disposal solution and, indeed, this is an intention within the origins of the concept – to place hazardous materials beyond human influence. In DBD expert (and Project Working Group participant) Neil Chapman's opinion, if retrievability is to be imposed on DBD as a demand on its inclusion in a national program, it will cause a major diversion of effort away from the critical areas of study on safety case development and borehole engineering and sealing. Retrievability could add considerably to cost and technical difficulty. Consequently, DBD could be seen as a one-way street with respect to flexibility on re-use of spent fuel, compared to a geologic disposal facility, where retrievability can be made a reasonable prospect (e.g. current designs on Sweden). If there is any likelihood that SF will be needed as a resource over the next century, then DBD is not a solution.

A final SF-related point is to do with the choice of having a centralized or many small, localized DBD facilities. Clearly, there are attractions to the idea of being able to dispose of spent fuel on-site at a NPP, with facilities being constructed at each major NPP complex. However, this will extend the period of interim storage either in the at-reactor pool or at a local interim dry storage facility (compared to moving the spent fuel away earlier to a potentially more secure, centralized facility). This appears to be counter to security considerations, although there are clearly design and strategy solutions. Cooling the SF for longer at reactor sites could also possibly delay the full decommissioning of reactor sites when reactors reach the end of their useful lives.

The best answer to security concerns seems to be to move SF in a timely fashion to high-security, possibly underground, dry storage and to assure a disposal solution that is available in good time for its ultimate disposition. International experience suggests that it takes at least 30 years to move from concept, through siting, design, licensing and construction to an operating GDF. New national programs might be expected to move forward more quickly now, based on 40 years of international experience. However, DBD will require some significant development and it seems unlikely that following the DBD route rather than the GDF route would accelerate a disposal timetable by more than a decade. Nevertheless, this may be significant. Combined with the potential for much earlier disposal (e.g. 25 rather than 50+ years), this may constitute an ability to go for 'early' disposal of SF, with security implications that could attract international support. It would seem worthwhile quantifying this better.

It can be seen that there are several provisos with respect to using DBD for disposal of spent fuel, but these could be clarified or removed by more R&D or by firm policy considerations. In addition, DBD certainly could have a place in national and regional waste management plans for HLW and other, small-volume wastes (e.g. considerations in Japan and ROK). DBD for small amounts of HLW is potentially attractive (e.g., requiring just a few boreholes for a complete national inventory), but few small (and new) NP countries use reprocessing and the current and possible HLW inventories in China, Japan and ROK are large.

4.3 Summary of Potential for Deep Borehole Disposal in China

As China's nuclear industry is relatively young and still small compared to the nuclear industries of the world nuclear leaders, the nuclear waste management segment of the nuclear industry is not yet well-developed and organized. The need for development of this waste management technology and infrastructure calls for more attention and financial support from the Chinese government and nuclear industry. Although China is not facing immediate pressure to manage its nuclear waste, it definitely needs a solid waste management plan to ensure the long-term safety and sustainability of a large-scale nuclear power program. China has previously proposed deep geological disposal for its high-level radioactive wastes from reprocessing. Recently, DBD has been studied and considered as an alternative for the storage and disposal of spent fuel and high-level radioactive waste (HLW) globally. As such, it might be worthwhile to analyze the potential for DBD as an alternative solution at least for storage/disposal of China's high-level radioactive wastes.

DBD is a newer concept, and thus it is considered in China to be a less mature and more novel idea in comparison with mined geological disposal. Currently, mined geological disposal is considered to be the most mature and well-studied HLW disposal methodology. Relative to mined geological disposal, however, DBD can offer more flexibility in siting and possibly better prospects for public acceptance. Although DBD provides more non-proliferation benefits than mined geological disposal, it is less attractive for countries that, like China, have closed fuel cycle policies due to its irretrievability. Economically, DBD could be potentially be cheaper in comparison with mined geological disposal.

Appropriate siting of DBD facilities is very important to assure the safety of disposal of spent fuel or HLW. The site used should have characteristics suitable to prevent or retard the potential movement of radionuclides from the disposal system to the biosphere. The natural geologic characteristics of the site play an important role in the disposal concept.

Desirable site characteristics of DBD ideally include a combination of:

(1) Crystalline rock at the surface or within 1 km of the surface;

(2) A region that is tectonically stable;

(3) An area located away from population centers; and

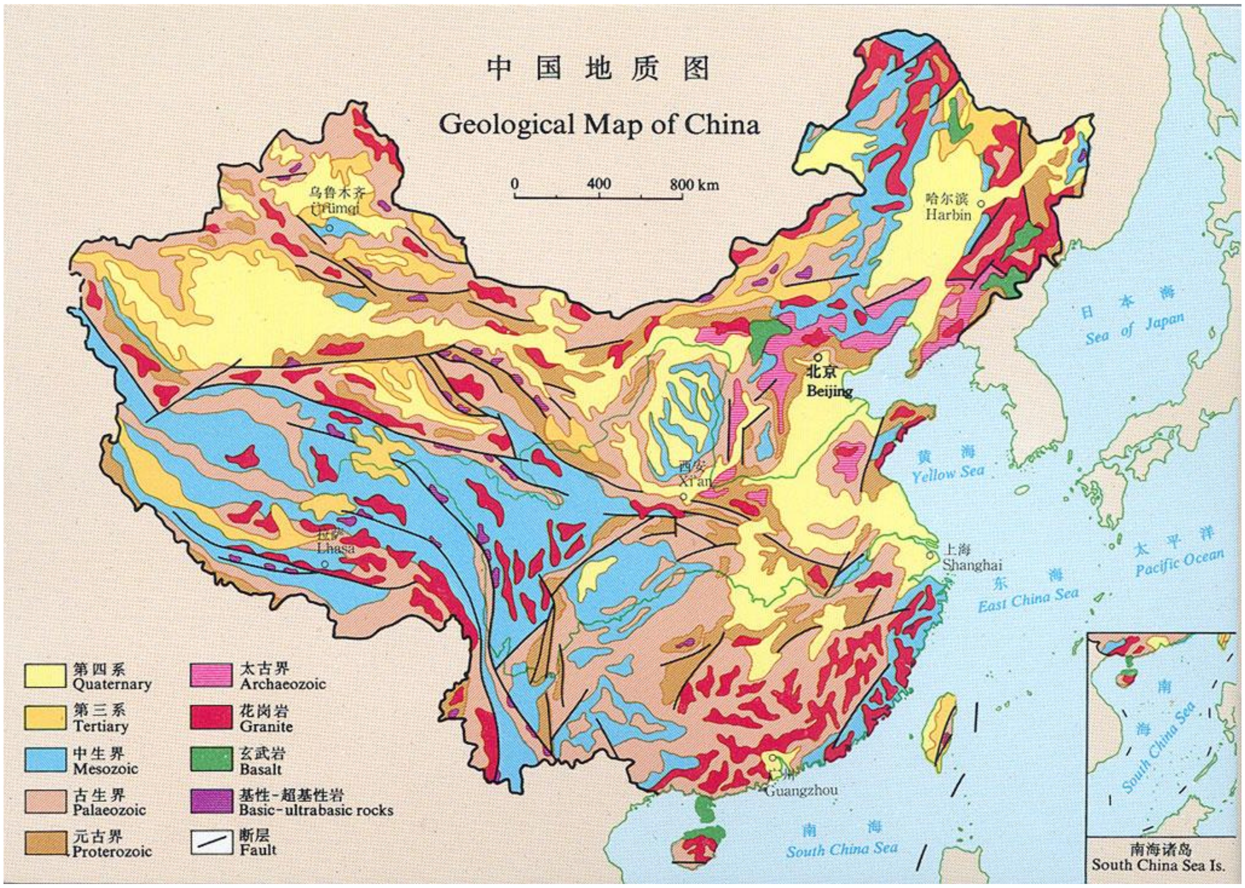
(4) A region not near international borders.[125]

[125] Y. Zhou, 2012. "An Initial Exploration of the Potential for Deep Borehole Disposal of Nuclear Wastes in China" prepared for the Nautilus Institute

China, situated in the southeast part of the Eurasian Continent, occupies a region where several intercontinental tectonic elements are superimposed on one another. In terms of history of the continental tectonic plates, China belongs largely to the "North Continent", except for the Himalaya region of China, which lies on the north edge of the Indian massif of the "South Continent". The greater part of the Oinghai-Xizang Plateau (Chinghai-Tibet Plateau) belongs to the middle segment of the huge-type Tethys tectonic zone, and the east part of China belongs to the Circum-Pacific tectonic zone of the Meso-Cenozoic era. [126] The 2008 Sichuan earthquake occurred along the Longmenshan fault, a thrust structure along the border of the Indo-Australian Plate and Eurasian Plate. China's geological structure is shown in Figure 4-2.[127]

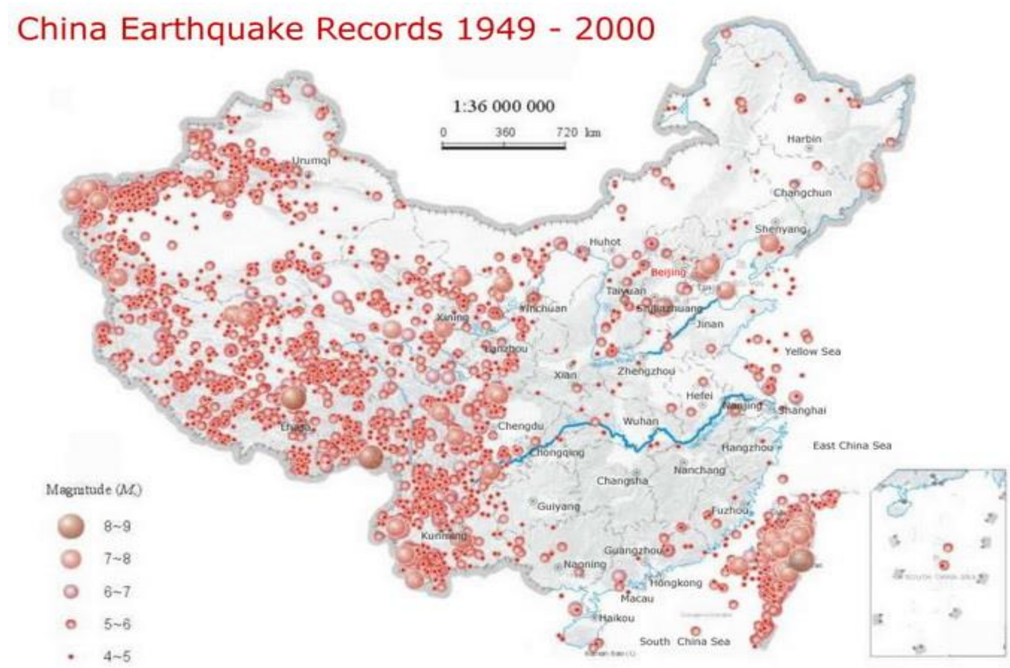
[126] Li, T., 1980. "The Development of Geological Structures in China". *GeoJournal*, Vol. 4, No. 6, Recent Research in China (1980), pp. 487-497
[127] Wang, J. 2010. "High-level radioactive waste disposal in China: update 2010". *Journal of Rock Mechanics and Geotechnical Engineering*. 2010, 2 (1): 1–11.

Figure 4-2: Geological Map of China



Siting of DBD facilities for disposal of nuclear materials requires tectonic stability. The locations for DBD sites need to be away from faults to avoid earthquakes. Figure 4-3 shows the earthquake record in China from 1949 to 2000, which indicates that a large portion of the quakes during that time happened along the Longmenshan fault, a thrust structure along the border of the Indo-Australian Plate and the Eurasian Plate.

Figure 4-3: China earthquake records from 1949 to 2000[128]



In addition, it is desirable that DBD facilities be located away from population centers, which in China means largely away from the urban areas of the eastern and southern coast and adjacent areas. Combining consideration of the tectonic provinces and the areas of low population density in China, the northwest part of Gansu province and north part of Inner Mongolia could be site candidates for further studies, which matches the candidate areas for potential geological (mined) repository facilities that have been under consideration by Chinese authorities.

Technical Capability for Drilling Deep Boreholes in China

Commercial technologies in China currently allow drilling up to 4 km in depth, and mainly focus on mining exploration.[129] The Chinese Continental Scientific Drilling (CCSD) Project, however, as one of China's Key Scientific Engineering Projects, had been working on drilling a 5000 meter deep hole at the eastern part of Dabie-Sulu ultra-high pressure metamorphic belt for geological science R&D purposes. In addition, the project aims to develop a complete and completely new system and technique for deep and hard rock drilling, with the goal of advancing China's commercial drilling technologies to a new level. The project's deep well CCSD-1 project was begun on June 25, 2001, and the drilling operation of the project was successfully completed on March 8, 2005, with a final depth reached of 5158 m for a borehole of 157 mm in diameter. The drilling of a 5000 m

[128] *China National Geography*, 2008 (6).
[129] Chinese Continental Scientific Drilling Project, China geological survey. Available from: http://old.cgs.gov.cn/Ev/ccdp/ccdp.htm

deep continuously-cored borehole in extremely hard crystalline rock, had never been carried out in China before.

Estimates of the Potential Costs of Deep Borehole Disposal in China

Zhou carried out estimates of the potential costs of deep borehole disposal of spent fuel and of high level wastes from reprocessing in China.[130] Overall, the estimates show that the undiscounted cost of disposing of spent fuel produced in China using DBD after a 40 year cooling period prior to disposal are in the range of about $2.5 to $5 billion total for all spent fuel cooled sufficiently for disposal in the years 2045 through 2070 in scenario 1, and increasing to about $230 million per year by 2070,while the same cost of disposing of HLW after a 40 year cooling period are in the range of about $0.1 to $0.2 billion in total during the years from 2051 to 2070. These lower costs shown for Scenario 2, however, do not include the capital or operating costs of reprocessing facilities, which are substantial in their own right. Placing these DBD costs in perspective, if China's nuclear fleet in 2050 is on the order of 200 GWe, which is probably on the lower end of the range of capacity expansion scenarios, its nuclear electricity output would be on the order of 1500 TWh/yr. At an assumed average retail price of $100 per MWh (just above today's non-residential electricity price in China), revenues from nuclear generation would be on the order of $150 billion per year in 2050 (and overall electricity sector revenues would probably be ten times that). Even the largest of the annual cost estimates for DBD, about $230 million in 2070, is therefore only a small fraction—approximately 0.1 to 0.2 percent—of the revenue from electricity sales from nuclear power plants in 2050.

Regulatory Issues and Public Opinion towards Nuclear Power and Wastes

Overall, China's budget expenditures on HLW R&D activities have been relatively low. Although the HLW R&D program has not to date been listed as a key national R&D program, expenditures on HLW R&D increased dramatically in the past several years due to a renewed focus on a long-term view and plan for the nuclear energy sector. Going forward, it is likely that China will pay more attention to its nuclear waste management in response to the rapid pace of China's nuclear power development and its ambitious plans for the future.

China has not issued a major law to govern the use of nuclear energy and related activities (for example, nothing akin to Japan's Japanese Atomic Energy Basic Law exists yet in China). The one nuclear-related statute currently in force in China is the Law on Prevention and Control of Radioactive Pollution, which was published by the Chinese State Environmental Protection Administration (SEPA) in 2003 and focuses on radioactive pollution, but does not cover nuclear waste or spent fuel management. The Fukushima accident had the impact of spurring calls in China for a more effective and updated regulatory system for nuclear materials management. As a result, the first draft of a proposed Atomic Energy Law was submitted to the Ministry of Industry and Information (MII) for review in December 2011. The law aims to provide a legal basis for all nuclear related activities in China, covering both front-end fuel cycle processes and back-end activities including nuclear waste management and storage.

[130] See Yun Zhou (2013), *Exploration of the Potential for Deep Borehole Disposal of Nuclear Wastes in China: An Update*, Report prepared for Nautilus Institute as a part of this Project, and available as http://nautilus.org/wp-content/uploads/2013/08/China-deep-borehole-2013_final.pdf.

Conclusions

In conclusion: 1) China's geology, seismology, geography, and population destruction suggest that DBD facilities would in all likelihood be mostly located in the northwest part of China, in areas such as the northern part of Gansu province. This matches the potential locations that are already under consideration for geologic mined repositories for spent fuel and high-level wastes from reprocessing; 2) Unlike other nuclear energy countries, China will be experiencing very little pressure to lessen the burden of at-reactor (pool-type) spent fuel storage in the next three decades due to its young industry and relatively plentiful potential sites for geological repositories. China could use on-site/off-site dry storage facilities or current and planned off-site wet storage facilities to meet storage demand, diminishing the near-term impact of this issue on China's spent fuel management and nuclear waste program. Therefore, DBD seems less mature and attractive in China due to China's relatively plentiful potential sites for geological repositories, China's long-term reprocessing policies and DBD's relatively untested technologies; 3) Due to the possible economic benefits from DBD when compared to mined geological repositories for spent fuel and HLW, additional study is desirable to further identify, explore, and reach a more detailed understanding of the relevant technical and economic issues associated with the development and use of DBD.

Considering China's tremendous projected energy demands, its huge commitment to nuclear energy, and its infrastructure in nuclear science and technology, China should place greater emphasis on its nuclear waste R&D program, both from the financial and technological perspectives. Only a solid back-end solution will allow China to develop a nuclear power program that is sustainable in the long term. Since China's nuclear waste management R&D program is still at its early stage, China still has the flexibility to consider and evaluate a range of options to pursue in providing future nuclear waste management solutions. Further investigation of and feasibility studies on DBD are recommended. In addition, although the public might not be aware of nuclear waste issues now, China should allow for more public participation in nuclear waste management policy development, which could result in a more effective and efficient decision-making framework for the development and siting of back-end nuclear fuel cycle facilities.

4.4 Summary of Prospects for Deep Borehole Disposal in Japan

Japan has conducted a research and development program related to the disposal of high-level radioactive waste.[131] Starting with a research and development program in 1976, the intensive development of a high-level radioactive waste disposal program based on the use of generic technologies and sites has been undertaken for more than three decades.

[131] The following description is a summary based on Masuda, S. (2003), "HLW Disposal program in Japan". Presentation at the 18th KAIF/KNS Annual Conference.

One important milestone of Japanese research on nuclear waste disposal was the issuing of what was called the second progress report, referred to as H12 (JNC, 2000), which examined a multi-barrier system with a mined repository as a disposal concept. Based on the technical achievements outlined in H12, the Japanese government promulgated a law named the "Specified Radioactive Waste Final Disposal Act" and through this law established the implementing organization, Nuclear Waste Management Organization of Japan (NUMO) in October, 2000. NUMO worked to clarify the scientific and technical basis for siting of disposal facilities, specified the regulatory processes for such sites, and provided a summary "Information Package for Volunteer Site" in December 2002 (NUMO, 2002). This package was sent to all 3,239 municipalities and other relevant organizations in Japan as the start of an open solicitation process for selecting disposal sites. The December 2002 documents stated that all municipalities have a right to apply to the open solicitation, for which no application deadline was set at the time. As of this writing, the solicitation remains open and no final deadline for submission has been set.

Experience with Deep Drilling in Japan

In Japan, several deep drilling activities have been conducted. These include wells drilled for oil and gas exploration, monitoring of seismic activities, and geothermal and hot spring exploration. As of year 2010, eighty five exploration wells had been drilled by METI/JOGMEC (Ministry of Economy, Trade and Industry/Japan Oil, Gas and Metals National Corporation) (Japan Natural Gas Association, 2012). Among them, fifty eight wells were drilled on shore and twenty seven offshore. The total number of wells drilled to date for oil and gas exploration in Japan is 1,620 (Japan Natural Gas Association, 2012). Some of these wells are up to 6 km in depth, and the majority of the wells are, or were, situated in petroliferous sedimentary rocks.

Since the early 1970s, NIED (the National Research Institute for Earth Science and Disaster Prevention) has drilled boreholes for monitoring seismic activities. Among them, two boreholes were drilled deeper than 3 km, eleven boreholes were drilled to depths between 2 and 3 km, and sixteen boreholes were drilled to between 1 and 2 km (NIED homepage). One of deeper boreholes drilled by NIED had a total depth (TD) of 3,510 m, and the diameter of the borehole was 12 1/4'' from 0 to 2,599 m, and 8 5/8'' from 2,599 m to the bottom of the borehole.

Previous Consideration of Deep Borehole Disposal in Japan

Long-term disposal (or storage) of high level wastes from reprocessing and spent nuclear fuel in Japan has with a few minor exceptions been limited to mined repositories. NUMO (2004) summarized possible variants to nuclear spent fuel and high level waste repository concepts, and in the appendix of the report, the concept of "vertical deep boreholes" was presented.[132] The appendix noted, however, that the option involved some fundamental changes in the basic safety philosophy that has so far guided the development of nuclear materials disposal facilities in Japan, and that the deep borehole concept was included for the sake of completeness. Based on research by Japan Country Team member Professor Tokunaga, this is the only document

[132] Nuclear Waste Management Organization of Japan (NUMO), 2004, Development of Repository Concepts for Volunteer Siting Environments. NUMO-TR-04-03, 54p.

authored by Japanese authorities that includes a discussion of the deep borehole disposal concept in Japan.

Deep Geology and Hydrology in Japan

As is well understood, Japan is located at a complicated tectonic setting caused by the convergence of four geologic plates. Because of this situation, fairly active tectonic processes such as earthquakes and volcanic eruptions occur frequently, and Japan's geology is considered to be complex. Even though the geology of Japan is known to be very complex, the spatial distribution of geological bodies has been fully described in detail, especially near the surface.

As noted in earlier sections of this Final Report one of the main safety features expected for deep borehole disposal is dependent on the existence of stagnant groundwater conditions at the depths considered for materials disposal. In typical continental settings, stagnant groundwater conditions are highly likely because of the low topographic reliefs and the increase of groundwater salinity as a function of depth. The former condition yields a quite small topographically-driven component to the hydraulic gradient, and the latter suggests an expectation of gravitational stability of groundwater at disposal depths such that deep groundwater is unlikely to mix significantly with groundwater coming into contact with the biosphere. There exists, however, significant geological evidence suggesting incidences of upward migrations of deep-seated fluid in the islands of Japan.

The Research Core for Deep Geological Environments (2012) recently published its report on the spatial distribution of helium dissolved in groundwater and hot spring water.[133] The 3He/4He ratio is considered to be useful to estimate the contribution of deep-seated fluid to the near-surface groundwater. The spatial distribution of $^3He/^4He$ found was quite variable, and it is apparent that the groundwater and hot spring waters on the Pacific side of northern Japan generally show very low $^3He/^4He$ ratios, indicating that the upwelling of deep-seated fluid is not occurring there even under the quite active tectonic conditions in the area. Considering the existence of a variety of evidence that deep-seated fluid could migrate up to the surface, further study is considered necessary to accumulate knowledge of ultra-deep geological environments in Japan before deep borehole or similar disposal can be undertaken. Further research is expected to lead to a better understanding of the geological processes associated with the upwelling of deep-seated fluids, and to a better explanation of the spatial distribution of the occurrence of such upwelling.

Potential Use of Deep Borehole Disposal for Vitrified Reprocessing Wastes

According to the current plan for high-level radioactive waste disposal as prepared by NUMO, the number of vitrified waste canisters to be disposed of will be on the order of 40,000 or more. This number may change in response to changes in Japan's nuclear power policy (see Sections 3.2 and 5.3 of this Final Report). The outer diameter of the vitrified wastes currently produced is 43 cm.

[133] Research Core for Deep Geological Environments (2012), *Technical Report on the Review and Assessment Features, towards the Submission of the Preliminary Field Investigations of HLW Geological Disposals*. Geological Survey of Japan Open File Report, no. 560, Geological Survey of Japan, AIST. Available as http://www.gsj.jp/data/openfile/no0560/gsj_openfile_560.pdf.

The difficulties in applying the deep borehole disposal concept to the current Japanese high-level radioactive waste disposal plan are as follows. First, the number of ultra-deep borehole needed may become large. For example, in the case in which 400 waste canisters are disposed per borehole, more than 100 ultra-deep boreholes would be needed to dispose of the vitrified wastes Japan will produce. Also, the outer diameter of the current vitrified waste is much larger than the oil industry's current ability to make larger ultra-deep borehole, and it is currently technically challenging to drill ultra-deep borehole with larger diameter. According to an interview with a drilling expert in the oil industry, it will be possible to set a casing with an outer diameter of 18-5/8" (ca. 47.3 cm) at a depth of 3,000 m if geological conditions are quite stable and appropriate for drilling. The inner diameter of the casing mentioned above can be ca. 45.1 cm if one uses low strength, thin casing. With this approach, it is theoretically possible to store the vitrified wastes with an outer diameter of 43 cm at a depth of 3,000 m. The number of waste canisters that can be stored in a single borehole, however, becomes significantly smaller in this scenario, because of the shallower total depth of the borehole. Of course, we can think of changing the diameter of the high-level radioactive wastes, i.e., the vitrified wastes, to fit into the diameter of the ultra-deep borehole. In this case, the number of vitrified waste containers would be larger, and the necessary number of ultra-deep boreholes also becomes larger. The coming decades may bring technological advances in ultra-deep drilling that may make accommodating vitrified wastes in the current 43 cm diameter easier, but these technologies remain to be developed and commercialized.

The other topic that must be taken into consideration is retrievability. As already discussed during the Security of Spent Nuclear Fuel Working Group meeting convened by Nautilus Institute in Seoul in April of 2012,[134] it will be very difficult to retrieve wastes from ultra-deep boreholes if multiple wastes are lowered into a borehole. Based on recent discussions in Japan, for example, discussions in the subcommittee (working group) mentioned above, maintaining an option of reversibility and retaining the possibility to retrieve high-level radioactive waste is considered to be quite important, and these concepts need to be taken into account very seriously until the disposal site is finally closed. Thus, it is not so straightforward to introduce the deep borehole disposal option into the current Japanese plan for the disposal of high-level radioactive wastes.

Use of Deep Borehole Disposal for Other Radioactive Wastes

A key advantage of the deep borehole disposal concept compared with mined repositories is that the former is much less affected by the type of the wastes to be emplaced because the deep borehole disposal concept principally isolates the wastes in deep subsurface settings where diffusion of heat and substances in the wastes is controlled by the long distance from the disposed wastes to the surface and by the limited interaction of deep groundwater with the biosphere. As such, the deep borehole concept can be applied to radioactive wastes with complex chemistry and/or those that are small in volume but highly radioactive, in addition, potentially, to high-level wastes from reprocessing, spent nuclear fuel (appropriately packaged),

[134] For presentations from the Working Group Meeting, see http://nautilus.org/projects/by-name/security-of-spent-nuclear-fuel/2012-working-group-meeting/papers-and-presentations/#axzz2xw2OJuPZ.

and potentially plutonium (in a diluted and vitrified form). Examples include the following wastes:

1. Debris from inside the partially-melted cores of three of the Fukushima-Daiichi nuclear power reactors;
2. Fuel and spent fuel from the pool at the Fukushima-Daiichi nuclear power plant;
3. Radioactive wastes from the research institutions; and
4. ^{129}I and ^{14}C in transuranic wastes.

To further explore prospects for deep borehole disposal of these special radioactive wastes, the amounts and volumes of these wastes were obtained from published information (Fukushima Prefecture website and NUMO, 2011). The number of fuel assemblies in the unit 1 to 3 of the Fukushima-Daiichi nuclear power plant reactor cores at the time of the tsunami accident was 1,496, that of the spent fuel assemblies in the unit 1 to 4 pools of the Fukushima-Daiichi nuclear power plant was 2,284, and that of the new fuel assemblies in the unit 1 to 4 pools of the Fukushima-Daiichi nuclear power plant was 360. As for the transuranic wastes, the volume of the ^{129}I-containing waste currently in storage in Japan is 319 m^3, and this volume can be significantly reduced by applying appropriate processing and packaging methods. The volume of ^{14}C-containing wastes is 5,792 m^3, and thus it may be a bit difficult to think these materials as "small volume" wastes because of their larger volume.

A few thoughts on the application of deep borehole disposal for "small volume" wastes present in Japan are as follows. First, for deep borehole disposal it may not be necessary to separate wastes based on their chemical characteristics. Avoiding this separation step could significantly reduce the required pre-disposal efforts need for the separation of wastes with complicated chemistries. Also, the "small volume" wastes can be accommodated in smaller-diameter boreholes, and hence current drilling methods can be directly applied. Side-tracking and multi-lateral drilling capabilities brought into commercial operation over the past decade for use in the oil industry make it possible to characterize deep geological formations surrounding a disposal site, and make it possible to monitor the temporal changes in the geosphere environment by using the side-tracked boreholes as monitoring sites. Further investigations towards the development of strategies for applying the deep borehole disposal concept to these "small volume" wastes in Japan will be necessary, and may well be of interest, as a possible alternative option for disposal and isolation of these wastes.

No matter which materials are to be disposed of, it will be necessary to develop scenarios for safety analysis specific to the deep borehole disposal concept because the engineered barriers that would be used in deep borehole disposal (waste packaging, borehole linings, and the materials used to isolate waste packages from each other, for example) may not be effective in very deep environments, and concepts related to long-term safety can be considerably different from those relevant to the operation of mined repositories. If the deep borehole disposal concept is to be applied in Japan, issues related to the upwelling of the deep-seated fluid should be further studied. Finally, cost estimation and other factors related to deep borehole construction and operation should be studied in much more detail if the deep borehole disposal concept is to become a possible alternative option for Japan's nuclear waste disposal program.

4.5 Summary of Potential for/work on Deep Borehole Disposal in the ROK

As in other countries with nuclear power plants, South Korea's public has concerns about the management of radioactive waste. As the available space in at-reactor storage pools become saturated with irradiated fuel assemblies, spent fuel management has become a hot issue. Korea Hydro and Nuclear Power (KHNP), South Korea's nuclear utility, has asserted that its nuclear power plants will begin to run out of spent-fuel storage capacity in 2016.[135]

At the moment, South Korea's debate regarding "back-end" nuclear fuel cycle issues (spent fuel management) is focused on "pyroprocessing," driven by researchers at the Korean Atomic Energy Research Institute (KAERI). This is partially because Japan has established its own spent fuel reprocessing capacity—and the agencies in the ROK nuclear sector would like to be able to have the same capabilities—and because, although a reprocessing plant could not be put into operation by the time that the PWR spent fuel pools begin to fill up, the expectation that the fuel will ultimately be reprocessed could provide a justification for establishing central storage for spent fuel near the site where the reprocessing plant would be built. Whether or not it pursues reprocessing, South Korea needs sites to accommodate geological repositories for its spent fuel and/or for the high level wastes (HLW) produced during reprocessing.

The deep borehole disposal concept has been recently receiving global attention due to its potential technical and cost advantages when compared with "normal" geologic disposal. The deep borehole concept involves drilling into crystalline basement rocks to a depth of 3 to 5-km, then placing waste canisters in the bottom 1-2 kilometers of the boreholes and capping the borehole such that the wastes are permanently isolated.

Suitability of the Korean Peninsula for Geologic Disposal

Appropriate siting of DBD is very important to assure the safety of disposal of spent fuel or HLW. The site used should have characteristics suitable to prevent or retard the potential movement of radionuclides from the disposal system to the biosphere. The natural geologic characteristics of the site play an important role in the disposal concept.[136]

As noted in earlier sections of this Chapter, the desirable site characteristics of DBD favoring a combination of crystalline rock at the surface or within 1 km of the surface, tectonic stability, an area located away from population centers; and a region not near international borders.

The Korean peninsula is located between the Eurasian continent and the west Pacific mobile belt. More than half of the exposed area of the peninsula consists of Precambrian metamorphic rocks

[135] Ki-Chul Park, "Status and Prospect of Spent Fuel Management in South Korea," *Nuclear Industry*, August 2008 (Korean).
[136] IAEA, *Siting of Geological Disposal Facilities: A Safety Guide*, Safety Series No. 111-G-41 (1994).

and Paleozoic-Mesozoic plutonic rocks, while sedimentary and volcanic rocks of Paleozoic and Mesozoic era are distributed on those basements accompanied with tectonic movement.[137]

According to a KAERI (Korea Atomic Research Institute) study,[138] the massif and fold belts are of primary interest among the tectonic units on the Korean peninsula with regard to radioactive waste disposal. The Nangnim massif, Kyonggi massif, and Sobaeksan massif are Archean-early Proterozoic massifs. The Hambuk fold belt and Okchon fold belt are upper Proterozoic-upper Paleozoic fold belts. The Kyonggi massif, Sobaeksan massif and Okchon fold belt are located in the southern part of the Korean peninsula.

It is desirable that DBD facilities be located away from population centers. In the ROK, major population centers include the Seoul area in the country's northwest, smaller cities south of Seoul on the western side of the nation, and Busan and other cities in the Southeast. Combining consideration of the tectonic provinces and the areas of low population density in South Korea provides a rough idea of which areas of the ROK might be suitable sites for DBD.

The geology of South Korea shows a few large-scale tectonic fractures, while small-scale fractures are evenly distributed throughout the southern peninsula, as shown in Figure 4-4.[139]

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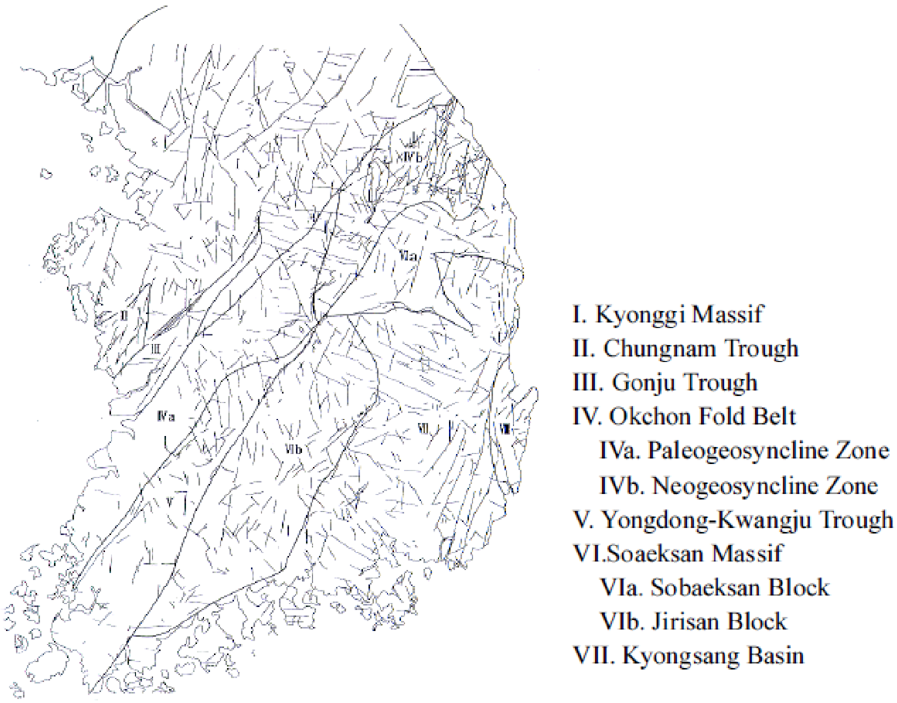
[137] C. S. Kim et al., "Lithological Suitability for HLW Repository in Korea," Proceedings of Symposium entitled *Technologies for the Management of Radioactive Waste from Nuclear Power Plants and Back End Nuclear Fuel Cycle Activities,* Taejon, Republic of Korea, 30 August - 3 September 1999.
[138] Ibid.
[139] C. S. Kim et al., "Lithological Suitability for HLW Repository in Korea," Proceedings of Symposium entitled *Technologies for the Management of Radioactive Waste from Nuclear Power Plants and Back End Nuclear Fuel Cycle Activities,* Taejon, Republic of Korea, 30 August - 3 September 1999.

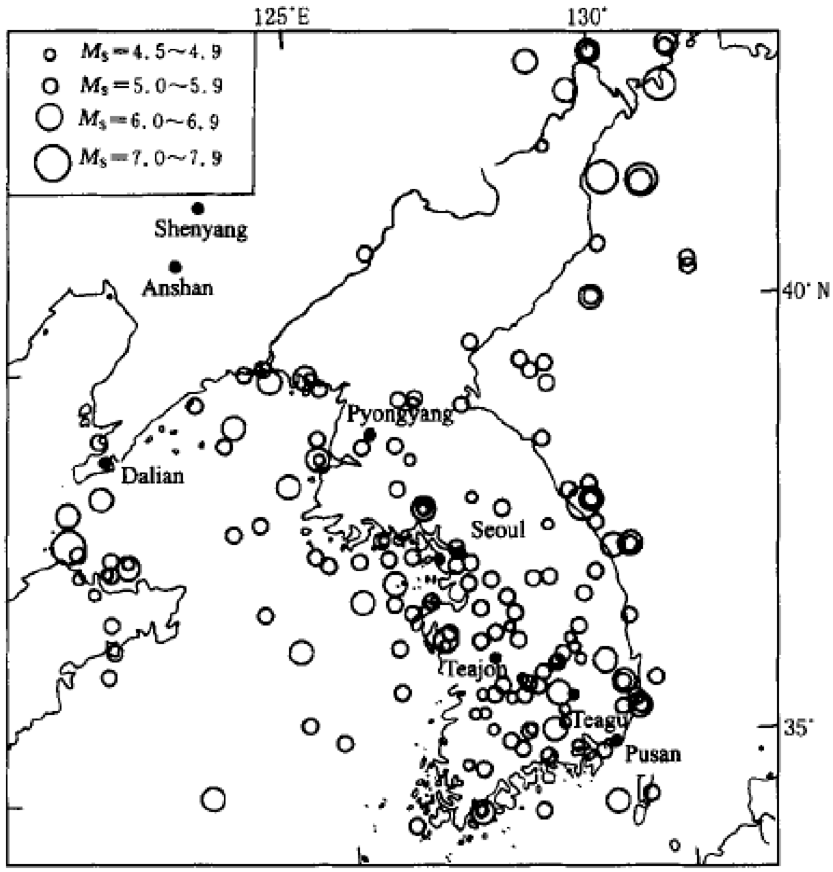
Figure 4-4: Fracture Map Superimposed on Tectonic Provinces in South Korea



As the Korean peninsula is located in the area where the Eurasian plate contacts with the west Pacific mobile belt, earthquakes in Korea are ascribed to intra-plate seismicity.[140] Figure 4-5 shows historical seismicity records for the Korean peninsula.[141] Though low-level earthquake activity has been a historical feature of the Korean peninsula, a large portion of the earthquakes that have occurred have been in the southern part of the peninsula.

[140] Ibid.
[141] Wenjie Zhai et al., "Research in historical earthquakes in the Korean peninsula and its circumferential regions," *Acta Seismologica Sinica*, Vol.17, No.3, p.366-371, May 2004.

Figure 4-5: Epicentral Distribution of Historical Earthquakes in the Korean Peninsula



<u>Existing Concept of Spent Fuel Disposal System in South Korea (Mined Repository)</u>

For comparison purpose, this study describes below a concept of a Korean disposal system as designed by the KAERI. KAERI's conceptual geologic repository is designed to be located in granite rocks at depth of 500 m, although the actual repository site has not been identified or chosen as yet. The total capacity of spent fuel disposal in the repository is assumed to be 20,000 tHM of PWR spent fuel and 16,000 tHM of CANDU spent fuel. Relatively little progress on researching or siting mined repositories in Korea, however, has taken place in recent years.

<u>Institutional and Legal Framework for Radioactive Waste Management in the ROK</u>

With regard to the governmental organizations concerned with radioactive waste, the main administrative authority in the ROK has been The Ministry of Trade, Industry and Energy (MOTIE), which supervises the nuclear power program. In addition to MKE, the Nuclear Safety and Security Commission (NSSC), established in October 2011, is responsible for nuclear safety regulations including the licensing of nuclear facilities. The Atomic Energy Committee (AEC) under the jurisdiction of the Prime Minister is the supreme organization for decision-making on national nuclear policies. The NSSC under the jurisdiction of the Prime Minister is responsible for matters concerning the safety of nuclear facilities and radioactive waste management. The NSSC is also responsible for developing licensing criteria for the construction and operation of radioactive waste disposal facilities, developing technical standards for operational safety measures, and for assuring safe management of radioactive waste at every stage of the site selection, design, construction, operation, closure and post-closure of radioactive waste disposal facilities. MOTIE also develops and implements management policies regarding radioactive waste treatment, storage and disposal. These policies are prepared by MOTIE and deliberated by the AEC before implementation.[142]

Key ROK National laws related to spent fuel and radioactive waste management are the Atomic Energy Act (AEA) and the Radioactive Waste Management Act (RWMA). The AEA provides for matters concerning safety regulations, including permission for construction and operation of radioactive waste disposal facilities. The RWMA, which determines all aspects of managing radioactive waste, was announced on March 28, 2008, and was enacted on March 31, 2010. Based on the RWMA, the Korea Radioactive Waste Management Organization and the Radioactive Waste Management Fund were established. According to the RWMA, KHNP, the utility company, should annually deposit to the Fund payments toward the ultimate cost of decommissioning of nuclear power plants, disposal of low and intermediate level waste (LILW), and spent fuel management.

Current Practice in the Management of the Spent Fuel

At its 253rd meeting in 2004, the AEC announced that national policy for spent fuel management would be decided later in consideration of progress of domestic and international technology development, and that spent fuel would be stored at a reactor site by 2016 under KHNP's responsibility, using existing spent fuel pools at reactor sites.[143] As noted above, South Korea has not decided whether to directly dispose of or recycle spent fuel. Currently, South Korea has no national plan for geologic disposal of spent fuel or HLW. As a consequence, there are no regulatory and licensing arrangements that would be relevant to DBD in South Korea.

A Korea Radioactive Waste Agency (KORAD) report assumes operation of AR and/or AFR interim dry storage of spent fuel in around early 2020s, operation of geologic disposal site for CANDU spent fuel in around 2050, and operation of geologic disposal site for PWR spent fuel and/or HLW from pyroprocessing in around 2070.[144]

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[142] OECD Nuclear Energy Agency (2010), *Radioactive Waste Management in Rep. of Korea*, available as http://www.oecd-nea.org/rwm/profiles/Korea_report_web.pdf.

[143] 253rd meeting of Korea AEC in 2004. See, for example, Ministry of Education, Science & Technology, *Korean Third National Report under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*, dated October, 2008, and available as www.kins.re.kr/pdf/Korean%20Third%20National%20Report%202008.pdf.

[144] Korea Radioactive Waste Agency (KORAD, previously KRMC), "Alternatives and Roadmap of Spent Fuel Management in South Korea," Final report prepared by Korean Nuclear Society, Korean Radioactive Waste Society and Green Korea 21, August 2011 (Korean)

Status and Prospects of Spent Fuel Generation

As of the end of 2009, 4,867 tons of spent PWR fuel and 5,894 tHM of spent HWR fuel were stored in the spent fuel storage facilities at South Korea's four NPP sites. As of 2012, the total spent fuel in storage at these four sites included 5,829 tHM of PWR fuel and 6,878 tHM of HWR fuel. As described in Section 3.3 of this Report, projections of spent fuel generation in the ROK suggest that approximately 52,000 tons of spent PWR fuel and approximately 20,000 tHM of spent HWR fuel will be generated over the entire lifetimes (that is, until each unit is decommissioned, whether before or after 2050) of the 35 PWR and 4 HWR units that will be deployed by 2030.

Rough Cost Estimate of DBD Implementation in the ROK

To estimate what the DBD option might cost as a spent fuel disposal option for South Korea, ROK Country Team member Jungmin Kang made the assumption that 200-400 canisters containing a total of about 100-200 tHM of spent PWR fuel can be accommodated in a borehole in crystalline basement rocks on the order of 5 km deep with a 1-2 km long waste disposal zone, while one borehole might hold about 1,600-3,200 canisters containing about 32-64 tHM spent HWR fuel, assuming a canister length of 0.6 m.[145]

Estimates were made of the annual costs of DBD construction through 2050 to accommodate the ROK's spent fuel that has cooled for approximately 30 years to that date. These costs are, based on an estimated cost of about \$20 million for construction of each 5 km-depth borehole, as included in a 2009 Sandia National Laboratory study referenced above[146]. These cost estimates do not include any additional costs for items such as administration cost, and reflect an assumption of no real escalation (or reduction due to learning) in costs assumed. 2030 is assumed to be the start year for borehole disposal. On the order of 50 to 100 boreholes would be needed to dispose of PWR spent fuel, plus another 150 to 300 for CANDU spent fuel, between 2030 through 2050. Spent fuel disposal by year is based on historical spent fuel quantities removed from ROK reactors through 2012. So, for example, the quantity of PWR fuel sent to borehole disposal in 2033 is the amount removed from reactor cores in 2003. After 2012, the estimates of annual new spent fuel production implied NPP capacity trends, plus 30 years, were used to estimate the amount of spent fuel sent to disposal.

Due to the larger volume of spent fuel discharged, the cumulative cost of DBD for CANDU (HWR) spent fuel for 2030 – 2050 is three times greater than that of PWR spent fuel, despite the fact that PWRs produce much more of the ROK's electricity than HWRs. To reduce the cost of DBD, CANDU spent fuel needs to be more densely packed into canisters before it is subjected to deep borehole disposal.

Overall, the undiscounted costs of disposing of the spent fuel generated in the ROK and sufficiently cooled (30 years) for DBD disposal are in the range of about \$4 to \$8 billion from

[145] Typical HWR fuel, for example, in a CANDU fuel bundle, is about 50 cm in length, 10 cm in diameter, and weighs about 20 kg HM. http://en.wikipedia.org/wiki/Nuclear_fuel#CANDU_fuel.
[146] Patrick V. Brady et al., *Deep Borehole Disposal of High-Level Radioactive Waste*, SAND2009-4401, August 2009.

2030 through 2050. Put into perspective, this cost amounts to about $0.001 to $0.002 per kWh of electricity generated in nuclear power plants in the ROK through 2020.

Local Communities Public Opinion on Hosting Nuclear Spent Fuel Facilities

Jungmin Kang, undertook a week-long research trip to South Korea's four NPPs sites in mid-September 2010. The followings are his key findings from the trip:

- The local people[147] who live near nuclear power plants sites are not aware of the safety superiority of dry cask storage of spent fuel, when compared with pool storage, and are also not aware of the potential safety superiority of deep borehole disposal of spent fuel, compared with normal geologic disposal.
- Local people showed an interest in considering on-site dry cask storage of spent fuel as well as possible in-situ deep borehole disposal if the safety of those options were assured by reliable experts and the local sites are properly compensated financially.
- Educating local people will be very important to achieving on-site dry cask storage of spent fuel as well as possibly in-situ deep borehole disposal in South Korea.

Political and Legal Issues

Implementation of DBD for spent fuel in South Korea would have political implications. The South Korean nuclear fuel cycle community, represented by KAERI, strongly insists on pyroprocessing as its favored alternative for future spent fuel management in the ROK, and would not support any kind of direct disposal of spent fuel in South Korea. Locals living near nuclear facilities, on the other hand, have as their major goal safe geologic disposal of spent fuel and/or HLW.

There are no current legal issues that might affect the practicality of borehole disposal of spent fuel in South Korea, since the current South Korean Atomic Energy Act does not includes any articles relevant to spent fuel disposal.

International Cooperation

A 2010 MIT study recommends research and development of deep borehole disposal for spent fuel and HLW management,[148] based on recent relevant research including a collaborative study done by MIT and Sandia National Laboratories.[149]

The US – Japan Joint Nuclear Energy Action Plan, a process started in 2007, reached a similar conclusion in its May 2010 report of Phase I of its Waste Management Working Group, as follows:[150]

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[147] Local people mentioned at this report are representatives of non-governmental organizations based near reactor sites who Jungmin Kang met during his trips in mid-September 2010.

[148] MIT, *The Future of the Nuclear Fuel Cycle: An Interdisciplinary MIT Study* (2011). Available as http://mitei.mit.edu/publications/reports-studies/future-nuclear-fuel-cycle.

[149] Patrick V. Brady and Michael J. Driscoll, *Deep Borehole Disposal of Nuclear Waste: Report from a Sandia-MIT Workshop on March 15, 2010 in Washington, DC.* Dated May 7, 2010, available as www.mkg.se/uploads/SNL_MIT_borehole_workshop_report_final_100507.pdf.

"… we view the deep borehole disposal approach as a promising extension of geological disposal, with greater siting flexibility and the potential to reduce the already very low risk of long-term radiation exposure to still lower levels without incurring significant additional costs."

Based on the results of these studies, opportunities for cooperation jointly with the US and Japan on DBD would help to spur interest in the South Korean nuclear (scientific and policy) community in DBD evaluation and consideration.

Conclusions

Considering its potential safety superiority when compared with normal geologic disposal, deep borehole disposal could be an alternative, which could be more acceptable to local communities, for the eventual disposal of spent fuel and/or HLW in South Korea.

Based on the siting criteria for DBD, better sites in the ROK would be toward the north and east of the country, with the northern part of the Korean Peninsula (that is, in the Democratic Peoples' Republic of Korea) perhaps having some of the best potential sites. Much additional research, however, is required to identify practical candidate locations for DBD in Korea.

Further study needs to be done to identify relevant technical issues, as well as to obtain comprehensive public and local opinions on the deep borehole disposal possibility for the ROK.

A government-supported committee for public consultation on spent fuel management in Korea was established in October 2013. The 13 committee members are from academia, local communities, and non-governmental organizations. The committee plans to provide recommendations to the South Korean government on spent fuel management by the end of 2014 after a public consultation process including meetings, seminars, fora, surveys, and other events and activities.[151] The results of this process are expected to critically affect nuclear fuel cycle activities and development, including deep borehole disposal, in the ROK in the coming years.

4.6 Summary of Issues Related to Potential Deep Borehole Disposal in DPRK

Little is directly known about the DPRK's consideration of the ultimate disposal or long-term storage of nuclear wastes in general, or about consideration of deep borehole disposal of radiological materials in the DPRK in particular. The DPRK has considerable experience building underground facilities,[152] and could presumably site and build a geologic disposal facility with considerably less difficulty (for siting, anyway) than the other countries of the region. The DPRK has relatively little experience, however, with drilling boreholes for petroleum prospecting, and presumably lacks experience digging boreholes at anywhere near the depth required for DBD. The DPRK does appear, however, to have geological areas suited to DBD, and the question arises whether the DPRK might, someday, host a DBD facility for the

[150] *Information Basis for Developing Comprehensive Waste Management System – US-Japan Joint Nuclear Energy Action Plan Waste Management Working Group Phase I Report*, FCR&D-USED-2010-000051, Published Jointly as JAEA-Research-2010-015, May 2010. Available as www.ipd.anl.gov/anlpubs/2010/05/67013.pdf.

[151] A public consultation committee on spent fuel, "Action Plan for Public Consultation Process on Spent Fuel," January 29, 2014 (Korean).

[152] For example, military aircraft storage and staging facilities located inside mountains.

region. For the DPRK to host a DBD facility would require considerably improved political relations with its neighbors and the international community, as well as a stringent regime of international (for example, IAEA) oversight of nuclear materials moved into the DPRK from other nations, probably already encased in packaging for final DBD disposal. The DPRK has in the past indicated a willingness to enter into commercial transactions to receive nuclear waste, albeit low-level waste from Taiwan. An interesting twist is the consideration of the DPRK as a potential host for a regional DBD facility is that it may require that the DPRK remain an independent nation, that is, that reunification with the ROK does not happen, as reunification probably would mean that the difficulty faced (and growing) in siting nuclear facilities in the ROK now would apply to the entire territory of a greater Korea.

4.7 Potential Next Steps on Deep Borehole Disposal Issues in NE Asia and Elsewhere

At a March 2010 workshop convened by Sandia National (US) Laboratory (SNL) and the Massachusetts Institute of Technology (MIT),[153] discussion focused on four main areas: borehole operations, retrievability, site characterization and licensing. It should be noted that this workshop was concerned mainly with the disposal of SF and with the US siting and licensing situation, so the conclusions are not necessarily transferrable elsewhere. Among the perceived favorable characteristics of DBD, the MIT group identified that the concept is inherently modular (drill as required – 'pay as you go'), there is widespread applicability and thus the possibility of sharing international R&D, a simpler safety case can be made and there is the possibility of separately licensing the borehole technology and the disposal facility (analogous to generic reactor design licensing).

The perceived disadvantages included two that are often cited: the difficulty of managing to drill large diameter boreholes (c. 0.5 m) and the difficulty of retrieving waste – although this could also be an advantage, as mentioned earlier when considering nuclear safeguards. The key MIT findings over the 20 years during which they have considered DBD were stated to be that the prospects for very effective sequestration of radioactive wastes are high, the concept is cost effective and the two main concerns in safety evaluation are the mobility of ^{129}I in SF and the quality of the borehole seal.

Brady and Driscoll record discussions on borehole operations focused on the need to understand drilling damage (extent and properties of the disturbed zone close to the borehole) and on the need for high integrity, low permeability seals to assure long-term isolation. Characteristics of the interface between the seals and the borehole wall will be particularly important. Potential operational problems during emplacement, including damage to canisters and waste during the trip down the borehole, should be minimized, and it may be desirable to line the hole for its entire length with steel casing. A reference design concept to provide a baseline for evaluating performance and impacts of alternative approaches may be useful.

[153] Brady, P. V. and Driscoll, M. J. Deep Borehole Disposal of Nuclear Waste: Report from a Sandia-MIT Workshop on March 15, 2010 in Washington, DC, 2010. Available at: www.mkg.se/uploads/SNL_MIT_borehole_workshop_report_final_100507.pdf.

On retrievability, the workshop concluded that this should be maintained up to the time the borehole is sealed. A slotted emplacement zone hole liner could be considered to facilitate grouting the liner to the borehole wall and to the canisters. This would also provide support against crushing of bottom-most canisters and permit use of the simplest configuration: filling a single-branch vertical hole in stages, allowing the grout (cement) to dry before inserting the next upper set of canisters.

Examples of favorable site characteristics, as described earlier in this Chapter, include tectonic stability, homogeneity of features such as permeability, high salinity of porewater at depth, and absence of over-pressured zones. Site characterization will be an important aspect of licensing. The use of natural analogues and evidence such as U-Pb indicators of transport can make major contributions to evaluating radionuclide mobility. Both small and full-diameter boreholes can be used for acquiring key scientific information and for demonstrating key engineering and procedural features.

During the 2010 SNL-MIT workshop, a list of R&D questions was generated and prioritized, the first ten of which can be summarized as follows:

1. Design Pilot Tests: (a) at shallow depth, for testing emplacement engineering and (b) at full depth to prove DBD can be done and containers recovered (both tests at actual diameter).
2. Borehole sealing/drilling: assess what happens if the borehole cannot be sealed and how many holes could fail or have to be abandoned.
3. Geochemistry: natural indicators of deep hydrogeochemical stability and heterogeneity, including the effects on performance and the sensitivity to drilling techniques.
4. Drilling: assess the link between drilling and disturbed rock permeability to evaluate whether the borehole environment and performance is deleteriously perturbed by drilling/emplacement.
5. Reliability and Surveillance: how to demonstrate key aspects of borehole and emplacement system design at depth, including sensor performance and sensor parameter targets.
6. Hydrogeology: establish lithological heterogeneity controls on large-scale fluid convection in the borehole disturbed zone.
7. Waste Form and Package Design: materials for packaging; the use of consolidation for SF.
8. Downhole Testing: tools that may need development, e.g. acoustic and electromagnetic techniques that allow continuous surveillance of vertical fluid motion.
9. Geology: how to detect, predict or pre-screen for geopressured zones at depth and how to determine if and when this is important.

10. Drilling: establish the value of casing all the way down the borehole.

In respect of the primary recommendation that a pilot demonstration should be performed, it is useful to note the conclusions of the 2009 Sandia report that preceded the workshop, which states:

> "It is recommended that ultimately a full-scale pilot project be undertaken, perhaps with surrogate waste, in order to fully explore the viability of a borehole disposal concept. The scientific and engineering advances gained from a single pilot project, and the applicability to subsequent borehole disposal implementations, are in contrast to site-specific mined repositories and their unique site characterization demands with relatively little transferable knowledge to subsequent repositories. Given the potential for standardizing the borehole design, and thus the ready extension to multiple borehole facilities, a single pilot project could provide significant gains on the scientific and engineering issues needing to be resolved, enable the development of international standards, and accelerate the evaluation of the viability of deep borehole disposal of spent nuclear fuel and high-level radioactive waste."

In summary, for DBD to move forward, work will be required on a number of topics – in particular:

- Large-scale testing/demonstration is essential if further progress is to be made – this may happen in the USA;
- A more comprehensive operational and post-closure safety evaluation for DBD is essential – this is not an obstacle, as it can be done readily today, with available international expertise and data.

How might international co-operation, including, perhaps, cooperation between the countries of Northeast Asia, help to move the concept forward? One attraction is that the DBD concept is sufficiently non-site-specific to attract an international effort on evaluation of the generic aspects of the technology. Such an effort would be amenable to an international co-operation project, and there is potentially sufficient interest from a number of countries to consider such a shared multinational project. The project would ultimately need a host country for the engineering trials. A first step in consideration of DBD by the countries of Northeast Asia, however, might be convening a regional meeting, attended by researchers and officials responsible for designing and managing nuclear waste disposal in the countries of the region, at which DBD concepts are described, and discussions are held on the specific barriers, especially institutional barriers, to DBD in the countries of the region.

Current experience in Europe suggests that shared regional solutions for radioactive waste management can help considerably for small nuclear power programs, with shared disposal facilities making sense, economically. In the China-Japan-ROK region, the amounts of material involved make shared disposal facilities look less attractive, for many reasons, but shared R&D could be highly appropriate, particularly given some of the potential institutional resistance to DBD (due to nuclear sector priorities) in many of the countries of the region. That is, it may be easier for a country to participate in a multi-nation project exploring DBD in than to negotiate internally for funding and support for a national DBD program.

Ultimately if DBD proves to be an attractive and acceptable means of spent fuel disposal, the location of a shared site remains a key question. Several countries of the region, including nuclear weapons states Russia and China, almost certainly have suitable geology suitably remote from population centers. Mongolia has been mentioned as a potential participant in the nuclear fuel cycle, likely has suitable sites for DBD, and is considered a neutral party, though indications are that substantial nuclear sector development in Mongolia appears to be off the table from a political perspective.[154] As a consequence, a regional DBD facility, as with other shared nuclear facilities, would likely require years of patient international negotiation and institution building, as well as the types of technical R&D mentioned above, to come to fruition.

In conclusion, one might ask why DBD has not advanced much over the last 30 years. The answer seems to be that national geologic disposal (GD) programs consider that they already have an entirely adequate, safe and secure solution in their conventional geologic disposal facilities and reprocessing/fast reactor plans and that this is supported by decades of independent and shared concept development and R&D. DBD is seen as an unhelpful digression that would require new R&D with an uncertain outcome. This situation is reflected not only in a lack of interest from national GD programs, but also in some resistance to the concept. Thus, with the exception of current developments in the USA, any new DBD program in the Asia-Pacific region might initially expect to receive rather weak support from other nations.

5 Energy sector development and energy policy in East Asia

5.1 Changes in the Energy Sector and Energy Policy are Drivers of Nuclear Energy and Spent Fuel Policy

A key element of this MacArthur-funded project, and of collaborative Nautilus projects in East Asia dating back to 2000 and before, funded by the MacArthur Foundation and other donors, has been to establish quantitative and qualitative energy sector and energy policy baselines. These baselines, including compilation of recent trends, current statistics, and future projections of key energy sector parameters were prepared in collaboration with country teams from the core nations of Northeast Asia and, in some years, broader teams incorporating other nations in the Asia-Pacific region (Vietnam, Australia, Taiwan, Indonesia, Mongolia, and Russia—represented by colleagues from the Russian Far East). The products of these periodically updated energy sector assessments, carried out by each nation using a common analytical tool, the Long-range Energy Alternatives Planning (LEAP) software system,[155] have formed the base from which Nautilus projects have explored a variety of critical themes. In this most recent project, the understandings of the energy sectors of the nations of Japan, the ROK, China and the DPRK

[154] Personal communications from a Mongolian official to D. von Hippel, 2013.
[155] LEAP is developed and supported by the Stockholm Environment Institute—United States. See http://sei-us.org/software/leap and http://www.energycommunity.org/ for additional information on LEAP and related tools and resources.

gained through these assessments, and the involvement of the Country Teams that carried them out, are a crucial "grounding" component of the assessments of radiological risk. In the remainder of this Chapter we provide summaries of the energy sector and energy policy assessments in each nation that underlie the current and future position on and need for nuclear power in each nation, and thus the radiological risk associated with nuclear energy facilities.

5.2 Energy Sector and Energy Policy in China

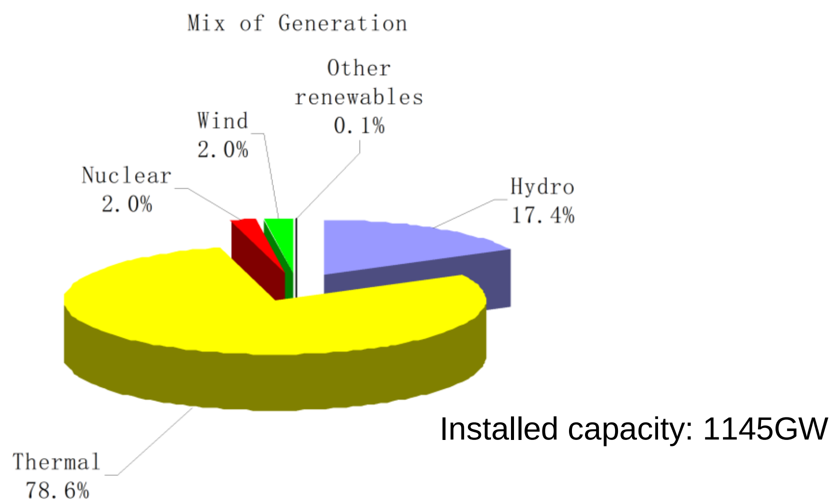
China has maintained rapid economic growth for three decades. Large growth in energy demand as a result of rapid economic growth has made China a major energy importer. China's high and growing dependence on imports of oil and natural gas has created significant concerns regarding energy security. To reduce the energy security risks—specifically risks of imported energy supply interruptions and price spikes, China has focused on the development of domestic resources such as coal, hydropower and nuclear power. The use of these domestic resources has in turn generated concern about China's environmental security.

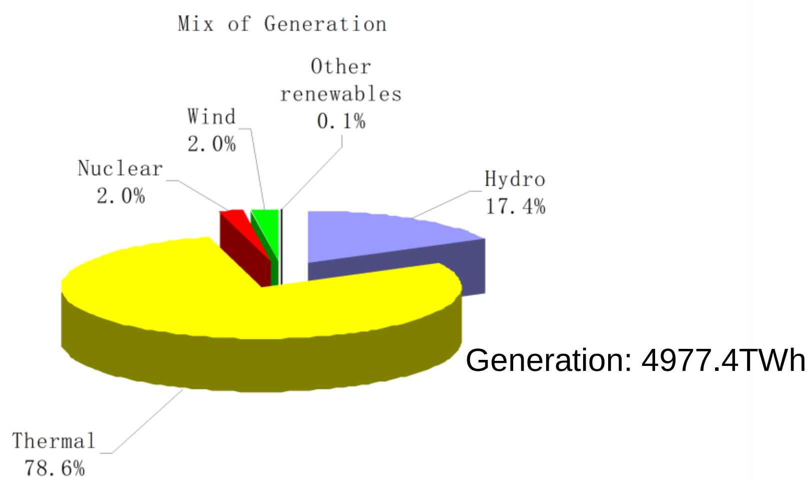
Since 1990, the Chinese GDP has increased more than 8-fold, with energy consumption increasing by nearly a factor of four. The installed capacity of power generation exceeded 1TW (terawatt) in 2011, and continues to grow at a rate of nearly 100 GW of capacity added per year. As a result China's power generation capacity is now the largest in the world. during most of the past 22 years, 70% of more of the total energy consumed in China was supplied by coal, most of which is from domestic sources, overall domestic energy production has failed to meet domestic demand. Although domestic energy production increased by a factor of 3.3 from 1990 to 2012, consumption increased by a factor 3.8 on a coal-equivalent basis. China's oil import dependency has been more than 50% for several years, and its natural gas import dependency reached 29% in 2012.

China has made great efforts to develop non-carbon-based power generation capacity to help to address the climate change and related air pollution issues. Fossil energy-based thermal power generation, however, especially coal-fired power generation capacity, still dominates the power sector, as shown in **Error! Not a valid bookmark self-reference.**.[156]

[156] Sources: *Renewable Energy Data Manual 2012*, *Energy Statistical Yearbook 2013*.

Figure 5-1: Structure of Power Industry--Capacity and Generation in China (2012)





Most Chinese cities are facing serious air pollution problems. Most air pollutant emissions come from energy use, especially coal consumption. PM2.5 (particulate matter, less than or equal to 2.5 micrometers in diameter) pollution in the eastern region of China is very serious, and is consistent with the spatial distribution of coal consumption intensity. China's CO_2 emissions increased 41% from 2005 to 2010. More than 50% of the increase in global carbon dioxide emissions in recent years has been as a result of increased emissions in China. Reducing the growth in China's CO_2 emissions may put significant pressures on China's future development.

Industrialization, urbanization and mobilization (increased personal mobility among citizens) are key drivers of energy sector trends. The output of most energy-intensive products and energy-consuming products in China increased significantly in the past two decades. The population of private vehicles in China increased by a factor of more than 330 from 1985 to 2012. A few large cities have started to limit the rate of increase of car populations by using various measures in order to deal with traffic jams and air pollution problems. Along with the expansion of urban boundaries, more and more rural residents are moving into urban areas. The population of urban areas passed that of rural areas in 2011 for the first time. All these factors drive the growth in energy production and consumption in China.

Recent Developments in the Chinese Energy Sector and Related Policies

After reviewing the implementation of the 11th Five-Year-Plan (FYP, 2006-2010) and other governmental policies in 2011, development plans for 2011-2015 (the 12th FYP) for various aspects of the Chinese economy were issued in 2012 and 2013. The general development targets include an average annual GDP growth of 7%[157]; an increase in the share of GDP produced by the service industries of 4 percentage points[158]; an intention to limit total energy consumption in 2015 to no more than 4 billion tce (tonnes of coal equivalent); a target to increase non-fossil energy to accounts for 11.4% of total energy consumption in 2015; and a goal to decrease the energy intensity of GDP by 16% or the carbon intensity of GDP by 17%[159]. Other recent policies related to energy, and the dates those policies were announced, are:

- Industrial Energy Efficiency 12th FYP (Feb. 2012)
- Shale Gas Development Planning (2011-2015) (Mar. 2012)
- Coal Industry Development 12th FYP (Mar. 2012)
- Renewable Energy 12th FYP (Aug. 2012)
- China's Energy Policies 2012 (Oct. 2012)
- The 12th Five-Year Plan and Long-Term Goals for 2020 for Nuclear Safety and Radioactive Pollution Prevention and Control (Oct. 2012)
- Power Industry 12th FYP (2011)

Nuclear Sector Policy

In the power industry 12th FYP, specific development targets and requirements for nuclear power development include the following: assuming that the total installed capacity of power generation in China rises to 1490 GW in 2015, the target for the commissioned capacity of nuclear power plants would be 40GW, accounting for 2.68% of the total. Another 18 GW of nuclear power plants will be under construction in 2015. All of the NPPs built during the 12th Five-Year Plan period must meet high safety requirements, including:

[157] 12th FVP FYP for Economic and Social Development
[158] Service Industry Development Planning (2011-2015)
[159] 12th Energy Development Planning

- core damage frequency (CDF) < 10^{-5} /reactor/year
- large release frequency (LRF) <10^{-6} /reactor/year

Nuclear power plants (NPPs) to be built during the 13th FYP period should include technologies such that the possibility of large radioactive materials release would be eliminated.

In response to the Fukushima nuclear accident in Japan in March, 2011, China suspended work on all NPPs under construction and in the pipeline for receiving approval. A detailed safety check was conducted at each plant. Starting in late 2012 through 2013, the government resumed all of the NPP projects. As a result, the construction of NPPs is back on the pre-Fukushima track as of early 2014. At present, the Chinese NPP fleet consisted of 17 commissioned units and 29 units under construction.

The National Nuclear Safety Administration has established a regular safety checking system designed to make sure that NPPs are reassessed for compliance with the latest nuclear safety regulations and standards every 10 years in order to identify weaknesses and make improvements accordingly. The safety checking system requires all existing plants to adopt additional safety measures through retrofits, including passive containment hydrogen elimination systems; auxiliary feed-water systems with two electric pumps and two pneumatic pumps or the two electric pumps and two diesel generator-powered pumps[160].

China is facing difficult choices in providing energy supplies to meet its growing demand. Should it consume more domestic high-carbon-content energy in order to make its energy supply situation more secure, or should it import additional clean energy to improve environmental protection? Although China has made great efforts to develop zero-carbon energy resources, renewable energy resources still provide only modest shares of China's total consumption. The negative impacts from the Fukushima nuclear accident are making more and more people in China concerned about the nuclear safety issue. Some people have started to raise their voices against NPP construction in the areas where they live. There is therefore uncertainty with regard to the prospects of nuclear power providing a large share of total energy requirements for China in the long run.

The most urgent issue currently is solving the air pollution problem in Chinese cities. So far, China has not figured out how the deal with this problem in an efficient way. Encouraging utilization of electric-driven cars and conversion of coal to gas for final use does reduce local smog somewhat, but only moves some pollutant emissions from city areas to industrial areas, and increases overall CO_2 emissions. It is clear that a multi-faceted approach that incorporates elements of energy efficiency, renewable energy, and zero/low-carbon fuels, together with clean technologies and other national and international initiatives, will be needed to fully address the scope of the issues confronting China in the energy sector.

Business as Usual Energy Scenario for China's Energy Sector

[160] The 12th Five-Year Plan and Long-Term Goals for 2020 for Nuclear Safety and Radioactive Pollution Prevention and Control

The scenario that serves as the reference for the study of the Chinese energy sector, and from which alternative nuclear scenarios depart, scenario is the baseline or "BAU" scenario, for which the China country team assumed no adoption of special energy or climate change policies, and for which the key elements are an extrapolation of recent economic development trends. Based on previous trends, the BAU scenario reflects a 20-year economic development path that yields average annual GDP growth rates of 8.38% between 2010 and 2020 and 7.11 between 2020 and 2030. China's population forecast in the model, adopting national population plans, shows the peak of total population arriving between 2030 and 2040, at 1.47 billion people, with continued and pronounced movement of population from rural to urban areas, as shown in Table 5-1.

Table 5-1: Population and GDP Assumptions for China LEAP Model

Year	Population (million persons)	Urban HH (million)	Rural HH (million)	GDP (10^8 Yuan RMB)
2005	1308	190	183	183132
2010	1360	222	190	290505
2020	1440	288	181	649852
2030	1470	337	160	1291047

Source: China low carbon scenario 2009, National population and family planning commission of P. R. China

China's per capita GDP is expected to quadruple by the year 2020 relative to 2000 levels, as indicated in the report of the 17th NCCPC (the National Congress of the Communist Party of China) on October 2007. This goal is much higher than the target set by the CPC seven years previously at the 16th National Congress, which was to quadruple the overall national GDP, rather than the per capita GDP, by 2020. But continued rapid economic growth will have to take place under conditions of reduced consumption of resources, and with greater efforts in environmental protection. The 12th Five-year Plan for the Chinese economy, approved by the National People's Congress in March of 2011,[161] eliminated mention of a growth rate target for per capita GDP, but emphasizes increased household income over time. The urban-rural income disparity increased significantly in 1996 through 2004[162], but has increased at a much slower pace recently

Industrialization and urbanization have increased the rate of economic development in China, particularly in cities. Per capita income is expected to continue to increase, and peoples' living standards will continue to improve. Although there remains a large income gap between urban and rural residents, the per capita household floor area is expected to be similar, on average, in rural and urban areas by 2050

[161] See, for example, CBI (2011), "China's Twelfth Five Year Plan (2011-2015) - the Full English Version", dated May, 11, 2011, and available as http://cbi.typepad.com/china_direct/2011/05/chinas-twelfth-five-new-plan-the-full-english-version.html.
[162] Source: *China Statistical Yearbook 2013*

China's overall end use energy demand by sector under BAU Scenario increases at an annual average growth rate of 3.6% from 2005 through 2030, as shown in Figure 5-2. In 2030, the industrial sector continues to dominate overall energy use, but the rate of increase of energy demand in the transportation and commercial sectors are higher than in the other sectors.

Under the BAU scenario, growth in end-use coal and oil consumption are equally strong because of the dramatic increase in the use of transportation in China, and especially in development of freight transportation. By the end of the 12th five year plan (2011 through 2015), the freight transportation fuel consumption will exceed fuel used for passenger transportation. A large part of freight transport energy consumption is in fuel for transporting coal to power plants and industrial and other end-users. Electricity generation in the BAU scenario shows the rapid growth of output in recent years slowing somewhat, but with strong growth continuing throughout the modeling period, and generation continuing to be dominated by coal-fired power despite strong growth in hydroelectric and nuclear generation.

The other two scenarios developed in the China LEAP model at present are named "maximum nuclear power" and "minimum nuclear power". These scenarios use different levels of nuclear power deployment, and as such consider different responses to coals such as national energy security, domestic resource-savings programs, and climate change and low-carbon economic development factors to produce different emission scenarios. Both scenarios mainly address domestic economic factors and address environmental development requirements through strengthening technological progress in the nuclear sector. Other sectors, not yet explored in detail, could be prepared in the future that emphasize improving China's economic development model, encouraging changes in living style, increasing energy efficiency beyond BAU levels, or placing an increasing emphasis on renewable energy development.

According to the document *Uranium 2005: Resource, Production and Demand*, in 2004 the total proved reserved uranium resource in China was 8500 tons of uranium metal. In the short term, China's domestic uranium resource is capable of meeting domestic demand. At present, domestic nuclear plants consume about 1300 tons of uranium annually. In the medium and long term, however, domestic uranium resources will not be able to supply all of China's needs.

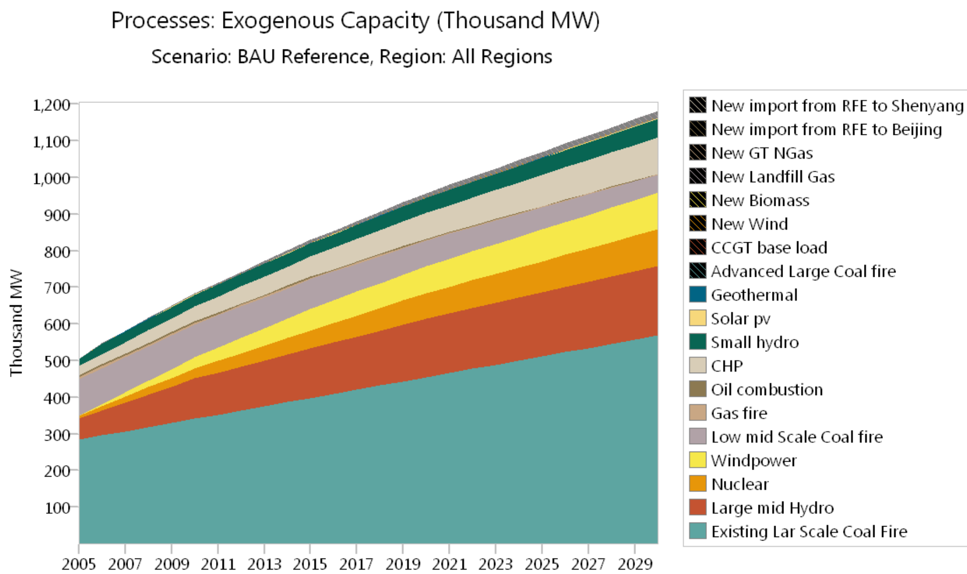
The current installed electricity generation capacity (as of 2010, all types of generation) in China reached about 966 GW, with annual electricity generation in 2010 of about 42.27 Trillion kWh[163]. Renewable energy has been developed rapidly in recent years, particularly wind generation capacity, and nuclear capacity has also increased. During the 11th Five-year

Key Assumptions in Nuclear Scenarios

Figure 5-2 shows the installed capacity forecast in the LEAP China under the BAU scenario. Large coal-fired power plants remain the dominant generation technology in the future. The installed capacities of wind power and nuclear power increase at similar rates.

[163] *Chinese Power Statistical Yearbook 2012*

Figure 5-2: Future Installed capacity in the LEAP China Model: BAU Case



Nuclear power plants in China, both those already operating and those currently and construction, have already incorporated a number of technical and safety improvements based on lessons learned by the worldwide nuclear industry since the Three Mile Island and Chernobyl nuclear accidents. Chinese nuclear power plants have had excellent operational safety records in recent years. Chinese nuclear units are generally at high international levels in terms of load factors, efficiency, and safety; the average capacity factor for China's nuclear fleet over the past five years has been 85.7%. Some of China's units are at advanced technology levels and even top ranking, being among the newest nuclear plants worldwide.

The Fukushima accident has resulted in a profound impact on nuclear power programs in many countries around the world, with China being no exception. Immediately following the outbreak of the Fukushima nuclear accident, the central government of China made, on the 16th of March 2011, several decisions in order to check and assure the nuclear safety of the Chinese nuclear power programs. The decisions required immediate nuclear safety inspections and examinations at all nuclear power plants under operation and under construction against very strict regulations, enhancement of safety management at operating nuclear units, enhancement of national nuclear safety programs, and adjustment and optimization of nuclear power development programs.

More than 16 provinces, regions and municipalities announced intentions to build nuclear power plants during the 12th Five Year Plan (2011-2015). As a result nuclear plants were operating or under construction in all coastal provinces except Hebei as of this writing (early 2014). Provinces put together firm proposals for nuclear power development by 2008 and submitted them to the central government's National Development and Reform Commission (NDRC) for approval during 2009. NRDC consideration of these proposals has been via the new National

Energy Administration (NEA). A great many proposals were received, many of which will be deferred to the 13th Five-year Plan. Table 5-2 provides a listing of the nuclear reactors operating in China as of early 2014[164].

Table 5-2: Operating Nuclear Reactors in China

Units	Province	Net capacity (each)	Type	Commercial operation
Daya Bay 1&2	Guangdong	944 MWe	PWR (French M310)	1994
Qinshan Phase I	Zhejiang	298 MWe	PWR (CNP-300)	April 1994
Qinshan Phase II, 1&2	Zhejiang	610 MWe	PWR (CNP-600)	2002, 2004
Qinshan Phase II, 3&4	Zhejiang	620 MWe	PWR (CNP-600)	2010, 2012
Qinshan Phase III, 1&2	Zhejiang	678 MWe	PHWR (Candu 6)	2002, 2003
Ling Ao Phase I, 1&2	Guangdong	938 MWe	PWR (French M310)	2002, 2003
Ling Ao Phase II, 1&2	Guangdong	1026 MWe	PWR (M310 - CPR-1000)	Sept 2010, Aug 2011
Tianwan 1&2	Jiangsu	990 MWe	PWR (VVER-1000)	2007, 2007
Ningde 1&2	Fujian	1020 MWe	PWR (CPR-1000)	April 2013, (2014)
Hongyanhe 1&2	Liaoning	1024 MWe	PWR (CPR-1000)	June 2013, Feb 2014
Yangjiang 1	Guangdong	1021 MWe	PWR (CPR-1000)	March 2014

Based on current national plans, the three scenarios for future nuclear development considered in the China LEAP model to date are shown in Table 5-3. Uranium consumption in 2020 is estimated to reach 7300 tons, assuming nuclear capacity expansion equivalent to that under the minimum nuclear power plan. In the development of nuclear power in China, the development of spent fuel management technologies is at present a key weakness. At the same time, however, the capital cost of nuclear power plants in China has decreased 33% in recent years, as domestic nuclear manufacturing and construction capabilities have grown. By 2020, China will be capable of constructing third-generation nuclear power plants, including mass-producing key components domestically.

[164] See http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China--Nuclear-Power/.

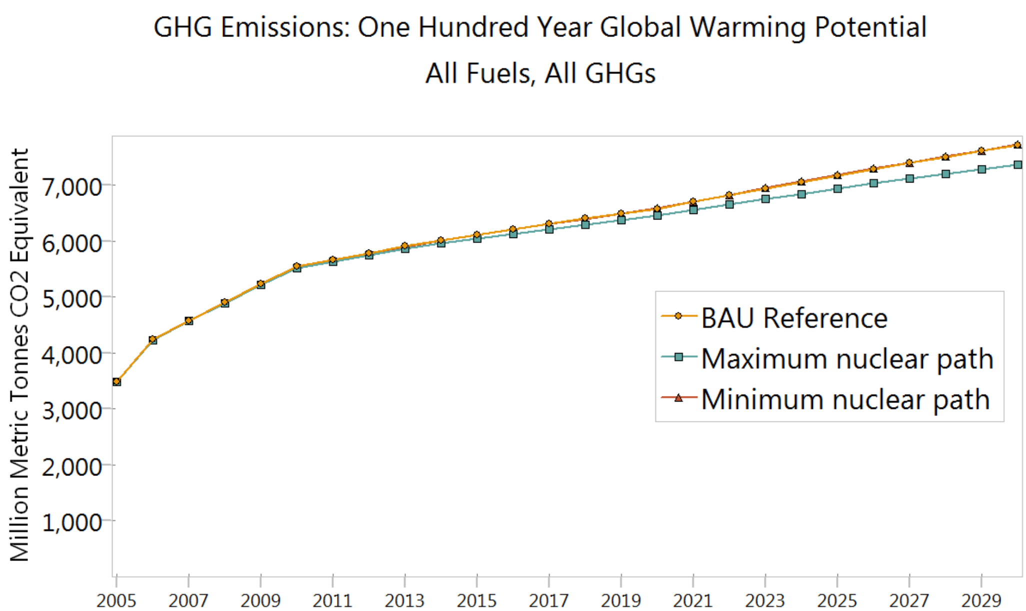
Table 5-3: LEAP Model Scenario Assumptions

Scenario	Description
BAU	From 2005 to 2030, the average annual GDP growth rate is assumed to be 7.5%, which implies a continued high rate of economic development. As part of the global economy, China will improve and increase its international trade, while at the same time emphasizing domestic energy savings and emissions reduction policies, continuing the process of energy technology development, and increasing technology investments. Nuclear power is assumed to develop according to the current national nuclear power plan. Through 2030, heavy industry continues to occupy an important position in the economy, tertiary industry starting to play the dominant position only after 2030. The capacity of nuclear power in 2020 is assumed to be 70 GW, rising to 100 GW in 2030.
Minimum nuclear power	In order to achieve sustainable development of energy China will implement policies ensuring domestic energy development supporting the social economic growth. This scenario considers the impacts of relatively moderate development of nuclear power, with nuclear capacity in 2020 reaching 60 GW, rising to 80 GW by 2030. The national energy development strategy includes policies that place a priority on energy conservation, and at the same time is vigorously developing renewable energy and new energy in China. In this minimum nuclear scenario, the future capacities of wind power, solar power, geothermal power and CCGT (combined cycle gas turbines) are assumed to be higher than in the maximum nuclear scenario.
Maximum nuclear power	This scenario considers more aggressive development of nuclear power development, with an assumed capacity in 2020 of 80 GW, and 150 GW in 2030.

Results

The three scenarios reviewed to date produce essentially the same amount of electricity throughout the modeling period, which is as expected since generation all three scenarios meets the same levels of electricity demand. Where the three scenarios differ, however, is in greenhouse gas (GHG) emissions. Here the BAU scenario has slightly higher GHG emissions overall in 2030 (totaling emissions from all sectors, not just electricity generation) than in the Minimum Nuclear scenario, on the order of a few percent. The Maximum Nuclear scenario in 2030 has a few percent lower GHG emissions overall than in the BAU case. Despite increasing nuclear capacity by 50 percent in 2030 relative to the BAU case, the Maximum Nuclear case has a relatively small effect on overall 2030 GHG emissions (see Figure 5-3) mostly because of the large amount of coal, and coal-fired power, consumed throughout the modeling period. The additional 50 GW of nuclear power included in the Maximum Nuclear case represents an offset of only a few percent in coal-fired power requirement.

Figure 5-3: Greenhouse Gas Emissions Trends under Three Scenarios



Summary

- China's rapid economic growth in the recent decades has triggered correspondingly fast growth in both primary energy supply and power generation. Various studies on the mid-term and long-term economic development prospects in China have all predicted continued economic and energy demand growth in the coming decades. Energy supply assurance to support economic growth has already become a tremendous challenge, particularly with regard to electricity generation.
- To realize China's sustainable development, the national energy development strategy includes an energy conservation priority policy, and at the same time includes vigorous development of renewable energy and new energy in China. A cleaner energy system and energy development strategy are needed, and should be established through government involvement leading to changes in all production processes and lifestyles through the applications of laws, regulations and fiscal policies.
- Nuclear energy is a practical energy source that can help, as one of a number of different measures to greatly ease the challenge in moving toward a cleaner economy, and is expected to play an increasingly important role in the energy economy of China. Nuclear safety has always been China's highest priority during its development of nuclear power. Following the Fukushima accident, a series of actions aiming at enhancing nuclear safety were and are being taken to draw lessons from Fukushima. A relatively large number of

nuclear power plants are currently being operated, constructed or in the planning stages in China. It is believed that nuclear power will play an increasingly important role in the Chinese energy economy.

- Vehicle emission problems in particular require special attention, especially those associated with increases in freight and passenger transport energy consumption. Future energy demand in the Chinese transportation sector will increase dramatically.
- Additional LEAP modeling work is needed to explore additional scenarios related to the development of a cleaner economy in China. Building off of the work presented here, scenarios including more aggressive implementation of energy efficiency and energy conservation measures, as well as accelerated deployment of renewable energy systems, along with different nuclear power scenarios such as those described above, should be explored.

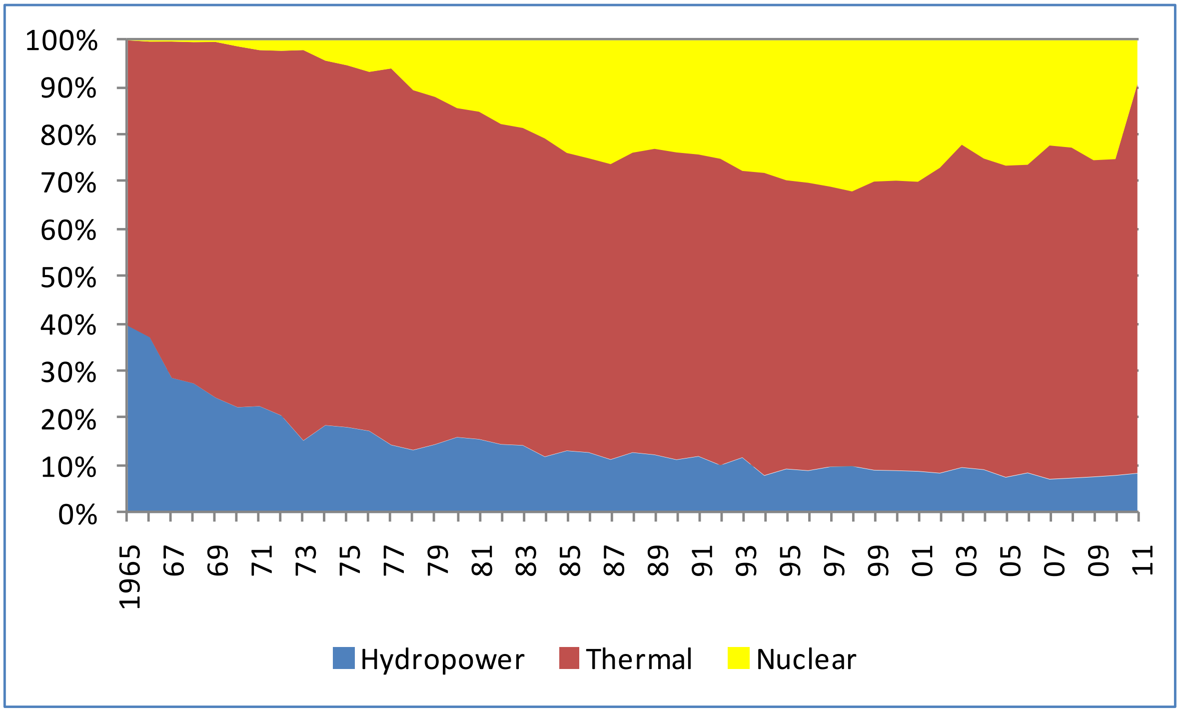
5.3 The Energy Sector and Energy Policy in Japan

The Japanese economy, as measured by gross domestic product (GDP) grew rapidly during the 1960s through the1980s. In 1991, what has been called Japan's " bubble economy", crashed, ushering in an era of much slower economic growth that continues to this day. Energy consumption per unit of GDP decreased after the first global "oil crisis" (a period during which international oil prices increased rapidly due to restricted supplies and price controls by major producers) in 1973. After the first oil crisis, Energy demand in Japan continued to increase in most years, but at a lower rate than GDP. National carbon dioxide (CO_2) emissions also continued to increase, but not as by much as energy demand, due in part to nuclear power development from the 1970s onward.

Japan's primary energy supply has shifted from an alliance on coal and hydropower in 1950s to oil and coal by 1970. After the 1st and 2nd oil crises in 1973 and 1981, the use of nuclear power and natural gas, mostly imported as liquefied natural gas and used directly as an end use fuel and for power generation, increased to provide 20-30% of primary energy supply.

Electricity was generated primarily in thermal and hydroelectric power plants until commercial nuclear power plants in Japan started operating in 1970. Nuclear power accounted for almost 30 percent of total generation until the Fukushima Daiichi accident in March of 2011. In the wake of the Fukushima accident, all of the remaining nuclear power plants in Japan were shut down for extensive safety assessments and retrofitting, as reflected in the much-reduced nuclear fraction for 2011 that appears in Figure 5-4. As of this writing, none of Japan's nuclear reactors are currently on line.

Figure 5-4: Electricity Generation by Source (% of kWh generated)



Source: EDMC/IEEJ, EDMC Handbook of Energy & Economic Statistics in Japan 2013

Recent Changes in Energy Policy in Japan

Following the elections of December 2012, the dominant political party changed from Democratic Party to the Liberal Democratic Party (LDP). As a result, that the Democratic Party energy policies, which included a plan, discussed and developed with the aid of a stakeholder group drawn from a number of different organizations, to phase out nuclear power in Japan by sometime in the 2020s, have essentially returned to the drawing board, and are being significantly revised.

Meanwhile, however, the feed-in-tariff (FIT) policy developed by the Democratic Party remained. Under the FIT, utilities are required to pay a premium to purchase power derived from most renewable electricity sources. Further, the tariff was set at high levels to provide incentives for various companies and groups to enter the renewable power business.

Prime Minister Abe (LDP) has promised to deregulate electricity retail market fully by 2016. Currently, only large and middle-sized industrial and commercial consumers can only choose their electricity retailer. Deregulation is to be followed by vertical separation of utility functions during the period 2018-2020.

The LDP and Prime Minister Abe's policy is to restart nuclear power plants for which compliance with safety regulations has been confirmed. This is a significant departure from the policy developed by the Democratic Party when it was in power.

Japan's retail electricity market is currently partially deregulated. Low voltage (less than 50 kW demand, served at 6000 Volts or less) customers have no choice but to purchase electricity from the utility designated to exclusively serve their area. Low voltage electricity sales were about 40% of total electricity sales in Japan as of 2010. Low voltage customers are small business such as convenience stores and offices, and households.

The market for supplying electricity supply is partially open to non-regionally-dominant companies (that is, to electricity producers other than the major utility in the area). Since only 3-4 % of the retail market is occupied by non- regionally-dominant companies, the 10 regionally-dominant companies that have traditionally controlled electricity generation, transmission, and retail sales in Japan continue to substantially dominate Japan's electricity markets.

Future Energy Scenarios in Japan

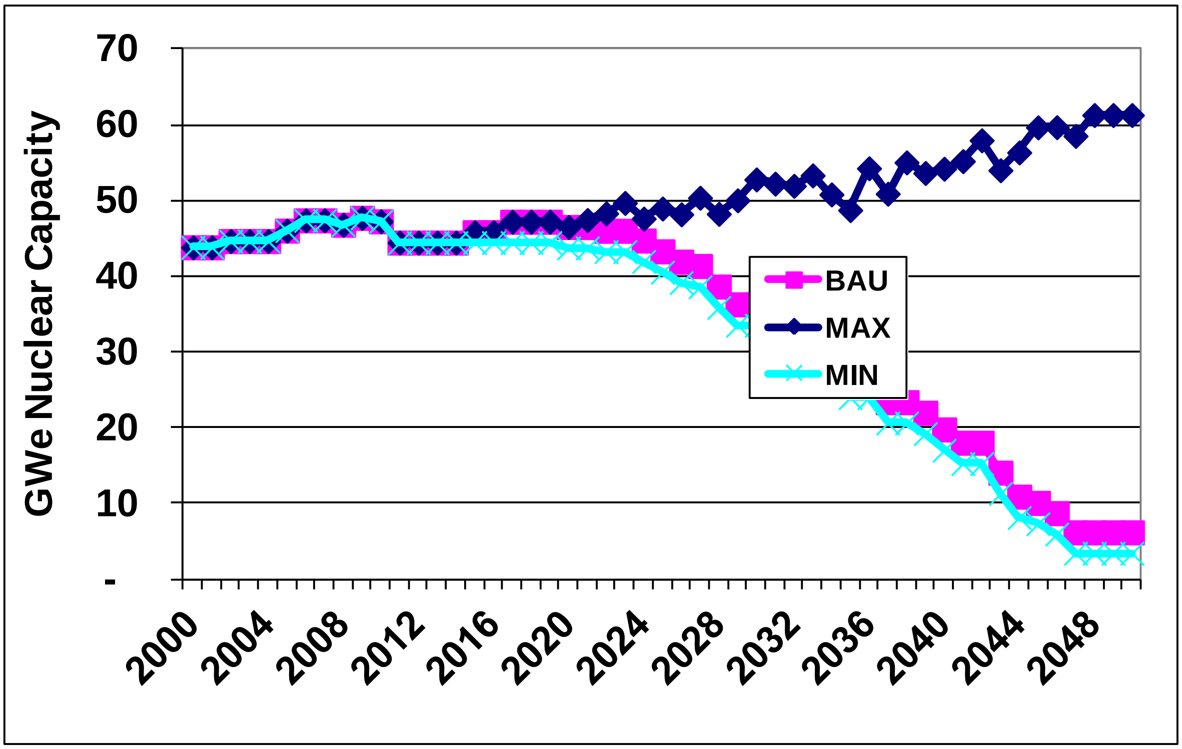
The LEAP model for Japan has updated been to a 2011 base year. Most LEAP data for recent years has been prepared using the "EDMC Handbook of Energy & Economic Statistics in Japan 2013" by EDMC/IEEJ. The LEAP Japan model has very a detailed demand and supply structure, reflecting the Japanese energy sector. The demand sector is divided into residential, commercial, industrial, and transport sectors. These are further divided as follows:

- The residential & commercial sectors are divided into 5 energy end-uses
- The industrial sector is divided into 13 subsectors.
- The transport sector is divided into passenger (passenger transport) and portage (freight transport).

The energy supply ("transformation") portion of the Japan LEAP model includes modules to simulate electricity generation, gas transformation, oil refining, electricity transmission, and other processes associated with production of end-use and intermediate fuels.

Within the Japan LEAP dataset, three scenarios for the future of nuclear power in Japan were prepared. A common assumption in all three scenarios is that the Fukushima Daiichi nuclear units #1-4, which were severely damaged and contaminated with radioactivity in the accident following the Sendai earthquake and Tsunami, are to be decommissioned. In the BAU scenario, only two new nuclear plants are added to Japan's fleet, both of which were under construction at the time of the Fukushima accident. In the BAU scenario, it is assumed that the Ohma is to start operations in 2015, with Higashidori starting in 2017. The addition of these plants might not, in fact, be realized due to strong opposition against nuclear power in Japan after the Fukushima accident. A reactor lifetime of 40 years or operation for existing and new nuclear units is assumed. Nuclear plants reaching the end of their operating lifetime are assumed not to be replaced with new nuclear plants. In the Maximum scenario, additional nuclear units are added as planned before Fukushima (addition of 17 plants), and the operational period is expanded to 50 years, which assumes that the utilities that run the plants are successful in receiving regulatory permission extend the operating lifetime of the reactors. In addition, as existing units reach the end of their operational lifetime, they are replaced with similar –sized (though updated) units. In the Minimum scenario, no additional plants are added from the present onward, and a 40-year operational lifetime is assumed for existing nuclear units. It is assumed, however, that nearly all of Japan's existing reactors will be restarted soon. Figure 5-5 shows the resulting trends in nuclear capacity in Japan under the three scenarios.

Figure 5-5: Trends of Nuclear Capacity in 3 Scenarios for Japan



Two of the main driving activities of energy demand in the residential and commercial sectors in Japan, namely, the number of households and total commercial floorspace, are assumed to decrease after 2020, as Japan's population continues to decline from the peak levels reached in the last few years.[165]

Final energy demand is common in all three scenarios considered, as only supply-side, nuclear capacity changes are implemented in Maximum and Minimum scenarios. As shown in **Error! eference source not found.**, total final energy demand is projected to decrease due to the decrease in the number of households and in commercial floorspace, as well as due to efficiency improvement in motor vehicles and elsewhere in the Japanese economy.

[165] See, for example, National Institute of Population and Social Security Research (2012), Population Projections for Japan (January 2012): 2011 to 2060, available as http://www.ipss.go.jp/site-ad/index_english/esuikei/ppfj2012.pdf.

Figure 5-6: Final Energy Demand Projections by Sector in Japan

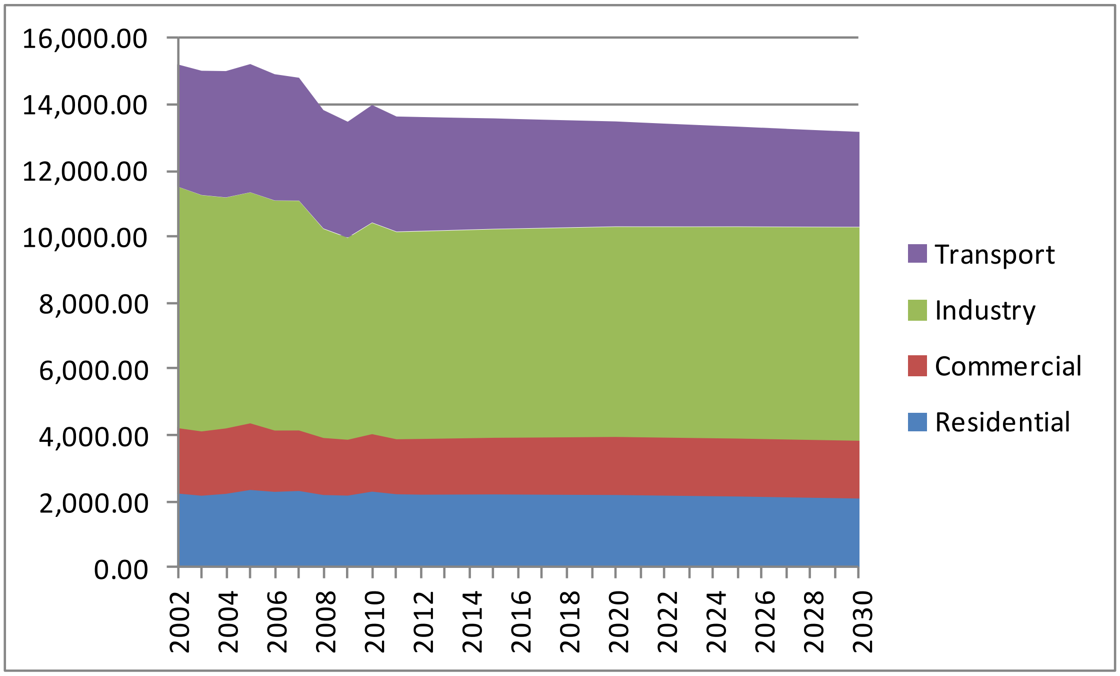
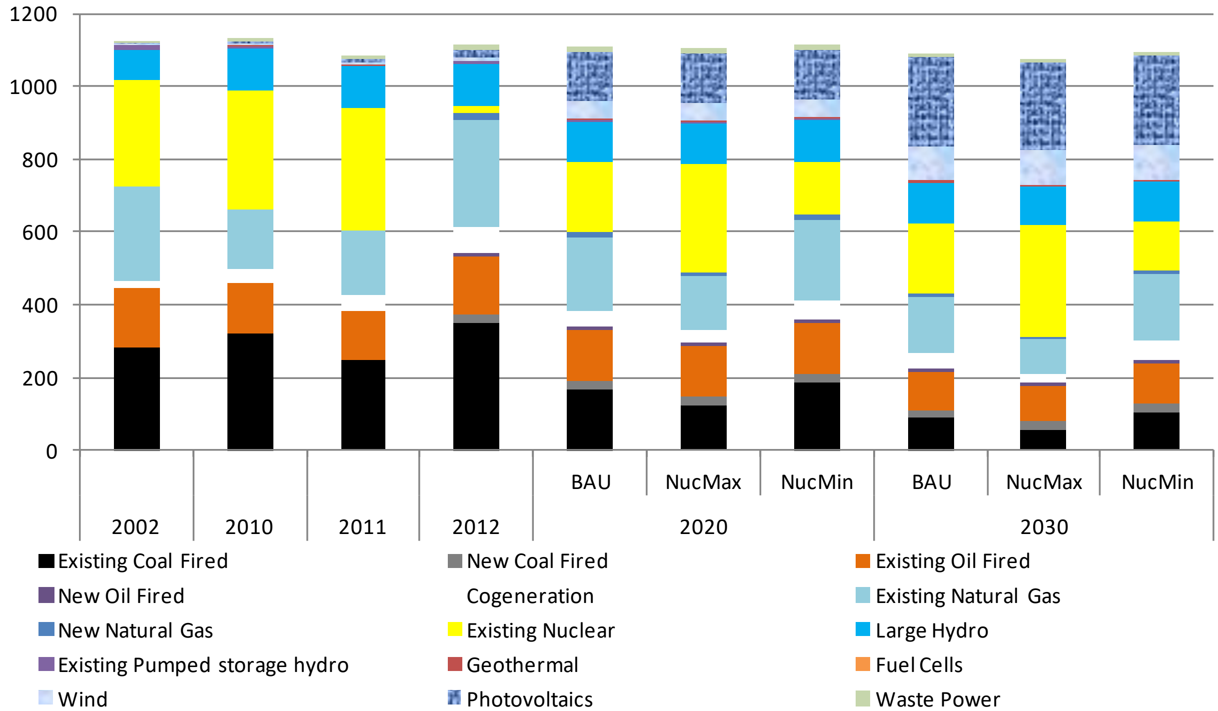


Figure 5-7 shows the historical division of electricity generation by source in several historical years and in each of the three scenarios in 2020 and 2030. Total generation is roughly the same in each case, but the nuclear fraction of generation is much higher in the Nuc Max (Maximum) case, while generation from coal, gas, and oil is much less than in the other two scenarios. In each case, electricity from PVs rises to a significant portion of the overall total.

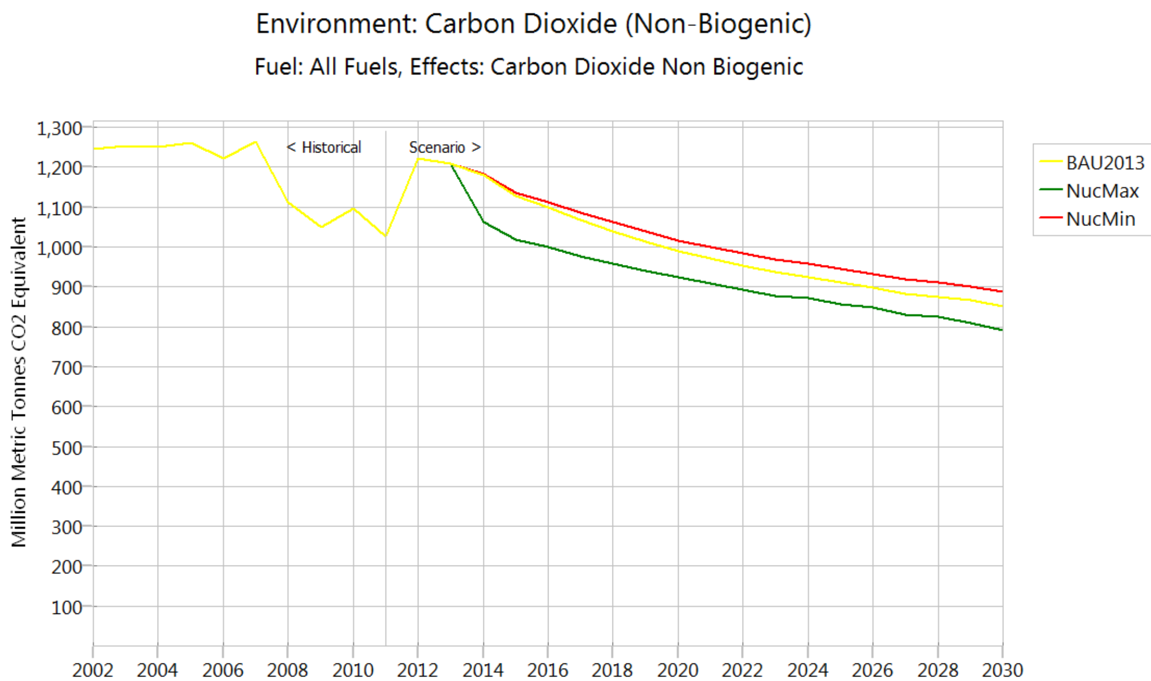
Figure 5-7: Electricity Generation by Type of Power Plant, 3 Scenarios (TWh)



Japan's total CO_2 emissions from the energy sector decrease in all three scenarios, but falls most rapidly in the Nuclear Maximum scenario, although the differences in emissions between the scenarios is relatively modest. The overall decline in emissions is due largely to non-fossil fuel energy deployment. The trends in emissions under the three scenarios are shown in Figure 5-8. If we compare the CO_2 emissions of our scenarios with statistics published by Ministry of Environment (MOE), the BAU scenario shows a 7% reduction from 1990 levels, the Nuc Max scenario, shows a 12% reduction, and the Nuc Min scenario shows a reduction of 4%. (MOE statistics[166] show 1059 Mt of CO_2 emissions from energy sources in 1990.)

[166] Source: Ministry of Environment, GHG emissions statistics in 2011, (2013.4) http://www.env.go.jp/earth/ondanka/ghg/2011gaiyo.pdf

Figure 5-8: CO_2 Emissions in Japan, Three Scenarios



Conclusion

After the Great East Japan (Sendai) Earthquake and the Fukushima nuclear accident, most Japanese conservative policymakers changed their public stance from "reluctant toward renewables, positive toward nuclear", to "positive toward both renewable and nuclear" or "positive toward renewables, negative to nuclear." It is an interesting indicator of the profound impact of the Fukushima accident on the Japanese public psyche that politicians such as former Prime Minister Koizumi are now supporting a "no nuclear", or no further nuclear, energy future for Japan, given their strong support for nuclear power in the past.

Feed-in tariffs started for all renewable sources of electricity in July, 2012. The tariff rates are set high enough to encourage many kinds of companies, from small to large, to enter the renewable power business. Since it has been only less than 2 years since the FIT started, the majority of newly operating renewable power plants are photovoltaic systems, because other types of renewable electricity sources require longer lead times for development and installation before they begin generating power. There are, however, many projects going on for other sources of renewable electricity, and if the Japanese government does its best to deploy renewables in the way that current policies direct, Japan can overcome deployment issues and reach a future in which a large percentage of the electricity used in Japan is generated from renewable resources.

Apart from the recent increase in renewable energy deployment, how Japan's power sector will evolve is at the moment very unclear, and depends substantially on how the government chooses to move forward, or not, with the nuclear power sector. Under the previous government, an agreement was reach to essentially phase out nuclear power within 20 years or so. This policy is being revisited under the Abe government, and it is possible that the existing nuclear reactors, all of which are currently off-line (or, in the case of units 1-4 of Fukushima Daiichi, damaged beyond repair), will eventually be brought back on line. The three nuclear capacity deployment scenarios described in this paper show very divergent results—in particular between the "Maximum Nuclear" and both the Reference and "Minimum Nuclear" cases, and also have different implications for the requirements for fossil fuels and, relatedly, for greenhouse gas emissions from the power sector.

Meanwhile, questions abound regarding Japan's future energy policy. How will Japan meet its GHG emissions targets, even factoring in declining population and a slow economy? Can meeting those targets be done without substantially restarting the nuclear sector? Will electricity sector restructuring actually come to fruition, how can a restructured Japanese electricity system be regulated so that public goal, such as GHG emissions targets, are salient to the planning process, and what will happen to the current electricity sector "players" if the sector is effectively deregulated? Will policies be kept in place to make sure that the post-Fukushima momentum for renewable energy deployment is maintained? All of these questions are crucial, but all have yet to be answered as of this unsettled moment in Japan's energy policy.

5.4 The Energy Sector and Energy Policy in the ROK

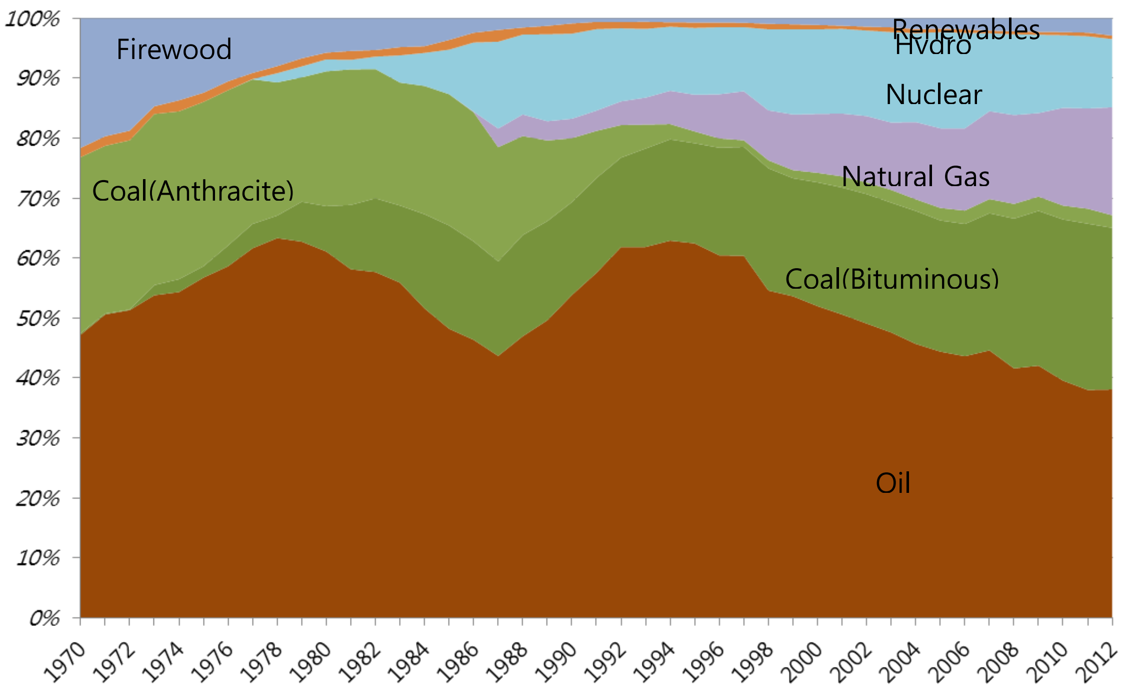
The land area of the Republic of Korea is comparatively small, at 98,480 km^2, but the ROK economy is the world's twelfth largest in terms of GDP, and the world's seventh largest in terms of energy consumption. The ROK has limited natural resources and is highly dependent on external sources of energy. The country has no oil and very limited reserves of natural gas. The ROK currently produces only small amounts of anthracite coal, though anthracite was the ROKs main energy source before the last few decades. Korea's economy has grown rapidly, with an average annual growth rate of 7.1% during the period from 1970 through 2012. Accompanying this high economic growth, the ROK's energy consumption has also shown rapid growth. During the 1970-2012 period, the ROK's economy and energy consumption rose by factors of 18 and 14, respectively.

Energy Sector Overview

Korea consumed 279 million toe (tonnes of oil equivalent) of primary energy in 2012, and imported 96.0% of the energy consumed. Energy efficiency, as indicated by energy consumption per unit of GDP, rose from the mid-1980s through 1997 as a result of the economic growth led by energy-intensive industries such as petrochemical, steel and cement sectors. The Korean economy, however, suffered from the impacts of the Asian financial crisis of 1997. From 1998 through the global financial crisis of 2007/8, there has been an effort to change Korea's industrial structure to make it less energy intensive. Although energy efficiency (energy per unit of GDP)slowly improved as a result of these policies, as well as other global economic shifts, it has deteriorated (that is, energy per unit of GDP has increased) since 2008, mainly as a result of pricing policies that have maintained low tariffs for energy products such as electricity and town gas. Energy consumption per capita grew very rapidly from 1970 to 2000, but the rate of increase of energy use per capita has slowed since 2000 as the ROK economy has shifted to less energy-intensive industries, and as the economy has matured to developed-country status.

Oil is the dominant energy source in Korea, but its share of total energy demand has fallen from the peak of 63% of total primary energy consumption (TPEC) in 1994 in response, in part, to strong measures taken by the Korean government to reduce the consumption of oil products, particularly in industry and for electricity generation. The share of oil stood at just 38.1% in 2012, and is projected to continue falling over time, but at a decreasing rate. Coal has the second highest share of total primary energy use. Anthracite coal produced in Korea accounted for the major part of coal use before the mid-1990s, but the production of domestic coal has sharply decreased since that time as a result of the implementation of policies to close most coal mines due to low productivity and high labor costs as the depth of mines increased. The consumption of bituminous coal has significantly increased as the use of anthracite coal was reduced, and in response to the need of Korean industry for coal with a higher heat content than typical domestic anthracite coals. Korea imports all of the bituminous coal that it uses from a number of supplier nations, with Australia and Indonesia being key suppliers in recent years. Coal is accounted for 29.1% of TPEC in 2012, as shown in Figure 5-9, including 2.1% as anthracite coal. The third major fuel type used in the ROK is natural gas, which accounted for 18.0% of primary energy use in 2012. Natural gas was introduced in the ROK in 1986 when Korea Gas Company (KOGAS) imported it in the form of liquefied natural gas (LNG) from Indonesia. Since that time, natural gas consumption has rapidly increased as the industry and household sectors prefer natural gas to other forms of fossil energy because it is clean and convenient to use.

Figure 5-9: Trends in Primary Energy Shares by Source



The share of nuclear energy was 11.4% of TPEC in 2012. The first nuclear power plant in Korea was built in 1979 using technologies imported from France. The ROK government has encouraged policies to raise the share of nuclear energy because nuclear power is considered a means to reduce overseas energy supply dependency, and emits no greenhouse gases. Nuclear power has become a major source of base load generation, but nuclear energy's shares of TPEC has fallen slightly in recent years, from 13.1% in 2009, because the consumption of other energy forms, such as natural gas and bituminous coal, have increased faster than that of nuclear energy. The contribution of hydroelectric energy to TPEC is negligible (0.6% in 2012) because the ROK has very limited hydro resources. Renewable energy accounted for 2.9% of TPEC in 2012, though the government has tried to significantly increase its share through various programs of subsidies for developing renewable energy technologies generally, and for promoting the adoption of distributed renewable energy systems in particular. Currently, the largest source of renewable energy is municipal solid wastes used for electricity generation.

The industrial sector uses the largest share of TFEC, accounting for 61.7% of energy demand in 2012. The transport and residential & commercial sectors accounted for 17.8% and 18.2% of 2012 TFEC, respectively, and other sectors accounted for the remaining 2.3% of the total. This pattern of energy demand by sector contrasts with past shares of demand in some key sectors. For example, shares of TFES were 51.3% for industry and 26.2% for residential & commercial in 1992. In the past two decades, the demand share of industry has significantly increased, while the share consumed by the combined residential & commercial sectors has decreased due to a combination of improved efficiency and reduced growth rate due to a combination of declining population growth in the ROK, and as the adoption of new energy-using devices by ROK households has moved toward saturation as ROK incomes have increased to developed-country status.

The ROK imports almost all of the energy it consumes except for anthracite coal, which is the major fossil fuel produced in-country (albeit currently at very low levels), and a very small volume of natural gas produced in South Korea's East Sea. The ROK's dependency on overseas energy has remained above 90% for the past 20 years, and was 96% in 2012. Along with this high overseas energy dependency, the ROK's energy import costs have sharply increased since 2004, when international oil prices began to rise. The ROK's bill for energy imports amounted to 184 billion dollars in 2012, an increase of nearly five-fold from the 38 billion dollars paid for imported fuels in 2004.

In order to diversify its sources of gas, and to reduce its gas costs, KOGAS has contracted for 3 million tons of LNG, derived in part from shale gas, to be supplied to Korea in 2017 via LNG exports from a US company Cheniere[167]. It is the first time that KOGAS has arranged to import

[167] See, for example, Tilak K. Doshi (2013), "Impacts of North American Shale Gas on Asian LNG Markets", dated March, 2013, and available as "http://www.esi.nus.edu.sg/docs/volume-4-issue-1---april-2011-%28energy-trends-and-development%29/impacts-of-north-american-shale-gas-on-asian-lng-markets_march2013_esi_final.pdf?sfvrsn=0; and Peter R. Hartley (2013), "Some issues arising from unconventional gas development", dated October, 2013, and available as http://grattan.edu.au/static/files/assets/8f0b13cb/532_presentation_hartley_131003.pdf.

LNG from North America. The price in the contract is linked to the price of natural gas at the Henry Hub, where prices of gas on the spot market in the United States are set. A number of energy sector actors and analysts in the ROK see this deal as the harbinger of a future in which the ROK is able to import large amounts of low-priced gas from North America, but regulatory issues and public opposition to new export terminals in the US may prove these hopes premature.

KOGAS and Gazprom (Russia's state-owned gas company) signed a memorandum for 25 years of supply of natural gas starting in 2017, with gas to be sourced from fields in East Siberia to the ROK. Under this arrangement, the ROK would receive gas, via pipeline passing through North Korea, or via pipeline to Vladivostok, with transport to the ROK by sea. The plan to import Russian gas to the ROK has been under discussion for many years, but progress has been limited due to the political sensitivities between the two Koreas. A delay in the start date for imports of gas from Russia beyond 2017 seems likely.

As of 2012, Korea's coal imports were the world`s third largest, following Japan and China. Coal imports have been rapidly increased as coal power generation has become the backbone of the Korean power system. 80.6 million tons of fuel coal (steam coal and anthracite coal) were supplied for power generation (43% of the fuel input to power generation) and industries (24.2% of industrial energy use) in 2012.

Renewable energy in Korea remains relatively underdeveloped, though the proponents of renewable energy in the ROK have tried to promote the development of renewable energy supplies for a long time. Renewable energy contributed only 3.18% of TPES (including hydro), a very small portion of total consumed energy, in 2012. Biofuels and renewable wastes are the largest current contributors to renewable energy supplies, and represented almost 82.8% of renewable energy production, with the balance coming from small hydro (9.2%) and to a lesser extent solar photovoltaic (PV) and wind power.

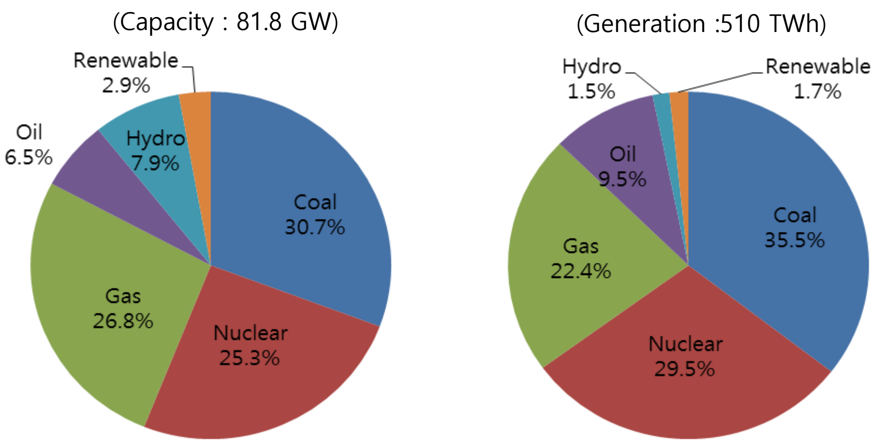
Electricity Generation

The total electricity generating capacity in Korea increased by more than a factor of three over the past 22 years, from 21 GW in 1990 to 81.8 GW in 2012. Coal-fired power plants constitute the largest portion of capacity (at 25.1 GW), followed by natural gas-fired plants (21.9 GW, most of which are combined-cycle plants) and nuclear power plants (20.7 GW). The remainder of generating capacity is made up by hydro (6.4 GW, of which 4.7 GW are pumped-storage hydroelectric plants used to store energy for use during times of peak power demand[168]), oil-fired capacity (5.3 GW) and a very small amount of capacity based on non-hydro renewable energy sources. Electricity generation in the ROK reached 510 TWh in 2012, meaning that an average annual growth rate in output of 3.8% has prevailed since 1990. 65% of the ROK's electricity was generated in coal-fired (35.5%) and nuclear (29.5%) power plants, with most of remainder coming from natural gas (22.4%), complemented with smaller shares produced from hydro (1.5%) and non-hydro renewable energy (1.7%). 53% of electricity is consumed by the industrial sector, followed by the combined residential and commercial sector (40%) and the public sector

[168] Korea Energy Economics Institute (KEEI, 2013) *2012 Yearbook of Energy Statistics*, available as http://www.keei.re.kr/keei/download/YES2012.pdf.

(5%). Figure 5-10 shows the current patterns of electricity capacity and generation by source in the ROK.

Figure 5-10: Electricity Capacity and Generation by Energy Source (2012)[169]



Korea has the sixth-largest nuclear generation capacity in the world. The government has tried to increase nuclear power capacity as a part of its effort to reduce the imports of fossil fuels since the first nuclear plant came on line in 1978. Korea Hydro and Nuclear Power (KHNP) currently operates all of the nuclear power units located at the four nuclear power plant sites in Korea. At present, there are 23 nuclear power units in operation and five more are under construction. Four of the 23 units are pressurized heavy water reactors (PHWRs), while the rest are pressurized water reactors (PWRs). Four of the reactors under construction are advanced PWRs. According to the Korean government's fifth basic plan of Electricity Supply and Demand, as announced in 2010, additional reactors are scheduled to be completed by 2024, with the goal of generating nearly half of the nation's power supply from nuclear sources. All Korean nuclear reactors have maintained over 90% availability, making their performance well above the world average of around 80%. Korea is fully dependent on foreign countries for its supply of natural uranium, as well as for uranium conversion and enrichment services. The Korea Atomic Energy Research Institute (KAERI) has a pilot plant for converting yellow cake (U_3O_8) to uranium dioxide (UO_2), but because it is politically sensitive, this plant is not yet in operation.

<u>ROK Energy Policies</u>

In compliance with the direction of the basic energy law, the first national energy basic plan was established in 2008. The core policies of the basic plan were to reduce national greenhouse gas emission and the consumption of fossil fuels through improving energy efficiency and strengthening market energy prices, and by expanding supplies of nuclear energy and renewable energy. The energy policy directions in the plan are as follows:

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[169] Source : Korea Power Exchange, 2013.7

- Achieve low carbon and low energy consumption by improving energy efficiency, strengthening market-based pricing systems, and through active involvement in global initiatives for addressing climate change.
- Reduce the consumption of fossil fuels by expansion of renewable energy supplies and increasing the capacity of nuclear power.
- Develop a green energy industry by developing green technologies for use in domestic markets as well as for export to global markets.
- Promote energy security by strengthening overseas resources development and stabilizing energy supplies.

Challenges to the implementation of this plan during the past few years have included:

- The failure of the ROK government has to strengthen the market price system in the electricity and gas industries, due to the reluctance on the part of policymakers to raise tariffs, and the resulting lack of price signals to consumers that would promote energy efficiency.
- Second, the Fukushima Daiichi nuclear disaster has provoked a nation-wide anti-nuclear movement in Korea. This shift in public opinion encouraged the view that the "nuclear renaissance" plan to increase the ROK's reactor fleet should be discarded or, at least, downscaled.
- Third, gas prices have sharply decreased in the USA as the production of shale gas has increased, thanks to the development and deployment of fracking technologies to extract gas trapped in shale formations. This US gas price trend has pressured the government to consider changing the energy mix in the National Energy Plan to anticipate the availability of cheap LNG from North America, and possibly elsewhere, though it is not yet clear to what extent the facilities to export large quantities of LNG from North America will be developed, and when.
- Fourth, the government administration changed in February of 2013, and though the Park Geun-hye administration is from the same political party as the previous government, the new administration may place less emphasis on the Low-carbon Green Growth when it completes its review of national energy policies.

The new government has placed a higher priority on the safety of nuclear power, as well as that of other energy facilities, than did the previous government. On the other hand, the policy of "Low Carbon, Green Growth" proclaimed by the previous president may be weakened as a reaction to recent critiques suggesting that the previous government's green energy policies have not had an impact on the ROK's energy structure, commensurate with the amount of financing that was provided to implement the policies.

The new government announced several overall energy policy directions at the time that it came into office. These included:

- Strengthen safety management and supervision in energy facilities, including nuclear power facilities.
- Encourage more competitive markets and market-value pricing in energy industries.
- Establish a societal system emphasizing resource circulation, for example, with extensive recycling of materials
- Work to implement energy cooperation with Northeast Asian countries through electricity and gas grid networks and energy trading.
- Increase support for basic energy services for low income-households.

The new government has not as yet, however, prepared a comprehensive energy policy or detailed directions for implementation of its energy policies. The Park administration is preparing the Second National Energy Basic Plan, and it is expected that detailed energy policies will be included in the plan.

In preparing the Second Plan, the government has organized an expert working group consisting of some 60 experts from the public and private sectors, including representatives from NGOs. The main goal of the working group is to advise and recommend policy directions to the government as the government prepares the Second National Energy Basic Plan. The working group includes five sub-working groups, each organized around important energy issues as follows; Energy Mix, Energy Demand, Electricity, Nuclear Power and Renewable Energy.

Future Energy Scenarios for the ROK

Three future energy scenarios for the ROK were created and evaluated using the LEAP software tool. The Business as Usual (BAU) scenario assumes a continuation of current policies, with a natural continued improvement in energy efficiency across many sectors, but with energy efficiency improvements not driven by strong efficiency policies, and modest gains in renewable energy. Economic growth continues, but moderates over time, with real GDP growth rates rising in the next few years from about 2 percent annually in 2012 to 3.6%/yr in 2020, but then falling again to 2.2 percent by 2030 as the economy matures and the ROK population stabilizes and begins to decline. Figure 5-11 shows energy demand by sector in the BAU scenario. Here growth in the residential sector is small, and growth in the commercial sector moderates over time, thus most of the 50 percent growth in overall energy demand between 2010 and 2035 derives from growth in the transport and especially, industrial sectors. Figure 5-12 show energy demand by fuel grouping, with electricity and heat demand showing the strongest growth over time.

The “MAX” scenario shares the same demand assumptions with the BAU scenario, but includes slightly higher assumptions for nuclear generation capacity trends, with nuclear capacity in the BAU case reaching 40.6 GW by 2035, while in the MAX scenario, 2035 nuclear capacity is 42.1 GW. In the MIN scenario, in which lower assumptions for reactor life are used, along with different assumptions for replacement of reactors at the end of their working life, the total nuclear capacity falls to 32.7 GW by 2035, which is still about 50 percent above current (2014) levels. Figure 5-13 shows the trends in electricity generation capacity by type for the BAU scenario. The MAX and MIN scenarios include somewhat less and somewhat more coal and gas-fired (combined-cycle) generation, relative to the BAU scenario, compensating for the differences in nuclear capacity between the three cases.

Figure 5-11: ROK Energy Demand by Sector, BAU Scenario

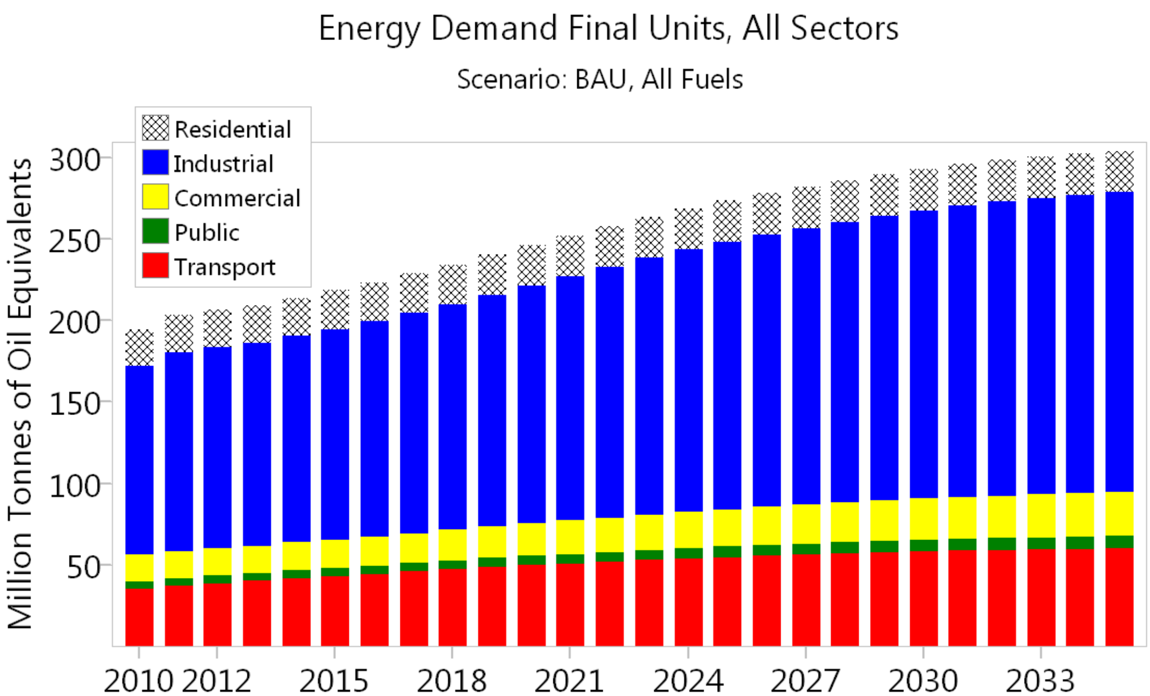


Figure 5-12: Energy Demand by Fuel, BAU Scenario

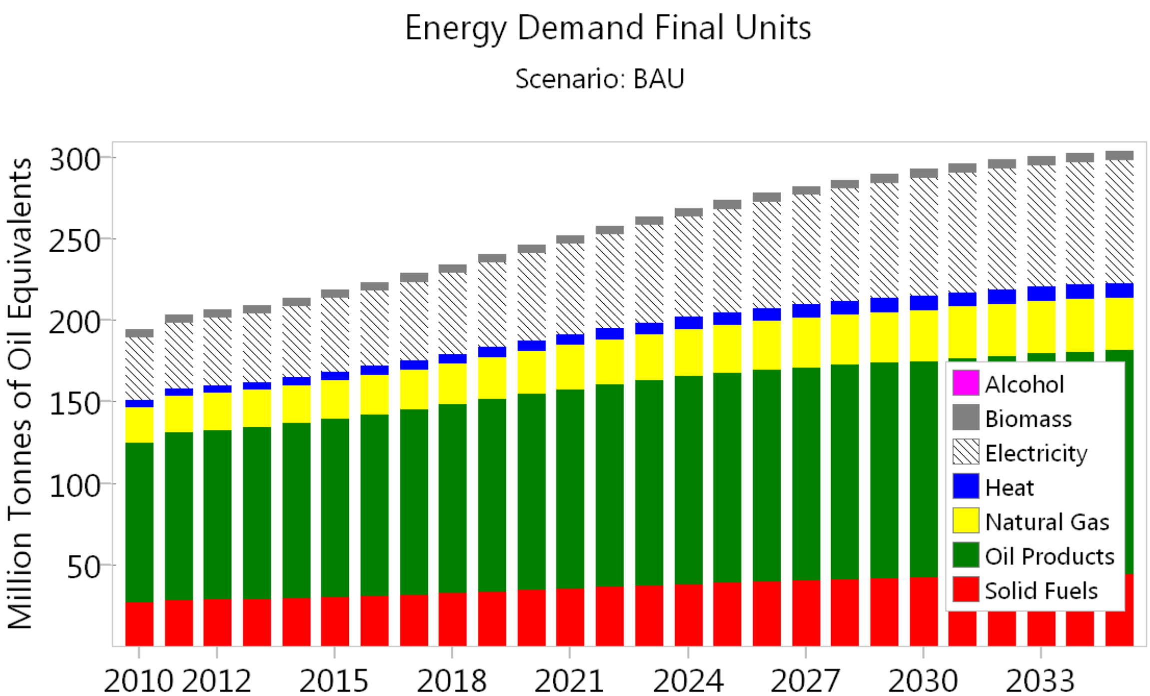


Figure 5-13: Electricity Generation Capacity by Type, BAU Scenario

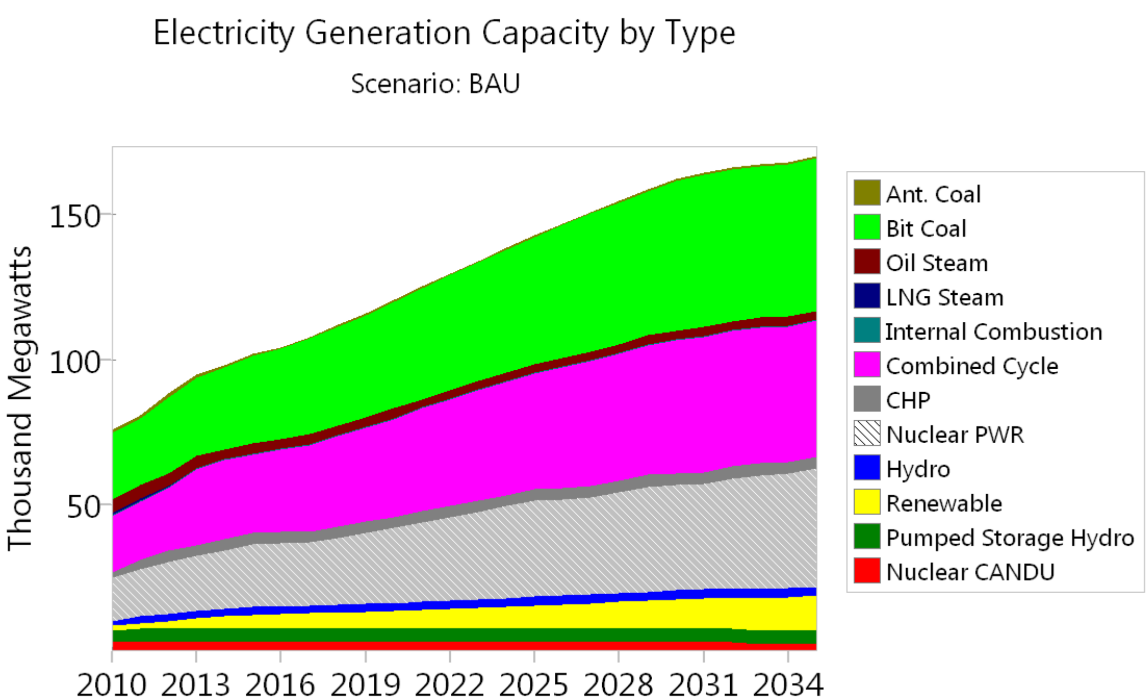
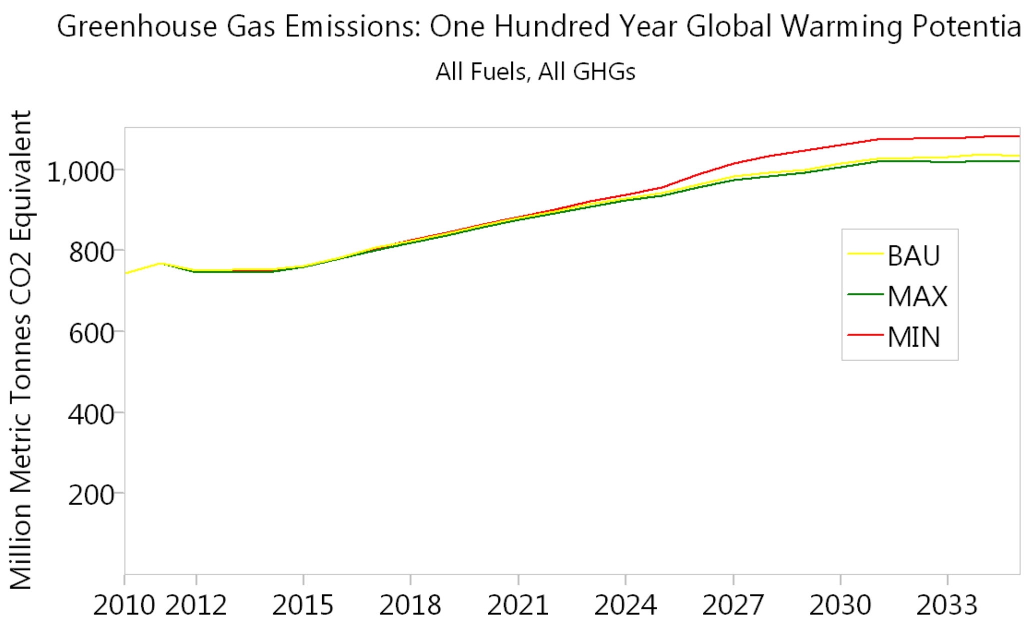


Figure 5-14 compares greenhouse gas emissions over time for the three different nuclear capacity scenarios described above. Overall GHG emissions in the ROK rise from somewhat under 800 million tonnes of CO2 equivalent in 2014 to between 1.0 and 1.1 billion tonnes by 2035, with the MIN scenario producing somewhat under 5 percent more GHG emissions in 2035 than the BAU case, due to the greater use of coal- and gas-fired power, and the MAX case producing about 1.5% less GHGs than the BAU case in 2035. Overall, the range of nuclear capacity scenarios explored here offer a relatively limited impact on GHG emissions, or on fuel imports.

Figure 5-14: Greenhouse Gas Emissions by Scenario



Conclusions

Korea, relying almost entirely on energy from overseas, is standing at an energy crossroads. Korea finds itself in this situation both due to ongoing debates with regard to its own domestic energy policies and because its energy fortunes are to a large extent embedded in the global energy economy. Further, the future of world energy is at present arguably more uncertain than usual, as a result of the continuing impacts on policies of the Fukushima nuclear disaster in Japan and of the uncertain ultimate impacts on international gas trade of the shale gas revolution in North America, among other energy policy issues. If the proportion of nuclear energy in the ROK's energy mix decreases over time, consumers will likely pay higher electricity tariffs due to the higher energy costs for fossil energy imports that KEPCO, the dominant electricity supplier, would have to pay to meet national electricity needs as a tradeoff for reducing public anxieties regarding nuclear accidents. On the other hand, many consumers may be reluctant to pay higher tariffs, and think that the concerns regarding nuclear accidents are exaggerated. These polarized viewpoints have resulted in conflicts between defenders and opponents to nuclear power that as of this writing are far from resolved.

Natural gas use in the ROK could significantly increase, and the Korea's use of other energy forms such as coal, nuclear energy and renewable energy would be reduced, if the shale gas revolution that has arisen in the USA expands to other nations such as China and Europe, lowering the natural gas prices paid by the ROK. The futures of shale gas as well as other nonconventional energy are, however, still uncertain due to geological barriers—it is unknown, for example, whether gas can be extracted from shale formations on other continents using the same technologies used in North America—technical problems, and environmental issues. Future energy policy directions in Korea are scheduled to be established in part with the upcoming publication of the Second National Energy Basic Plan. At present, there is a likelihood that the proportion of nuclear energy included in the ROK's plans for its future energy mix will decline in the new plan, meaning that shares of fossil fuels such as coal and gas would rise, perhaps consistent with the "MIN" scenario shown above, or even higher.

Increasing fossil energy consumption in the ROK would create a conflict with the low carbon policies that are now in place. Solutions to this problem include increasing renewable energy use and/or significantly improving energy efficiency. It is not expected, however, that the proportion of renewable energy will rise to more than the target proportion for renewable energy included in the First National Plan, because the renewable target has been regarded as too ambitious by many energy analysts and policymakers.

Energy pricing policies should be core tools for improving energy efficiency. The previous government announced and tried to strengthen policies to support a more market-based energy price system, with the goal of achieving a less energy-intensive economy, but that plan has failed, and energy efficiency has further deteriorated since the plan was put into action in 2009. This indicates how difficult it is for governments to raise energy prices to reasonable levels in Korea. The new government has also announced an intention to undertake strong improvements in energy pricing systems, especially for electricity tariffs, since the public electricity company financial losses are increasing due to the widening gap between tariffs and generation costs. As a result, the, Korean government must take a strong position with regard to tariff hikes in order to improve the energy efficiency of the Korean economy, as well as implementing policies, including tax, regulation, and incentive polices, to actively encourage improvements in efficiency of energy use by industrial, residential, commercial, and other energy consumers in Korea.

5.5 The DPRK Energy Sector and Energy Futures

During the decade of the 1990s, and continuing into the second decade of the 21st century, a number of issues have focused international attention on the Democratic People's Republic of Korea (DPRK). Most of these issues—including nuclear weapons proliferation, military transgressions, provocations, and posturing, economic collapse, transboundary air pollution, food shortages, floods, droughts, tidal waves, and, most recently the death of DPRK leader Kim Jong Il and the passing of the leadership mantle to the third generation of the Kim dynasty in Kim Jong Un—have their roots in a complex mixture of Korean and Northeast Asian history, global economic power shifts, environmental events, and internal structural dilemmas in the DPRK economy. Energy demand and supply in general—and, arguably, demand for and supply of electricity in particular—have played a key role in many of these high-profile issues involving the DPRK, and have played and will play (and are playing, as of November, 2013) a central role in the resolution of the ongoing confrontation between the DPRK and much of the international community over the DPRK's nuclear weapons program.

It is unclear as of this writing whether the Six-Party Talks process for addressing DPRK nuclear weapons and related issues, a process that have been moribund for some years, will be revitalized or will be replaced in the near or more distant future with a similar process, in all likelihood involving many or all of the same actors (and perhaps others). As long as the DPRK's nuclear weapons issue remains unresolved (or at least in the process of resolution), external powers will continue to squeeze the DPRK with sanctions, and external aid will be minimal. What is clear, however, is that energy sector issues will continue to be a key to the resolution of the crisis, as underscored by the formation of a Working Group under the Six-Party Talks that was (and nominally, still is) devoted to the issue of energy and economic assistance to the DPRK. Carefully-designed energy sector assistance projects of modest scale, particularly those that combine economic development and humanitarian focus, should be sought out, designed, and, as soon as conditions permit, undertaken. The ROK is in a unique position to develop and deliver such projects, and it stands to gain considerably if such projects are successful. For the ROK, engagement with the DPRK on energy issues offers many possible benefits, including an opportunity to improve its relationship and understand its neighbor, a chance to potentially improve the environment which the two nations share, an opening for the ROK to invest in and benefit from the development of the DPRK's economy, opportunities to potentially link its energy system with potential resource suppliers, most notably the Russian Far East, and an opportunity to improve the ROK's security by promoting peace on the Korean Peninsula.

In the remainder of this section we provide a brief overview of the current status and recent past of the DPRK energy sector, an introduction to key energy sector problems, and a summary of our estimate of the current and recent energy supply and demand situation in the DPRK, and a summary of our recent work on DPRK "Energy Futures"—an application of the LEAP software tool used by the Country Teams in the MacArthur-funded project, and the lessons that the results of that work provides for the design of energy sector assistance to the DPRK.

DPRK Energy Sector: Status and Problems

In the two-plus decades since 1990, the effective end of the Cold War and the substantial withdrawal of economic aid from the former Soviet Bloc, together with other world and regional events, have set the DPRK economy in what most observers agree is either a downward spiral or (at best) stagnation, with years of modest improvement interspersed with years in which economic conditions worsen.

Key economic resources for the DPRK, include:

- A well-trained, disciplined work force;
- An effective system for dissemination of technologies;
- The ability to rapidly mount massive public works projects by mobilizing military and other labor; and
- Extensive reserves of minerals and significant other natural resources.

The DPRK economy has been stagnating since 1990 as a result of a number of factors, including:

- Foreign debt incurred in purchasing industrial equipment and oil.

- The decline and eventual collapse of the Soviet Union, and the resulting reduction in Soviet/Russian aid to the DPRK and in markets for many DPRK-made goods.
- Poor grain harvests, particularly in the early 1990s, due to a combination of weather-related factors, lack of fuel and fertilizer, and environmental degradation.
- Economic isolation due to international sanctions.
- Natural disasters, including floods, severe storms, tidal surges, and droughts.

Although the DPRK has raw materials—particularly minerals—that are of interest to trading partners, it has produced few finished goods (with the exception of armaments) that are of high enough quality to attract international buyers. The DPRK's major trading partners as of 1990 were China, Russia, Iran (reportedly trading oil for armaments), and Japan. The DPRK at that time had limited trade with other Asian nations, as well as, on and off, with some European and other nations. The value of imports to North Korea already exceeded that of exports by $600 million in 1990. Trade even in 1991—both exports and imports—was down markedly from 1990 as a result of the dissolution of the USSR[170].

The economic, if not social and political, landscape in the DPRK changed markedly during the 1990s. In the early 1990s, the DPRK government openly admitted the country's failure to achieve the economic goals of its most recent seven-year plan[171]. Although little data have been available from inside the DPRK, information from outside observers of the country indicates that the North Korean economy was at best stagnating, and most probably in considerable decline, through the mid-1990s[172]. This economic decline has been both a result and a cause of substantial changes in energy demand and supply in DPRK over the last decade. Observers of the DPRK economy have suggested that at least a modest improvement took place in the years around 2000—ROK sources, for example, estimated that the DPRK economy grew approximately 6 percent in 1999, and another 1.3 percent in 2000[173]. A more recent estimate by the Bank of Korea showed the DPRK economy (as measured by GDP) growing at 0.4 percent in 2000, and by amounts varying from 1.2 to 3.8 percent annually from 2001 through 2005, followed by a period of slow decline (-0.5 to -1.2 percent/yr) in all years from 2006 through 2010 except 2008, when growth of 3.1 percent was estimated, meaning essentially zero overall growth in the DPRK economy from 2006 through 2010[174]. Other observers, however, tended to argue that most of any economic upturn in the DPRK economy in the years 2000 through 2005

[170] Korea Foreign Trade Association (1993), *Major Economic Indicators for North Korea*.
[171] The Economist Intelligence Unit (1994), South Korea, North Korea No. 1 1994. The Economist Intelligence Unit, London, United Kingdom. Country Report, 1st Quarter 1994.
[172] Far Eastern Economic Review (1995), 1995 Asia Yearbook, North Korea.
[173] Korea Trade-Investment Promotion Agency (KOTRA) data (from http://www.kotra.or.kr/main/info/nk/eng/main.php3, visited 6/3/02) in "South/North Korea's Trend of Real (GDP) Growth Rate", which lists the Bank of Korea as a Source. Similar growth in the North Korean "GNI" was also cited in data provided to Nautilus by the Korea Energy Economics Institute.
[174] Bank of Korea (2011), New Release: Gross Domestic Product Estimates for North Korea in 2010, dated November 3, 2011, and available as http://www.nkeconwatch.com/nk-uploads/GDP_of_North_Korea_in_2010.pdf.

appears to have been driven by food and other aid from abroad, inputs that have diminished over the last few years[175].

Among the energy-sector changes on the supply side in the DPRK since 1990 have been:

- A vast drop in imports of fuels (particularly crude oil and refined products, but coal and coke as well) from the Soviet Union and Russia. An index of these imports declined from a value of over 140 in 1987 to 8.7 in 1993, and crude oil imports from Russia in 1993 were on the order of one-tenth what they were in 1990[176], and have fallen to practically zero since, though more modest supplies of refined oil products continue to be imported into the DPRK from Russia, and there have been recent, though not yet verified, reports of some crude oil imports from Russia.
- A steady decline in the exports of coal to China between 1988 and 1993, with the value of those exports receding in 1993 to approximately a tenth what they were in 1990. This fall may have been a sign of reduced output in the DPRK coal industry, particularly as coal imports to DPRK from China remained near the same level (in dollar terms) from at least 1982 through the early 1990s[177].
- In recent years, however, the exports of coal and other raw mineral products (largely iron and steel scrap and metals ores) to China have increased dramatically, with coal exports to China reaching 2.8 million tonnes in 2005 and 4.6 million tonnes in 2010, followed by a vast increase to 11.2 million tonnes in 2011[178]. This is one manifestation of a recent increase in investment in the DPRK by Chinese businesses, particularly in the raw materials sectors, but also, to some degree, in manufacturing[179].

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[175] For example N. Eberstadt (2001), If North Korea Were Really "Reforming", How Could We Tell—And What Would We Be Able To See? states "...official claims of 'turning the corner' and 'completing the Forced March' notwithstanding, the North remains in dire economic straits". Eberstadt goes on to cite the UN Food and Agriculture Organization's finding that DPRK cereal production in 2000/2001 "is expected to be fully a third below the level of 1995/96", and asserts, based in part on the DPRK's meager reported export earnings in the first half of 2001, that "The country's export capabilities are likewise in a state of virtual collapse…".

[176] U.S. Bureau of the Census (1995a), The Collapse of Soviet and Russian Trade with the DPRK, 1989-1993: Impacts and Implications. Prepared by N. Eberstadt, M. Rubin, and A. Tretyakova, Eurasia Branch, International Programs Center, Population Division, U.S. Bureau of the Census, Washington, D.C., USA. March 9, 1995.

[177] U.S. Bureau of the Census (1995b), China's Trade with the DPRK, 1990-1994: Pyongyang's Thrifty New Patron. North Korea Trade Project Memorandum, International Programs Center, Population Division, U.S. Bureau of the Census, Washington, D.C., USA. May, 1995.

[178] N. Aden, "North Korean Trade with China as Reported in Chinese Customs Statistics: Recent Energy Trends and Implications", as prepared for the Energy Experts Working Group Meeting, June 26th and 27th, 2006, Palo Alto, CA, USA). Dr. Aden's paper is available as http://nautilus.wpengine.netdna-cdn.com/wp-content/uploads/2012/01/0679Aden1.pdf. Data for 2010 and 2011 from United Nations Comtrade Statistics database.

[179] Issues related to Chinese investment in the DPRK, and changes in DPRK policies that have made investment possible, are addressed in the Nautilus Institute Policy Forum Online 06-70A, August 23rd, 2006, "DPRK's Reform and Sino-DPRK Economic Cooperation", by Li Dunqiu (http://www.nautilus.org/fora/security/0670Li.html). See also Professor Li's presentation as prepared for the Energy Experts Working Group Meeting, June 26th and 27th, 2006, Palo Alto, CA, USA, and available as http://www.nautilus.org/DPRKEnergyMeeting/Papers/Li.ppt. Professor Li describes two "waves" of recent Chinese investment in the DPRK, with a first wave of investment led by private companies and businessmen, mainly from China's northeast provinces, and the second wave described as

- Continuing degradation of electricity generation and transmission and distribution (T&D) infrastructure, though with modest local rehabilitation of power plants and T&D systems in a few areas and for key purposes (including, reportedly, military facilities).

Oil import restrictions have reduced the availability of refined products in the DPRK. These problems arose partly (if indirectly) from economic sanctions related to the nuclear proliferation issue (see below), and partly from North Korea's inability to pay for oil imports with hard currency. This lack of fuel, particularly for the transport sector, has probably contributed to the DPRK's economic malaise since 1990. Another factor contributing to the decline in the country's economic fortunes has been the inability (again, partly due to lack of foreign exchange, and partly due to Western economic sanctions) to obtain key spare parts for factories, including factories built with foreign assistance and/or technology in the 1970s[180]. Also, as mentioned above, there has been, in the years since 1990, a virtual halt in economic aid, technical assistance and barter trade on concessional or favorable terms from Russia and other Eastern European nations. This reduction, coupled with a sharp decline in similar types of assistance from China (including, in the years between 1995 and 2000, a more than 50 percent reduction in crude oil shipments to the DPRK), had resulted in a total estimated loss of aid to the DPRK economy of more than $ US 1 billion per year[181] by the mid-1990s. The DPRK's trade deficit as of 2000 stood at $US 856.88 million[182], remained at near one billion dollars through 2004[183], and was over one billion dollars in 2009 and 2010[184], despite increasingly lucrative exports to China.

The economic difficulties mentioned above have been exacerbated by an untimely combination of climatic events. The early 1990s saw a series of poor grain harvests in the DPRK. Compounding these difficulties, 1995 and 1996 brought severe flooding to many areas of the DPRK, washing away topsoil from areas at higher elevation, and burying many areas of crucial low-lying farmland in tens of centimeters of silt or sand[185]. An additional blow to DPRK agricultural production was dealt by a tidal wave, caused by a typhoon at sea, that swept over and heavily damaged a long dike on the west coast of the DPRK in September of 1997,

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"mostly represented by large state-owned enterprises, in areas like heavy industry, energy, mineral [resources] and transportation".

[180] As of 1995 the DPRK's trade deficit was estimated at $879 million, based on United States Department of Energy's Energy Information Administration (UDOE/EIA, 1996), Country Analysis Brief, North Korea.

[181] United States Department of Energy's Energy Information Administration (UDOE/EIA, 1996), Country Analysis Brief, North Korea. Part of USDOE/EIA World-wide Web site, WWW.eia.doe.gov/emeu/cabs/nkorea.html.

[182] For example, see Joongang Ilbo, Lee Young-jong, "North Korea Overseas Trade Reaps $1.97 Billion For Last Year," Seoul, 06/04/01.

[183] As estimated by ERINA (Economic Research Institute for Northeast Asia) in Chapter 5 of Northeast Asia Economic Databook 2005, dated approximately December, 2005. ERINA's estimates are based on data from the Korea Trade-Investment Promotion Agency (KOTRA) for trade between the DPRK and nations other than the DRPK, plus figures on trade between the Koreas from the ROK Ministry of Unification. Avalable as http://www.erina.or.jp/En/Lib/datab/2005pdf/05-De.pdf. Page 53.

[184] Bank of Korea (2011), New Release: Gross Domestic Product Estimates for North Korea in 2010, dated November 3, 2011, and available as http://www.nkeconwatch.com/nk-uploads/GDP_of_North_Korea_in_2010.pdf.

[185] One such affected region is the Sinuiju area, where, after the 1995 floods, "…sand poured in from the Yalu River and destroyed all the rice fields in the region" (Bernard Krisher "Urgent Proposals To Get Food & Drugs To North Korea", extracted in Northeast Asia Peace and Security Network Daily Report, 30 May 1997. Nautilus Institute, Berkeley, CA, USA.

inundating hundreds of thousands of hectares of rice fields. The combined effects of flooding and poor harvests—even before the damage from the tidal wave was factored in—were a food shortage severe enough to spur the DPRK government to take the unusual step of publicly requesting food aid from the international community. Additional floods and tidal waves in several areas of the country caused damage to agricultural areas in 2006, and left tens of thousands of residential homeless. This cycle of misery caused by flooding returned to the DPRK in the summers of 2007, 2010, and, most recently, 2011[186].

Many observers of the DPRK, particularly in areas away from the major cities, report that official rations are far from sufficient to meet dietary requirements, that people are supplementing their rations with not only production of private gardens but wild foods, tree-bark, grass, and whatever other semi-edible materials they can obtain. Apart from the overriding human concerns associated with the food shortage, the slow starvation of the DPRK populace cannot help but decrease economic production still further, as poorly-fed people are less capable of work[187]. The flooding of 1995 and 1996 damaged an unknown number of irrigation dams and canals. Additional flooding in 1999 damaged both agricultural and industrial areas, as did flooding in more recent years. Cumulative damage to and "wearing out" of agricultural and other infrastructure, coupled with damage to farmlands (both related to climatic events and long-term degradation), means that it may be years before the DPRK is able to grow enough food to feed its populace again, even if the required agricultural inputs (fertilizer, machinery, and fuel for the machinery) do become more available.

Overall energy use per capita in the DPRK as of 1990 was relatively high, primarily due to inefficient use of fuels and reliance on coal. Coal is more difficult to use with high efficiency than oil products or gas. Based on our estimates, primary commercial energy[188] use in the DPRK in 1990 was approximately 70 GJ per capita, approximately three times the per capita commercial energy use in China in 1990, and somewhat over 50 percent of the 1990 per capita energy consumption in Japan (where 1990 GDP per-capita was some ten to twenty times higher than the DPRK). This sub-section provides a brief sketch of the DPRK energy sector, and some of its problems.

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[186] See, for example, Cankor (2011), "DPRK Flood Damage Reports by KCNA", dated 8 August 2011, and available as http://vtncankor.wordpress.com/2011/08/08/dprk-flood-damage-reports-by-kcna/; and United States Central Intelligence Agency (2010), North Korea: Assessing the Impact of Flooding on Agricultural Output (U//FOUO), dated 15 December 2010, and available as http://www.fas.org/irp/cia/product/nk-flood.pdf.

[187] Another way in which the food shortage likely has affected the economy is that scrap metal, some taken from industrial facilities, apparently has been (we do not know to what extent the practice continues) used as barter to obtain food via cross-border trade with China (Korea Times, "N. KOREA BARTERS SCRAP IRON FOR CHINESE FLOUR, CORN," Beijing, 05/18/97). Although the extent to which operational industrial facilities have been dismantled to trade for food is unknown, we find it conceivable that even if the DPRK does manage to obtain the needed inputs and investment to restart industrial production, many plants will be found to be inoperable due to key missing (sold for scrap) parts. In the same vein, there have also been reports from defectors that North Koreans have cut pieces of telephone and electrical wire to barter the copper in them to Chinese smugglers in exchange for food and other items (Korea Times, "RUMORS OF WAR RAMPANT IN N. KOREA," 05/23/97).

[188] Primary energy counts all fuel use, including conversion and transmission/distribution losses. Commercial energy excludes, for the most part, use of biomass fuels such as firewood and crop wastes.

As shown in Figure 5-15, the industrial sector is the largest consumer of all commercial fuels—particularly coal—in the DPRK. The transport sector consumes a substantial fraction of the oil products used in the country. Most transport energy use is for freight transport; the use of personal transport in the DPRK is very limited. The residential sector is a large user of coal and (in rural areas, though more recently, reportedly, in urban and peri-urban areas as well) biomass fuels. The military sector (by our estimates) consumes an important share of the refined oil products used in the country. The public/commercial and services sectors in the DPRK consume much smaller shares of fuels supplies in the DPRK than they do in industrialized countries, due primarily to the minimal development of the commercial sector in North Korea. Wood and crop wastes are used as fuels in the agricultural sector, and probably in some industrial subsectors as well. Figure 5-16 shows the increasing importance of biomass fuels to the DPRK economy since 1990.

Figure 5-15: DPRK Energy Demand by Sector

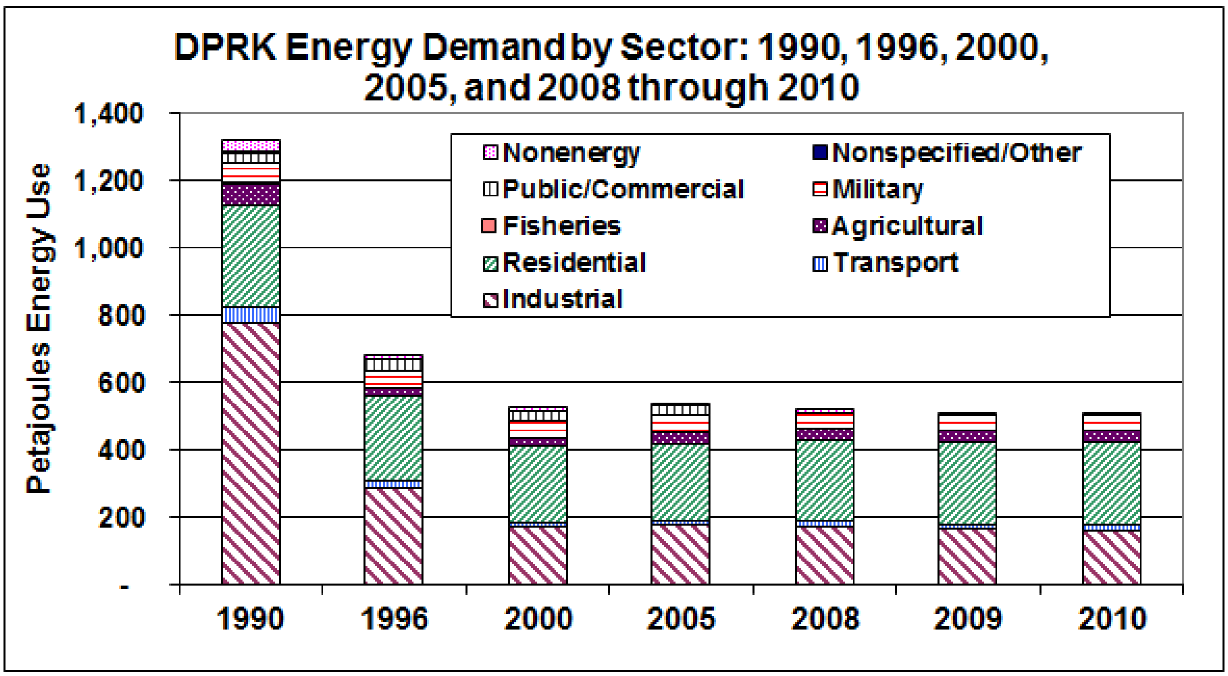
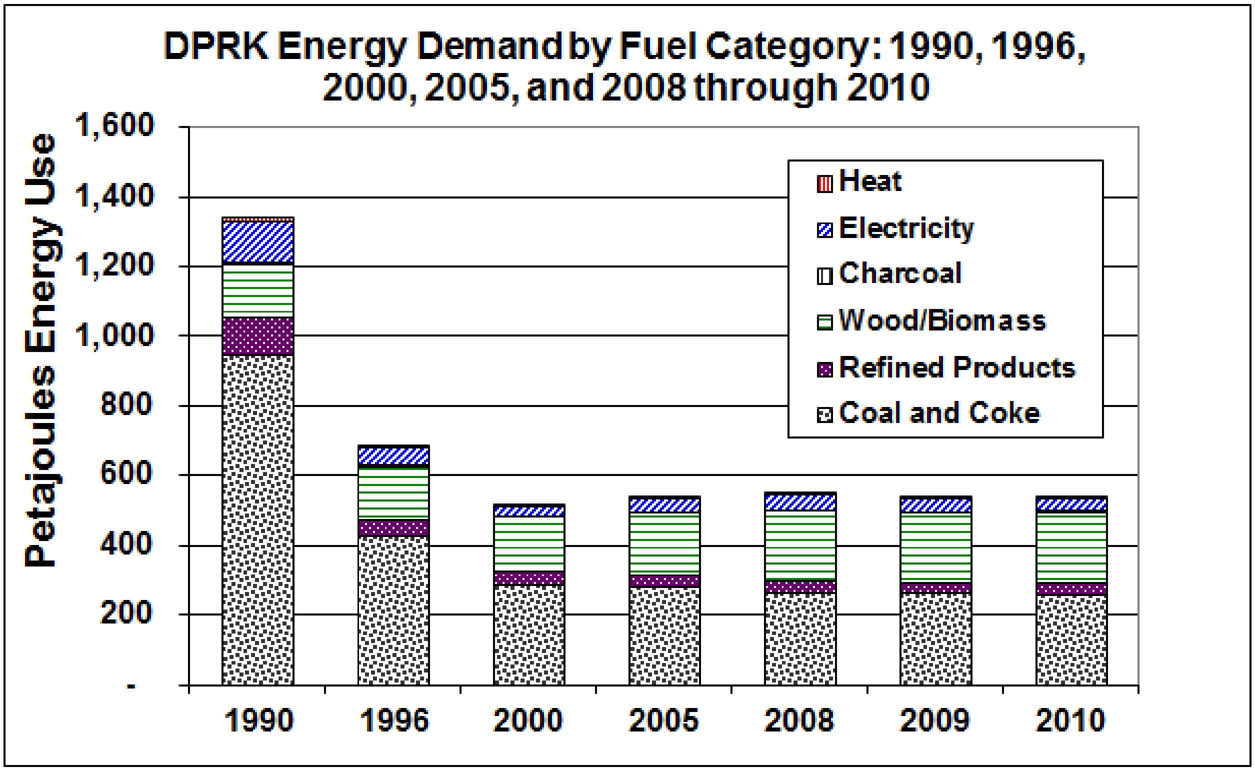


Figure 5-16: DPRK Energy Demand by Fuel Category



Key energy-sector problems in the DPRK include:

- *Inefficient and/or decaying infrastructure*: Much of the energy-using infrastructure in the DPRK is reportedly (and visibly, to visitors to the country) antiquated and/or poorly maintained. Buildings apparently lack significant, and often any, insulation, and the heating circuits in residential and other buildings for the most part apparently cannot be controlled by residents. Industrial facilities are likewise either aging or based on outdated technology, and often (particularly in recent years) are operated at less-than-optimal capacities (from an energy-efficiency point of view).
- *Suppressed and latent demand for energy services*: Lack of fuels in many sectors of the DPRK economy has apparently caused demand for energy services to go unmet. Electricity outages are one obvious source of unmet demand, but there are also reports, for example, that portions of the DPRK fishing fleet have been idled for lack of diesel fuel. Residential heating is reportedly restricted in the winter (and some observers report that some public-sector and residential buildings have not received heat at all in recent years) to conserve fuel, resulting in uncomfortably cool inside temperatures.

  The problem posed by suppressed and latent demand for energy services is that when and if supply constraints are removed there is likely to be a surge in energy (probably particularly electricity) use, as residents, industries, and other consumers of fuels increase their use of energy services toward desired levels. (This is a further argument for making every effort to improve the efficiency of energy use in all sectors of the DPRK economy as restraints on energy supplies are reduced.)

- *Lack of energy product markets*: Compounding the risk of a surge in the use of energy services is the virtual lack of energy product markets in the DPRK. Without fuel pricing reforms, there will be few incentives for households and other energy users to adopt energy efficiency measures or otherwise control their fuels consumption. Recent years have seen limited attempts by the DPRK government to reform markets for energy products. Some private markets exist for local products like firewood, and some commercial fuels have in recent years reportedly been traded "unofficially" (on the black market), but for the most part, energy commodity markets in the DPRK essentially do not exist[189]. Energy consumers are also unlikely, without a massive and well-coordinated program of education about energy use and energy efficiency, to have the technical know-how to choose and make good use of energy efficiency technologies, even when and if such technologies are made available.

The DPRK's energy sector needs are vast, and at the same time, as indicated by the only partial listing of problems many of these needs are sufficiently interconnected as to be particularly daunting to address. The DPRK's energy sector needs include rebuilding/replacement of many of its power generation and almost all of its substation equipment, repair, replacement, and/or improvement of coal mine production equipment and safety systems, updating of oil refineries, improvement or replacement of most if its energy-using equipment, including coal-fired boilers, electric motors and drives, transport systems, and many other items, modernization of energy use throughout the country, rebuilding of the DPRK forest stocks, and a host of other needs. As one example of the interrelations of energy problems in the DPRK, renovating the DPRK's coal mining sector is made more difficult because coal mines lack electricity due to electricity sector problems, and electricity generators in some cases have insufficient coal to supply power demand because of coal mine problems and problems with transporting coal to power plants.

Energy Supply—Resources, Technologies and Processes

North Korea's major energy resource is coal. The DPRK has substantial reserves of both anthracite and brown coal, though the quality of its coal reserves varies substantially from area to area. There is little, if any, coal cleaning (washing and sifting of coal to remove impurities such as sulfur and ash) in the DPRK. There have been reports of some operating oil wells in the country, with production starting around 2000, but these reports are far from fully substantiated. Modest oil resources reportedly have been located offshore in DPRK waters, and have been the subject of reported agreements between the DPRK and, variously, other countries and foreign companies. All crude oil and some petroleum products were imported as of 1990 from Russia,

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[189] In his paper and presentation "Changes In The North Korean Economy And Implications For The Energy Sector: Is North Korea Really Short of Energy?", as prepared for the Energy Experts Working Group Meeting, June 26th and 27th, 2006, Palo Alto, CA, USA, William B. Brown discussed the state of DPRK energy markets, and noted that by one measure of electricity cost, the ratio of the price of rice to the price of a kilowatt-hour of electricity, power was one hundred times as expensive in the United States in 2006 than it was in the DPRK. See http://www.nautilus.org/DPRKEnergyMeeting/Papers/Brown.html and http://www.nautilus.org/DPRKEnergyMeeting/Papers/Brown.ppt.

China, and Iran, plus some purchases on the Hong Kong spot market and elsewhere. Since 1990, crude oil imports have been restricted by a number of economic and political factors. Two operating oil refineries produced (as of 1990) the bulk of refined products used in the country. As of 1995 and 1996 (and apparently for at least most of 2000 through 2012), only one of the two refineries was apparently operating, and imports of refined products had not expanded sufficiently to replace the lost production. A third, simple, smaller refinery on the West Coast of the DPRK reportedly operates sporadically when crude oil shipments are available.

The estimated per-capita electricity end use in the DPRK in 1990 was about 1,500 kWh per capita. By comparison, overall 1990 electricity demand in South Korea was about 2,200 kWh per capita.[190] Per capita electricity consumption in the DPRK has declined very substantially since, due largely to reduced availability of power, though also as a results of reduced economic activity.[191] As with coal, the bulk of the electricity demand in the DPRK has traditionally been in the industrial sector, with the residential and military sectors (by our estimates) also accounting for significant fractions of electricity use.

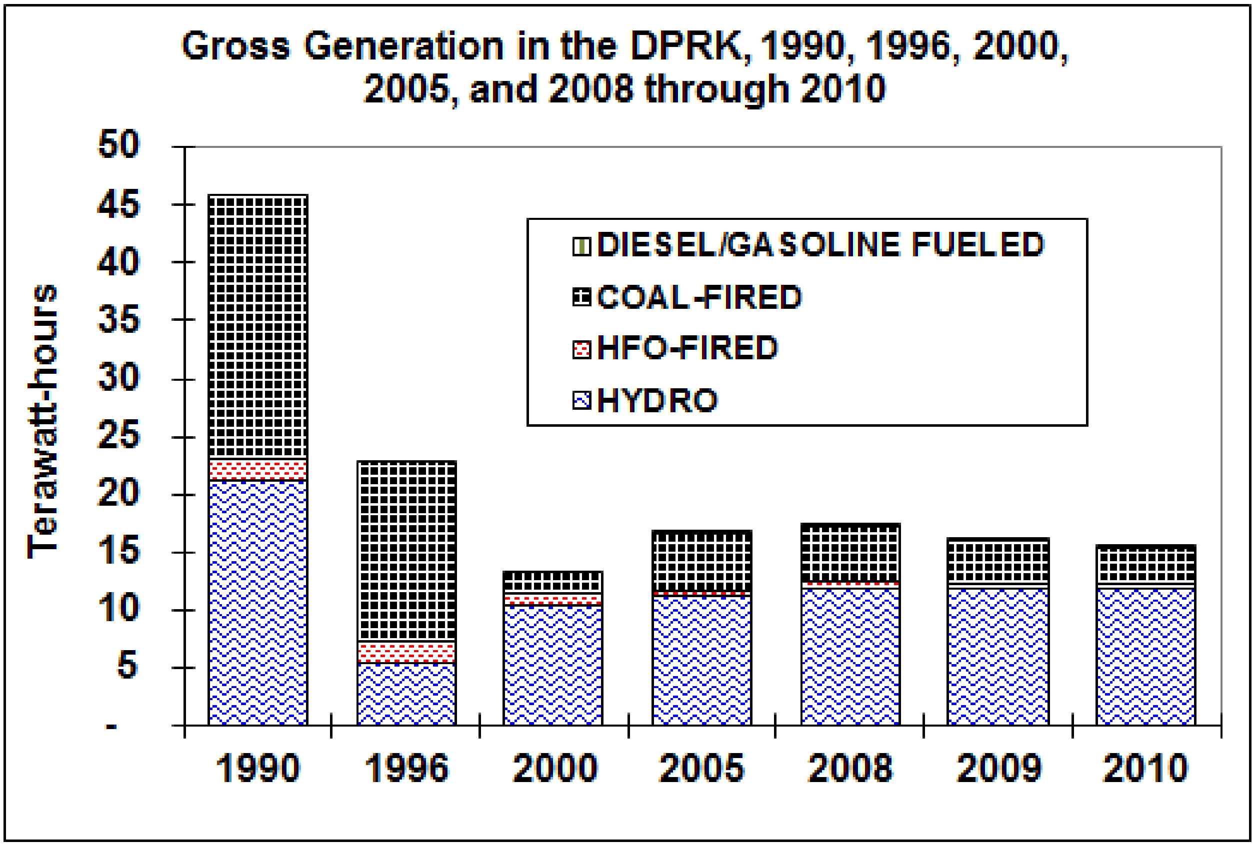
Electricity generation as of 1990 was primarily hydroelectric and coal-fired, in approximately equal proportions, with a small amount of oil-fired electricity generation capacity associated with the oil refinery at Sonbong and in two other plants. Much of the generation capacity was installed in the 1970s and 1980s, although a significant portion of generation facilities—particularly hydroelectric facilities—date back to the Japanese occupation[192]. Since 1990, the ratios of hydro to "thermal" power production have varied from year to year, based on the availability of hydro power (including low output in the mid-1990s following plant damage due to flooding) and on the condition and fuel supply for coal-fired power plants. Figure 5-17 presents our estimates of electricity output by fuel type in the DPRK over the last two decades.

[190] Korea Energy Economics Institute (KEEI, 1991), Yearbook of Energy Statistics, 1991. KEEI, Seoul, Republic of Korea

[191] By contrast, the ROK's per capita electricity consumption had more than quadrupled, to 8900 kWh per capita, by 2009, based on World Bank figures.

[192] Many of the hydroelectric facilities built during the Japanese occupation were reportedly disabled or dismantled by the Japanese (during retreat from the Peninsula) or by the USSR, but were later refurbished with technical assistance and equipment from the USSR.

Figure 5-17: DPRK Gross Generation



The DPRK has the coal resources necessary to expand thermal power generation, but it is not clear that the coal mining or transport infrastructure is capable of supplying coal to power stations at a rate much greater than that prevailing in 1990 (and in fact, given problems in the coal industry, only a fraction of this rate of coal supply is currently achievable). In a series of vicious spirals, electricity and coal infrastructure problems feed back on each other and link to problems throughout the economy. For example:

- No or sporadic electricity availability means that lights and pumps in coal mines don't stay on, reducing coal output;
- No or sporadic electricity means difficulties with coal (and other goods) transport, meaning less coal is made available for power plants and industry
- Lack of power and coal for industry limits production of spare parts for transport, generation and mining infrastructure;
- Lack of power makes outside investment in mining, manufacturing more difficult/less attractive; and so on.

Given weather patterns in the subregion, North Korea probably has a significant wind power resource, as yet untapped (and largely unmapped), but it is far from equally distributed throughout the nation, with average winds in many of the most populous onshore areas (including the western coastal plains) being relatively light. The DPRK also has some remaining undeveloped hydroelectric sites.

Power generation facilities are reported to be in generally poor, and often failing, condition and sometimes (because they are based on technologies adopted from China or the Former Soviet Union) not well adapted to the coal types with which they are fired. As a consequence, the generation efficiency of the thermal power stations in the DPRK is reportedly low. Thermal power plants generally lack all but the most rudimentary pollution control equipment, and also, in almost all cases, lack any kind of computerized combustion control facilities. In-station use of power is reportedly fairly high, and "emergency losses" of power have been reported at major stations.

The system of electricity dispatching is inefficient, minimally or not at all automated, and prone to failure. Estimates of transmission and distribution (T&D) losses vary from an official 16 percent up to more than 50 percent, but any estimates of T&D losses are difficult to confirm, as there is minimal end-use metering in the DPRK[193].

Current Context of Energy Cooperation with the DPRK—Overview of Opportunities and Challenges

As noted briefly above, North Korea suffers under a host of energy sector problems, as well as many economic, humanitarian, environmental, and other problems that are often intertwined with, or exacerbated by (at least in part), energy sector problems. Addressing these problems, sometimes termed the DPRK's "energy insecurity", will require significant, concerted, and sustained effort by and coordination among a vast suite of actors from different nations. At the same time, these problems, in the types of cooperation that will be required to address them, also offer significant opportunities to all Koreans and to the peoples of Northeast Asia and beyond.

Key economic resources for the DPRK to address its "energy insecurity" include a large, well-trained, disciplined, and eager work force, an effective system for dissemination of technologies, the ability to rapidly mount massive public works projects (or, in fact, any project, large or small, requiring hands and shovels) by mobilizing military and other labor, extensive reserves of minerals, and significant energy resources. What the DPRK lacks are modern tools and manufacturing methods, adequate supplies of fuel, reliable transport and energy infrastructure, sufficient arable land to reliably feed its populace, and above all, investment capital to enable the import and/or manufacture/development of tools, equipment, materials and know-how to fill these key gaps. As a consequence, a coordinated program of assistance from the ROK, the United States, and/or other countries that builds upon these attributes will be needed. Providing key assistance in a timely manner will enhance security in Northeast Asia, accelerate (or, given recent events, help to re-establish) the process of Northern Part rapprochement to its neighbors,

[193] That is, for the most part, even as of 2010 and 2011, power was and is reportedly simply provided to consumers largely without metering, so "sales records" as such generally do not exist.

and help to position countries and firms as major suppliers for the DPRK economic redevelopment process.

The nature of the DPRK's energy sector problems, however, mean that an approach that focuses on one or several massive projects-such as a single large power plant-will not work. A multi-pronged approach on a number of fronts is required, with a large suite of coordinated, smaller, incremental projects addressing needs in a variety of areas. This approach is not necessarily well-suited to a top-down policies designed to help reach political agreements to rapprochement between the Koreas (and between the DPRK and others in the international community), which have tended, at least in the past, to look for solutions that involved large and hugely complex initiatives[194]. The multi-pronged requirement fits extremely well, however, with the need to engage DPRK organizations and individuals on a broad basis to bring the peoples of Korea and the region together, thus offering opportunities for many different ROK (and other) organizations to lend their diverse expertise to the solution of Korea's individual and shared problems. A multi-pronged approach also offers the opportunity for even organizations with limited budgets and staffing to cooperate with DPRK actors, given suitable authority to do so and with careful coordination between organizations providing assistance.

Below, we identify priority areas where we see DPRK energy sector assistance as both necessary and in the best interests of all parties. All of these interventions would put foreign (US, European, ROK, Australian, or other) engineers and other program staff in direct contact with their DPRK counterparts and with DPRK energy end-users, thus providing broad-based human interactions with the DPRK that are crucial to a lasting reconciliation between the DPRK, the ROK, and the international community.

- Provide **technical and institutional assistance** in implementing energy efficiency measures. Focusing in particular on energy efficiency, regional cooperation would be useful to help the DPRK to provide the DPRK with access to energy-efficient products, materials and parts, pursue sector-based implementation of energy efficiency measures, and carry out demonstration projects. This type of assistance has the additional benefit of helping to improve markets for ROK and other suppliers of these products and services.
- Work to **open opportunities for private companies to work in the DPRK**. Grants or loans from foreign governments cannot begin to fill the needs for energy infrastructure in the DPRK, but the US, ROK, European, and other governments can help to facilitate the efforts of private companies (including independent power producers) from abroad in the DPRK energy sector. One key, in the medium and longer-term, to facilitating the involvement of private companies is to provide assistance for policy and legal reforms in the DPRK that are needed to make it possible, or at least more straightforward, for private companies to work there.
- Cooperation on **technology transfer for energy efficiency and renewable energy applications**.

[194] The 2 x 1000 MW light water reactors (LWRs) previously under construction near Simpo in the DPRK by the Korean Peninsula Development Organization (KEDO), and the 2006 offer by the ROK to provide the DPRK with 2 GW of power through a transmission line across the DPRK/ROK border, are examples here.

Specific energy sector initiatives that will assist the process of rapprochement with the DPRK, help the DPRK to get its economy and energy sector working in a sustainable (and peaceful) manner, and help to pave the way for additional cooperative activities in the energy sector include:

- *Assistance for internal policy and legal reforms to stimulate and sustain energy sector rebuilding in the DPRK*. This should include, early in the process, reform of energy pricing practices, and the physical infrastructure to implement them, capacity building for careful energy planning to allow aid to be based on need and rational objectives, training for energy sector actors, strengthening regulatory agencies and educational/research institutions in the DPRK, and involving the private sector in investments and technology transfer.
- *Rebuilding of the electricity transmission and distribution (T&D) system*. The need for refurbishment and/or rebuilding of the DPRK T&D system has been touched upon earlier in this paper. The most cost-effective approach for international and ROK assistance in this area will be to start by working with DPRK engineers to identify and prioritize a list of T&D sector improvements and investments, and to provide limited funding for pilot installations in a limited area-perhaps in the area of a special economic zone or in a "demonstration" county.
- *Rehabilitation of power plants and other coal-using infrastructure*. An initial focus should be on improvements in small, medium, and district heating boilers for humanitarian end-uses such as residential heating, as well as in small institutional settings such as schools and hospitals.
- *Rehabilitation of coal supply and coal transport systems*. Strengthening of the coal supply and transport systems must go hand in hand with boiler rehabilitation if the amount of useful energy available in the DPRK is to increase. Coal supply system rehabilitation will require provision of basic systems for providing ventilation, light, and motive power for water pumping and extraction of coal to mines, as well as improvements in mine safety. Coal may or may not be the fuel of the future for the DPRK, but it is the fuel of the present, and it is hard to conceive of an economic improvement in the DPRK, in the short-to-medium term, that does not rely substantially on coal.
- *Development of alternative sources of small-scale energy and implementation of energy-efficiency measures*. The Koreans from the Northern Part that Nautilus has worked with have expressed a keen interest in renewable energy and energy-efficiency technologies (see below). This interest is completely consistent with both the overall DPRK philosophy of self-sufficiency and the practical necessities of providing power and energy services to local areas when national-level energy supply systems are unreliable at best. Such projects should be fast, small and cheap, and should (especially initially) emphasize agricultural and humanitarian applications.
- *Rehabilitation of rural infrastructure*. The goal of a rural energy rehabilitation program would be to provide the modern energy inputs necessary to allow DPRK Korean

agriculture to recover a sustainable production level and the basic needs of the rural population to be met.

- *Begin transition to gas use in the DPRK with Liquid Petroleum Gas (LPG) networks*. LPG is more expensive than natural gas, but the infrastructure to import LPG, relative to liquefied natural gas (LNG) is much easier, quicker, and less expensive to develop, and allows imports in smaller quantities. LPG is also clean burning, has limited military diversion potential, and setting up LPG networks can be a first step toward the use of natural gas in the DPRK-if done with a future transition to natural gas use in mind. Ultimately, natural gas pipelines and LNG terminals, shared with (most likely) the ROK, can serve as a step toward economic development coupled with regional energy system/economic integration.

Additional and more detailed descriptions of these options are provided in previous reports by the authors[195].

By way of historical context, the process of energy engagement with the DPRK, which began around 1994, has sought to provide short-term energy aid to the DPRK while at the same time (though to varying degrees) looking ahead to types of energy assistance that would help the DPRK in redeveloping its energy sector and economy. Because it is a fuel that has limited military uses, heavy fuel oil has been the form of energy aid most frequently provided to the DPRK as the agreed direct energy assistance. Other types of energy aid provided under the Six-Party Talks agreement have included parts and materials to repair/maintain DPRK power and heating plants, and of course the Kumho/Simpo LWR construction program was the focus of long-term energy assistance under the terms of the 1994 Agreed Framework. A variety of other options for energy sector assistance to the DPRK have, however, been suggested over the years.

The DPRK's energy sector needs are vast, and at the same time, many of these needs are sufficiently interconnected and particularly daunting to address. The DPRK's energy sector needs are described briefly above and referred to in what follows, but they include rebuilding/replacing many of its power generation and almost all of its substation equipment, repair/replacement/improvement of coal mine production equipment and safety systems, updating of oil refineries, improvement or replacement of most if its energy-using equipment (i.e. coal-fired boilers, electric motors and drives, transport systems, and many other items), modernization of energy use throughout the country, rebuilding of the DPRK forest stocks, and a host of other needs. As one example of the interrelations of energy problems in the DPRK,

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[195] For example, as von Hippel, D.F., and P. Hayes (2009b), "DPRK Energy Sector Development Priorities: Options and Preferences", in the Asian Energy Security Special Section on Asian Energy Security of Energy Policy, Volume 39, Issue 11, November 2011, Pages 6781-6789 available as http://dx.doi.org/10.1016/j.enpol.2009.11.068; von Hippel, D.F., and P. Hayes (2007), Fueling DPRK Energy Futures and Energy Security: 2005 Energy Balance, Engagement Options, and Future Paths (Nautilus Institute Report, available as http://www.nautilus.org/fora/security/07042DPRKEnergyBalance.pdf); von Hippel, D.F., and P. Hayes (2007), "Energy Security for North Korea", Science, volume 316, pages 1288 – 1289, June 1, 2007; and von Hippel, D. F., P. Hayes, J. H. Williams, C. Greacen, M. Sagrillo, and T. Savage, 2008, "International energy assistance needs and options for the Democratic People's Republic of Korea (DPRK)". Energy Policy, Volume 36, Issue 2, February 2008, Pages 541-552.

renovating the DPRK’s coal mining sector is made more difficult because coal mines lack electricity due to electricity sector problems, and electricity generators in some cases have insufficient coal to supply power demand because of coal mine problems and problems with transporting coal to power plants.

International and ROK engagement of the DPRK on energy sector topics is also made more difficult by a number of challenges related both to the DPRK's situation and to circumstances facing the other nations that would seek to engage with the DPRK. We return to these challenges later, but very briefly, some of the circumstances that make engagement with the DPRK on energy sector issues particularly difficult include (but are by no means limited to):

- A lack of institutional capacity in the DPRK to efficiently engage groups from outside the country and to use energy aid in significant amounts.
- A lack of energy product markets that could help to sustain energy assistance activities.
- A lack of basic tools and materials to facilitate energy projects in the DPRK-in some cases, virtually every bolt needed for an energy project must be imported.
- Logistical difficulties posed by poor transport facilities within the DPRK, as well as by often complicated arrangements and authorizations needed to ship into the DPRK key pieces of equipment needed for a project.
- Difficulties in reaching consensus within the DPRK between the different groups likely to be involved (for example, the Foreign Affairs Office, national ministries, local authorities in the area where a project is to be developed, and technical counterparts).
- Difficulties in aligning the goals of a project with the views and needs of different political constituents within the DPRK.
- Difficulties in aligning the goals of a project with the views and needs of different political constituents within the ROK and within key partner countries, including the United States.

At present, the key impediment to ROK engagement with the DPRK to provide energy aid and related development assistance is the political stalemate between the ROK and the DPRK, as well as the tension between the DPRK and the ROK’s allies. The already poor relationship between the DPRK and the ROK was further strained by the sinking of the ROK’s naval vessel Cheonan by a DPRK Korean torpedo on March 26, 2010 in the Korea West Sea, and the DPRK’s shelling of Yeonpyeong Island in November 2010. Despite apparent offers summit meeting extended by the ROK to the DPRK, and despite an occasionally more conciliatory tone by the DPRK since the succession of Kim Jong Un to DPRK leadership (and recent suggestions of a more open attitude to the DPRK on the part of ROK leadership), contacts between the ROK and the DPRK have been limited over the past few years. The continued operation of the Kaesong Industrial District just north of the demilitarized zone (DMZ) is the only significant cooperative project currently ongoing. Even the Kaesong project, though important for both Koreas, has seen disputes over the number of workers that the ROK can bring into the district and other issues.

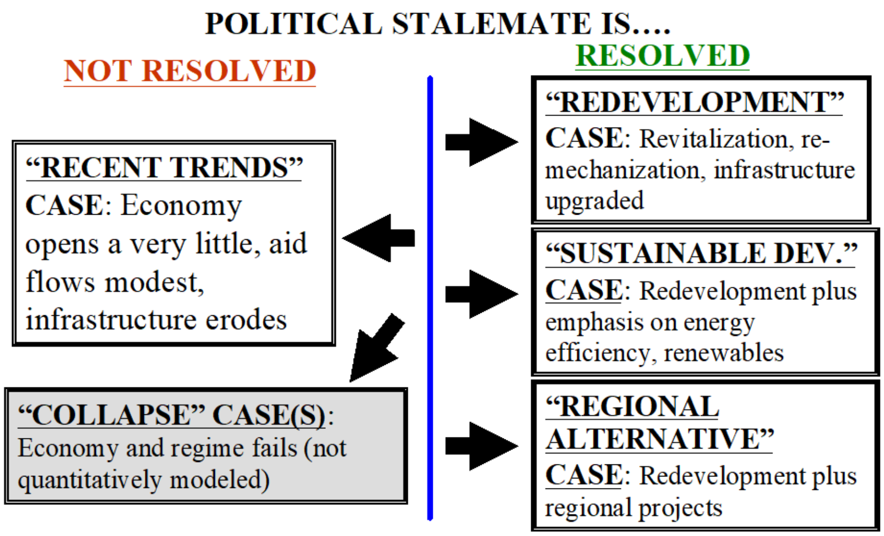
Despite the bleak outlook for near-term cooperation between the nations of the Korean Peninsula, history suggests that setbacks in talks with the DPRK are not at all unusual, and can and will be overcome with time, patience, and some flexibility on the part of negotiating partners. Since the negotiations could reconvene on relatively short notice, it is important for the international community to give serious consideration to the types of assistance options that would be required to address the DPRK's energy insecurity, and thereby to gain collectively a good a sense as to which types of energy sector assistance will be useful, practical, and possible in return for DPRK concessions on its nuclear weapons program. This is particularly true for the Republic of Korea, which has far more to gain or lose from the relations with the DPRK than any other nation.

The DPRK's Energy Future

Despite a few outward though often intermittent signs (and the key word here is "outward") of economic recovery in recent years—including more activity in the capital and a population that looks, in general, better nourished (to at least some visitors)—it is clear, if our estimates as presented above are not drastically in error, that the DPRK energy sector is a long way from good health. What does the near- and medium-term future hold for the DPRK, and what can be done by the international community in general, and the ROK in particular, to make the lives of DPRK citizens less burdensome? This section provides a summary examination of these questions, and provides some ideas for initiatives that could assist the DPRK in building a sustainable energy sector.

There are essentially three different ways that the DPRK energy sector and economy could evolve from their current status. First, the economy could open, leading to economic redevelopment. This process, of course, could occur slowly or rapidly, and could take on very different characteristics, depending on how it is managed. Second, the economy could fail to open substantially, leading to a continuation of recent trends of stagnation in the economy and in energy supplies. Third, the current DPRK regime could collapse in one of many possible ways, leading, in most scenarios, to actual or de-facto economic integration with the ROK. We must emphasize that we do **NOT** think that DPRK regime collapse is likely in the near- or even medium-term, but it is instructive to think through the implications of collapse scenarios. Variants of the economic redevelopment scenarios fall on the right hand side of Figure 5-18, while recent trends and collapse scenarios fall on the left side.

Figure 5-18: DPRK Energy Paths/Scenarios Considered Quantitatively to Date



In the following we:

- Summarize our exploration of the energy, environmental, and cost implications of a possible economic redevelopment scenario for the DPRK, as well as various variants of that scenario, with results for a "recent trends" scenario provided by way of comparison;
- Summarize our previous work in evaluating the potential energy sector impacts of qualitative "collapse" scenarios; and
- Explore the Lessons learned" from both quantitative scenarios and qualitative "collapse" scenarios, regarding the type and likely magnitude of future DPRK energy sector energy and infrastructure requirements, and the implications of those requirements for potential energy sector redevelopment/rehabilitation/assistance activities.

The DPRK under a Medium-Term "Redevelopment" Pathway

Below we describe, in a very qualitative way, what a medium-term "Redevelopment" path might look like for the DPRK economy and, by extension, for the DPRK energy sector[196]. This qualitative sketch is a first step to the estimation of the quantitative attributes of such a path—

[196] Note that in this discussion we use the words "path" and "scenario" somewhat interchangeably. In general, we consider an energy "path" for the future to follow on to existing conditions, sometimes with a change in trends, and thus not take into account possible large dislocations or other events. Although we more typically refer to "scenarios" in the context of qualitative exercises designed to encourage participants to think broadly about how the future might look (see, for example, Nautilus Institute (2009), "Northeast Asia 2050: Is There a Role For Civil Society in Meeting the Climate Change Challenge?", available as http://nautilus.wpengine.netdna-cdn.com/wp-content/uploads/2011/12/Scenario_agenda.pdf), or for qualitative analysis of the type described below in the context of "collapse" scenarios, wet use the word "scenario" in this paper more broadly because "scenario" is the word used for energy path in the LEAP modeling software we use to quantitatively model the energy paths (see below).

what the path might mean, for example, in terms of future terajoules of petroleum, tonnes of coal, and megawatts of power.

First and foremost, the "Redevelopment" pathway implicitly assumes a major breakthrough in relations with the ROK, and probably with the United States as well, resulting in some investment in the industrial and energy infrastructure in the DPRK from outside the country, and much-increased foreign development aid. The "Redevelopment" path also assumes, however, that the DPRK government essentially maintains its integrity. If the current DPRK government loses power, rapid reunification of North and South Korea may result, which probably means very large, very fast changes for the DPRK energy sector (as e, providing that the unified Korea can obtain internal and external financing for infrastructure reconstruction in the Northern Part. Some of these "collapse" scenarios—which the authors of this paper again stress that we feel are unlikely—are presented and discussed qualitatively below.

A "**Redevelopment**" pathway for the DPRK would likely be built upon the following assumptions:

- With some political and economic opening, coupled with increased foreign aid, the DPRK economy starts to revive in earnest (for example, in 2014)—but note that the structure of the economy may well evolve along quite different patterns than those prevailing in 1990.
- Industrial production increases, particularly in the lighter industries; and there is increased demand for transport and consumer goods.
- There is an increase in household energy use, as improved supplies become available and incomes increase, with trends toward using more electricity, LPG, and kerosene in homes.
- There is a considerable increase in commercial sector activity, and a relatively small increase in military sector energy use[197].
- Refurbishment of electric transmission and distribution infrastructure takes place, coupled with refurbishment of existing hydro plants, building of new hydro capacity, the re-starting and expansion of the DPRK's east coast refinery (recently the topic of news announcing investment in the refinery by a Mongolian enterprise), and partial retirement of coal-fired electricity generating capacity.
- Modest improvements in energy efficiency take place.

This pathway, or one very much like it, may in fact be one of the only ways that DPRK infrastructure can be sufficiently rehabilitated to be able to use within the DPRK even some of the power from nuclear reactors such as those that were being built by KEDO until 2002. There

[197] Depending on the nature of the diplomatic breakthrough, the degree to which it is embraced by the DPRK leadership, and the economic opportunities it offers to North Korean citizens, it is entirely possible that the DPRK armed forces may be partially demobilized, resulting in lower military energy activity, but force modernization accompanying redevelopment, including modernization of military buildings, communications, and other elements, might increase energy use per soldier even as the size of the armed forces decrease. Partial demobilization seemed to be under discussion in the DPRK as of about 2002, so should not be considered out of the question.

is at present no way to use 1000 MW-class reactors within the existing DPRK grid[198], so to use such a reactor interties to other countries must be constructed, and preferably, from a political and practical perspective, the DPRK grid would need to be totally rebuilt as well. Had the construction of the KEDO reactors at Simpo continued, interconnection issues could have been both a huge problem that could have led to poor relations between the DPRK and the outside for years to come, or, if handled correctly, could have constituted a huge opportunity for building of economic links (and better relations) between the countries of the region. If construction of the LWRs at Simpo is taken up again in the future, this technical consideration, and its various solutions and non-solutions, will remain. Given the unresolved nature of the various nuclear-related issues (nuclear weapons, uranium enrichment, the DPRK's stated aim to develop a domestic small light water reactor, and the lingering possibility of resuming work on the large Simpo LWR units with ROK or international assistance), we have chosen to leave nuclear power out of the modeling of the Redevelopment path, and also out of the major variant paths described below. We have, however, also prepared preliminary "with nuclear" scenarios corresponding to the Redevelopment path and to each of its variants. In those paths, we assume the construction of large (1000 MW) reactors, with the bulk of the power from those reactors, at least initially, exported directly to the ROK through a direct tie-line to the larger, stable ROK grid.

In the context of collaborative research on regional energy security in Northeast Asia[199], Nautilus Institute has developed and evaluated alternative paths that provide the same energy services as the Redevelopment path described (in summary) above, but incorporate in an expanded way, relative to the Redevelopment path, features of energy efficiency and renewable energy, as well as strengthened regional cooperation in the energy area. The two main alternative paths evaluated are:

- The "Sustainable Development" Path. This path provides the same energy services as "Redevelopment" Path—with, for example, the same demographic assumptions, and the same levels of economic output—but applies energy efficiency, renewable energy, and other measures, in an aggressive fashion, including upgrading of industrial infrastructure to levels approaching high-efficiency international standards, a rapid phase-out of existing coal-fired power plants, and earlier addition of an LNG (liquefied natural gas) terminal and of gas CC (combined cycle) generating plants using the gas from the LNG plant.
- The "Regional Alternative" Path. This path resembles the Sustainable Development path, but as a result of regional cooperation, efficiency improvement targets are reached two years earlier than in Sustainable Development path, and at costs that are 10 percent lower. In the

[198] Nuclear safety concerns (back-up power for coolant pumps and controls) and the attributes of a large-capacity nuclear unit operating in a small power grid (the DPRK grid is far below the minimum size to support the KEDO reactors) are key reasons why these reactors cannot operate under current conditions. See D. Von Hippel et al (2001), "Modernizing the US-DPRK Agreed Framework: The Energy Imperative" as referenced earlier in this report.

[199] In the Asian Energy Security project, and the related and follow-on East Asia Science and Security project, collaborating groups of researchers from each of the countries of Northeast Asia work together to research the energy security implications of different energy policy choices, both within their countries and regionally. See, for example, "East Asia Science and Security Meeting 2010", at http://nautilus.org/projects/by-name/science-security/workshops/2010-east-asia-science-and-security-meeting/.

fuel supply sector, a gas pipeline from the Russian Far East to the DPRK and the ROK begins operation in 2016, with 3 percent of the gas throughput of the pipeline used in DPRK initially, 10 percent by 2020, and 15 percent by 2030. The DPRK receives $10 million per year as "rent" for hosting the pipeline. Also, a larger LNG facility is installed than in the Redevelopment or Sustainable Development paths—and is again shared with the ROK. A power line from the Russian Far East through the DPRK to the ROK is also installed. Cooperation in renewable energy technologies yields earlier deployment of those technologies, and a 10 percent reduction in cost of wind and small hydro technologies relative to the redevelopment path. In the Regional Alternative Path, the last of the DPRK's existing coal-fired plants are retired by 2020.

One further scenario, the "Recent Trends" path, assumes that the DPRK remains largely a closed economy, but continues to trade with China and others in quantities such that it is able to maintain its economy at close to current levels, with possible modest improvements in some sectors. This assumes that the DPRK's energy infrastructure, in particular its electricity generation and T&D infrastructure receives just enough investment to keep it from failing, but not enough to make significantly enhanced supplies of energy services available to the DPRK's citizens, at least on average. The Recent Trends case serves as a counterpoint to the scenarios above, but is not strictly comparable to them, because it does not produce the same level of economic activity or energy services.

Energy Path Results

Selected results of the evaluation of the paths described above are provided below. The results were prepared with LEAP.

Figure 5-19 shows final demand by fuel for the Redevelopment Path. Trends here of note after 2010 include the decrease in the use of biomass fuels, the increase in the use of electricity, and the introduction of natural gas after about 2016. Final demand by sector for the same path shows the increase, in future years, of consumption in the transport, public/commercial (commercial/institutional), and residential sectors relative to the industrial sector. Relative growth in residential sector energy use would be greater were it not for the gradual phasing out of biomass use in households.

Figure 5-19: Redevelopment Case Final Energy Use

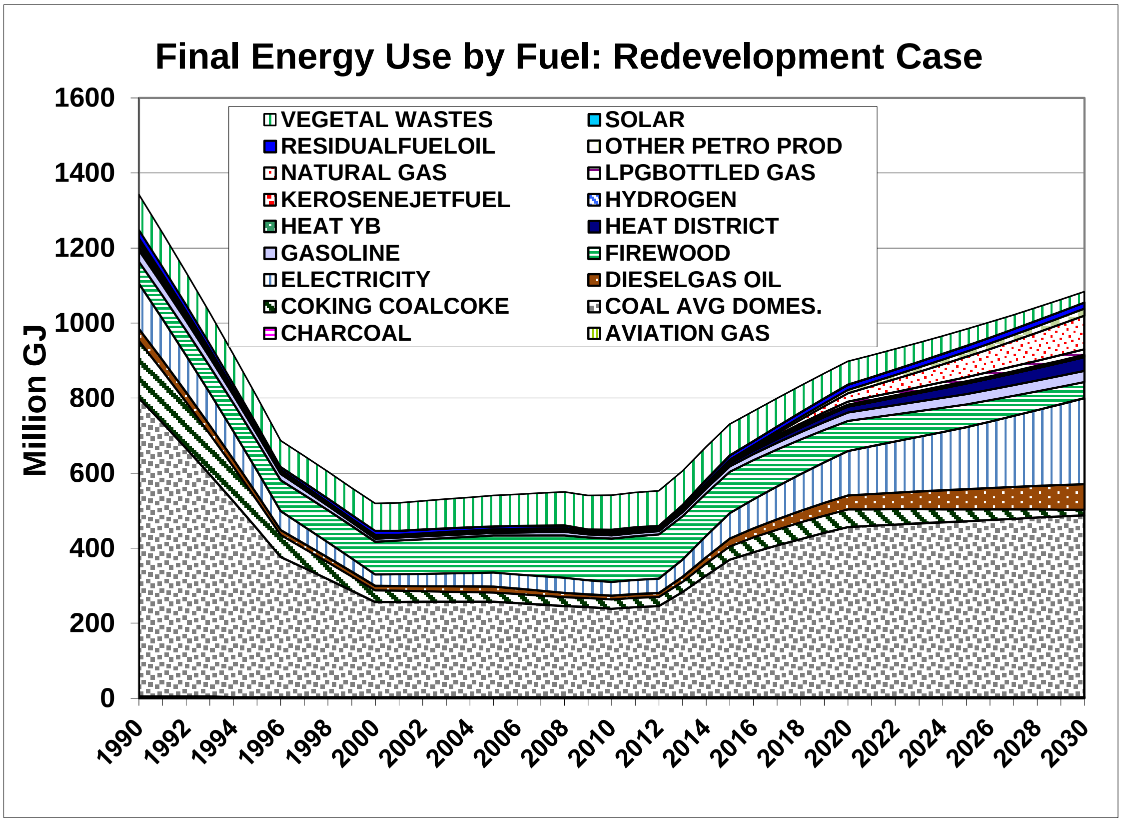
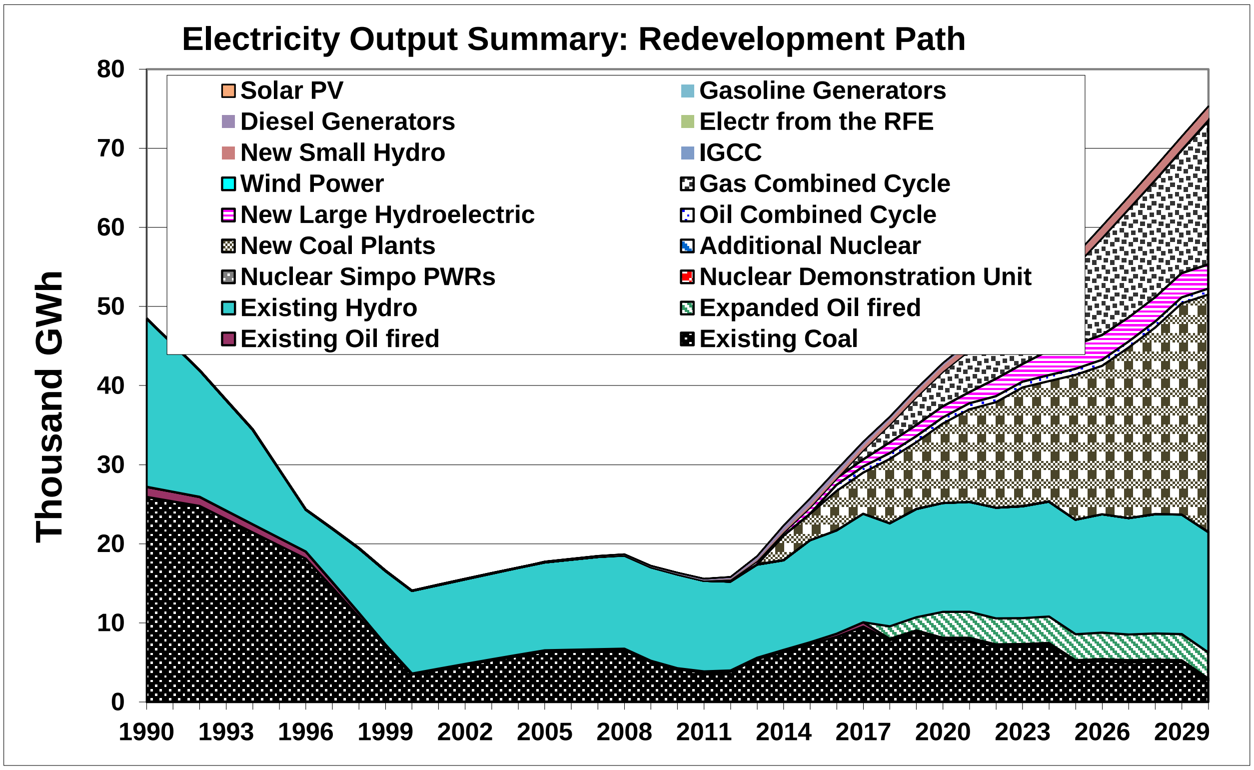


Figure 5-20 shows the changing patterns of electricity generation output by type of generator in the Redevelopment path. Other than hydroelectric generation, renewable energy plays only a small role in electricity production even as the DPRK redevelops. Existing and some new hydro remains a significant, though declining, portion of total capacity through 2030, but constitutes a smaller portion of output due to the limited capacity factor of hydro facilities (due to seasonal variations in water supply. As older coal plants are phased out, new coal plants and new gas combined cycle plants are brought on line, constituting a significant share of capacity, and a larger share of electricity output, by 2030.

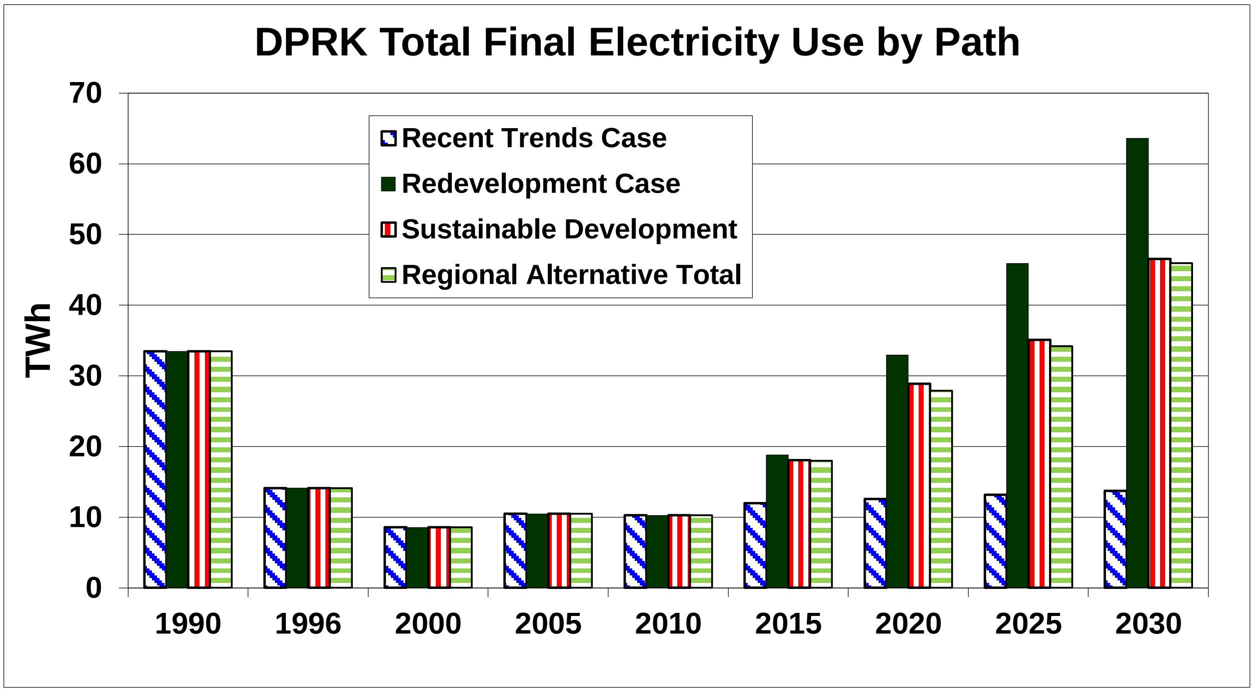
Figure 5-20: Redevelopment Case Electricity Output



The "Sustainable Development" path for the DPRK is an illustration of the potential impacts of applying a selected set of demand-side energy efficiency measures, together with expanded deployment of renewable energy systems (in this case, renewable electricity generation options). As such, it is designed to provide the same "energy services" (lighting, heating, cooking, transport, and industrial output, for example) as the Redevelopment case, but in a different way.

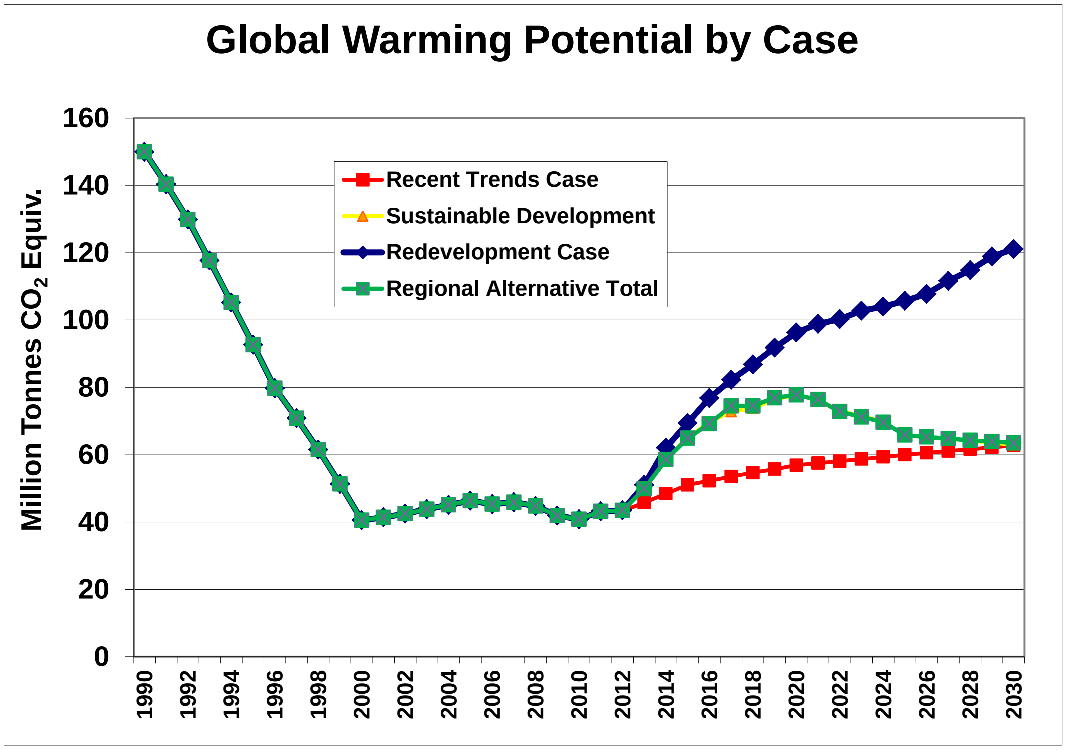
Figure 5-21 compares electricity use over time in the three main paths evaluated that include DPRK economic redevelopment, as well as in a "Recent Trends" path where a solution to the current impasse over the DPRK's nuclear program is not found, and large-scale economic redevelopment in the DPRK does not occur. Note that as a result of the aggressive implementation of energy efficiency measures, as noted above, the consumption of electricity (and thus the need for power generation facilities) is much less, by 2030, in the Sustainable Development and Regional Alternative paths, relative to the Redevelopment path. The reduced need for generation capacity is underlined by the result that in the Sustainable Development path, even with the incorporation of more low-capacity-factor renewable power sources, the overall generation capacity in 2030 is nearly 3000 MW less than in the Redevelopment path. This difference is significant in terms of avoided costs of generation capacity and of fuels for generation, as noted below.

Figure 5-21: Electricity Output by Path



The result of aggressive energy efficiency and renewable energy implementation in the Sustainable Development and Regional Alternative Paths is that air pollutant emissions (including carbon dioxide, as shown in Figure 5-22) are much lower in those paths by 2030. Though costs on the demand side (for higher-efficiency equipment) are considerably higher than in the Sustainable Development path than in the Redevelopment path, offsetting savings in the transformation sector (mostly due to the reduced need for electricity generation capacity) and in resources (avoided fuel production and imports) mean that the Sustainable Development path are less expensive than the Redevelopment path, overall.

Figure 5-22[200]: GWP by Case



5.6 Summary of Overall Northeast Asia Energy/Energy Policy Situation

The energy and, by extension, nuclear energy and nuclear spent fuel management situation in Northeast Asia is a mix of both shared and unique problems and approaches among a group of very different countries. Energy demand in the mature Japanese economy is not growing, and perhaps decreasing, as population begins to decline. The Fukushima accident has led Japan, more than any other nation, to rethink its national energy priorities. Though the jury is still out on how that re-think will affect nuclear power, it has already had a remarkable impact on deployment of renewable energy, and, to perhaps a lesser extent, energy efficiency. These developments may shake up Japan's energy sector in unexpected ways, in large part through their effect (together with that of the nuclear shut-down) on the finances of the large utility companies that dominate the energy sector, and their relationship with government. In Japan, significant growth in the nuclear energy sector seems unlikely.

Both energy demand and the nuclear sector in the ROK continues to grow, but at a decreasing rate. Very large scale additional deployment of new reactors in the ROK now seems unlikely.

[200] Global Warming Potential is a measure of how the radiative forcing of air pollutant emissions with direct or indirect impacts on climate compare, on a per unit basis, to that of Carbon Dioxide (CO_2). As such, it allows the tonnes of emissions of different pollutants to be totaled within a common metric, but CO_2 dominates the total.

Japan and the ROK share several conundrums. First, both are highly dependent on energy imports, which was a key driver of the development of nuclear energy in the first place. Second, both are running out of pool space to store spent nuclear fuel, are hamstrung by a combination of laws and regulations, and local opposition, with regard to siting of alternative at-reactor dry cask spent fuel storage. In addition, a lingering commitment among nuclear industry actors inside and outside of government to reprocessing in Japan, and to the not-yet-allowed (by the United States) pyroprocessing in the ROK, also acts to slow movement toward a sustainable spent fuel management solution.

China faces different issues. With significant resources of its own, though not enough to fuel its massive economic growth, its energy imports are increasing, but are not yet at the 90-plus percent level in the ROK and Japan. China's nuclear sector is young by comparison to Japan and the ROK, but growing fast, as most of the reactors built worldwide are being built in China. With a large land area and a not-yet-powerful civil society sector, siting of nuclear plants and spent fuel facilities is not yet a major problem for China, though it may grow to be so in the future. China's use of many different kinds of reactors, ordered and funded by different provinces, and only loosely coordinated with power grid development, may prove to be problematic soon, and may complicate nationally coordinated management of spent fuel.

Added to this mix are:

- Taiwan, also suffering from a lack of storage space for spent fuel, and facing difficulties in developing alternatives for spent fuel storage similar to those in Japan and the ROK.
- Mongolia, rapidly becoming a large exporter of coal and metals to (mostly) China, and with a large, open land area and a nuclear weapons-free zone status that, some have argued, may make it a potential host for a regional nuclear facility (though many Mongolians say otherwise);
- Russia, which would like to export oil, gas, and electricity to the major markets of the region, and has started to do so, albeit not to the extent that has been projected for many years; and
- The DPRK, which physically stands in the way of gas and electricity exports from Russia to the ROK, and whose relationship with its neighbors and the international community in general, specifically regarding its nuclear weapons program, but in many other ways as well, adds considerations to nuclear plans in the ROK and Japan, but at the same time, because of the desperate situation of its energy sector, may offer opportunities to catalyze energy cooperation in the region.

Overall, this complex and varied region shares many energy sector problems, though not all, and although cooperation on energy sector and nuclear sector (and other) issues has not generally been the hallmark of the region, cooperation may, in fact, bring mutual benefits, as discussed in the next Chapter of this Report.

6 Cooperation Scenarios on Spent Fuel Management in East Asia

Over the past two decades, economic growth in East Asia—and particularly in China, the Republic of Korea (ROK), Vietnam, Taiwan, and Indonesia—has rapidly increased regional energy requirements, especially electricity needs. Although economic growth slowed in much of the region during the global recession of 2008-2010, and electricity demand in Japan declined in the aftermath of the accident at the Fukushima reactor following the March, 2011 Sendai earthquake and Tsunami, overall growth in demand for electricity in the region continues. As a recent, eye-opening example of these increased needs, China added nearly 100 GW of generating capacity—more than the total generation capacity in the ROK as of 2010—between 2009 and 2010 alone. Despite efforts to boost hydroelectric and other renewable generation, the vast bulk of the capacity Chinas adds each year is coal-fired, underlining concerns regarding the global climate impacts of steadily increasing coal consumption.

With the lessons of the "energy crises" of the 1970s in mind, several of the countries of East Asia—starting with Japan in the mid-1970s, and continuing with the ROK, Taiwan, and, in the early 1990s, China—have sought to diversify their energy sources and bolster their energy supply security, as well as achieving other policy and social objectives, by developing nuclear power. Several other East Asian nations are currently discussing adopting nuclear power as well, if not, like Vietnam, taking concrete steps toward developing their own nuclear facilities. At the same time, global security concerns related to terrorism and to the nuclear weapons activities of the Democratic People's Republic of Korea (DPRK), Pakistan, and India, as well as the (nominally peaceful) uranium enrichment programs pursued by Iran and, as revealed publically in 2010, the DPRK, have focused international concern on the potential for proliferation of nuclear weapons capabilities associated with nuclear power. In addition, old concerns regarding the management of nuclear spent fuel and other wastes, including the safety and long-term implications of various means of spent fuel management and/or disposal, as well as the siting of spent fuel facilities, remain, at best, only partially addressed.

One means of addressing proliferation concerns, reducing environmental and safety risks of nuclear power, and possibly of modestly reducing the costs of nuclear energy to the countries of the region, is regional cooperation on nuclear fuel activities. A number of proposals for regional cooperation on safety, enrichment, spent-fuel and waste management, and other issues have been offered over the years, some from within the region, and some from outside the region. The net impact, however, of regional nuclear cooperation on the energy security—expressed broadly to include supply security, economic impacts, environmental security, and security related to social and military risks—requires a more detailed look at how cooperation on nuclear power might be organized and operated. Working with a network of collaborating teams in nine countries of the region, Nautilus Institute has defined several different scenarios for nuclear fuel cycle cooperation in East Asia, evaluated those scenarios under different sets of assumptions regarding the development of nuclear power in the region. These evaluations of the physical flows of nuclear fuel cycle materials and services, and of the costs of different elements of the fuel cycle, help to shed light on the relative readily quantifiable costs and benefits of different regional fuel cycle cooperation options. At least as important, however, are the relative impacts of different fuel cycle options on other aspect of (broadly defined) energy security, which can be evaluated qualitatively.

East Asia and the Pacific includes three nuclear weapons states—including the United States based on its physical proximity and presence in several territories, as well as its geopolitical and cultural importance in the region—plus one (the DPRK) that is nuclear-armed since 2006. The region also includes three major economies that are nearly completely dependent on energy imports and for which nuclear energy plays a key role, a nuclear materials supplier nation currently without commercial reactors of its own, and at least two populous and fast-developing nations with stated plans to pursue nuclear energy. Table 6-1 provides a summary of the status of major nuclear fuel-cycle activities in each country covered by the analysis summarized here. To this listing can be added Mongolia, which has significant uranium resources and a history of uranium production and exploration during Soviet times. Though Mongolia has no other active commercial nuclear facilities, its involvement in regional nuclear fuel cycle activities related to uranium supply has been proposed.[201] Mongolia's status as a nuclear weapons-free state, a process begun in 1992 and recently (2012) formalized through recognition by the five permanent members of the United Nations Security Council,[202] also potentially makes it an interesting "player" in nuclear weapons policy in the region, though when one of the authors of this Report visited Mongolia, the officials he talked with seemed less than enthusiastic about Mongolia's participation in nuclear activities, and indicated that recent energy policies omit nuclear power and related endeavors.[203]

[201] Agvaanluvsan, U. (2009), "The Global Context of Nuclear Industry in Mongolia". Mongolia Today, the Mongolian National News Agency, December 2009, available as http://iis-db.stanford.edu/pubs/22822/AgvaanluvsanMongolia_nuclear_industry.pdf. See also, for example, J. Berkshire Miller (2012), "Mongolia Eyes Nuclear Ties", *The Diplomat*, March 6, 2012, available as http://thediplomat.com/flashpoints-blog/2012/03/06/mongolia-eyes-nuclear-ties/.
[202] See, for example, Daryl G. Kimball (2012), "Mongolia Recognized as Nuclear-Free Zone", Arms Control Today, October 2012, available as http://www.armscontrol.org/act/2012_10/Mongolia-Recognized-as-Nuclear-Free-Zone.
[203] David von Hippel's personal communication with Mongolian officials, 2013 and early 2014.

Table 6-1: Summary of Nuclear Energy Activities in East Asia/Pacific Countries

Country	Nuclear Generation	Front-end Fuel Cycle Activities	Back-end Fuel Cycle Activities
Japan	Mature nuclear industry (~47 GWe as of 2010) with continuing slow growth until Fukushima accident. Post-Fukushima 4 units closed, all other power reactors in Japan shut down for inspection as of late May, 2012[204]; some since at least briefly restarted, including Sendai units in late 2015/early 2016	No significant mining, milling. Some domestic enrichment, but most enrichment services imported.	Significant experience with reprocessing, including commercial-scale domestic facility now in testing (though much delayed), plus significant reprocessing in Europe; interim spent-fuel storage facility in use.
ROK	Mature nuclear industry, 23 units totaling 20.7 GWe at 4 sites as of early 2014[205].	No significant uranium (U) resources, enrichment services imported, but all fuel fabrication done domestically.	No reprocessing, but “pyroprocessing” under consideration; at-reactor spent fuel storage thus far.
DPRK	Had small (5 MWe equivalent) reactor for heat and plutonium (Pu) production, partly decommissioned, now at least intermittently back in operation; policy to acquire LWRs, and currently building LWR with domestic technology estimated at 100 MWth[206] (see section 2.7 of this Report).	At least modest uranium resources and history of U mining; some production exported; operating 2000-centrifuge enrichment plant recently revealed.[207]	Reprocessing of spent fuel from 5 MWe reactor to separate Pu for weapons use. Arrangements/plans for spent fuel management for new reactor unknown.
China	Relatively new but rapidly-growing nuclear power industry; 26.9 GWe in 30 units as of 2016.[208]	Domestic enrichment and U mining/milling, but not sufficient for large reactor fleet.	Nuclear weapons state. Small reprocessing facility; plans underway for spent fuel storage facilities.

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[204] Akira Nagano (2012), “Current Status and Efforts in Japan after Fukushima Accident”, JAIF International Cooperation Center (JICC), June, 2012, available as http://www.iaea.org/NuclearPower/Downloads/Infrastructure/meetings/2012-06-18-20-TM-Vienna/10.Status_and_Efforts_after_Fukushima.pdf.
[205] See, for example, World Nuclear Association (2014), “Nuclear Power in South Korea”, dated 30 January 2014, and available as http://www.world-nuclear.org/info/Country-Profiles/Countries-O-S/South-Korea/.
[206] This thermal output is the equivalent of approximately 25-30 MWe.
[207] Hecker, S.S. (2010), A Return Trip to North Korea’s Yongbyon Nuclear Complex. NAPSNet Special Report, dated November 22, 2010, and available as http://www.nautilus.org/publications/essays/napsnet/reports/a-return-trip-to-north-korea2019s-yongbyon-nuclear-complex.
[208] World Nuclear Organization (2016), “Nuclear Power in China”, dated March, 2016, available as http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx.

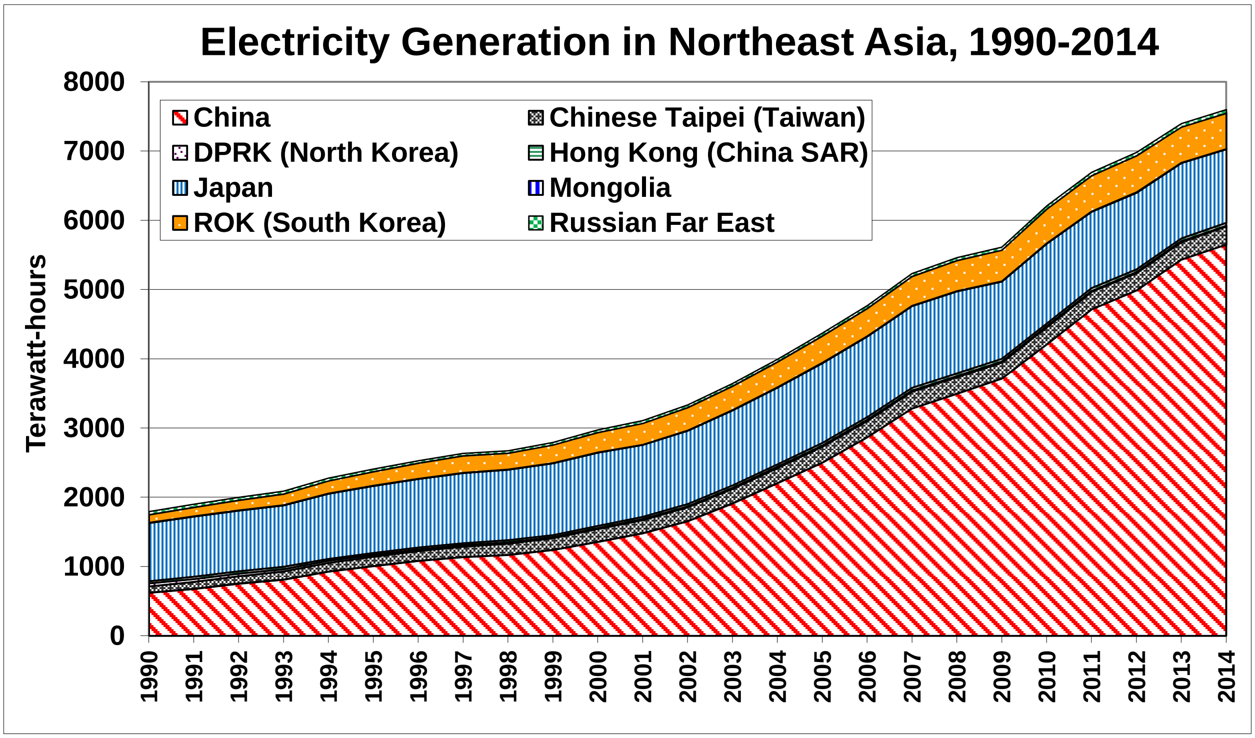
Country	Nuclear Generation	Front-end Fuel Cycle Activities	Back-end Fuel Cycle Activities
Russian Far East (RFE)	One small plant (48 MWe) in far North of RFE, with others planned. (Russia itself has a large reactor fleet); plans for larger (1 GWe scale) units for power export.	Domestic enrichment and U mining/milling (but not in the RFE).	Nuclear weapons state. Russia has reprocessing facilities, spent fuel storage facilities (but not in RFE).
Australia	No existing reactors above research scale; has had plans to build power reactors, but currently very uncertain.	Significant U mining/milling capacity, major U exporter (over 6000 t U in 2011[209]); no enrichment.	No back-end facilities.
Taiwan	~5 GWe in 6 reactors at 3 sites, 2 additional units at 4th site under construction since late 1990s, but their completion is under review post-Fukushima, with conversion to gas being investigated[210].	No U resources, no enrichment—imports enrichment services.	Current spent-fuel storage at reactor, no reprocessing. Siting of low-level waste and intermediate spent fuel storage under discussion.
Indonesia	No current commercial reactors, but full-scale reactors planned.	Some U resources, but no production; no enrichment.	Consideration of back-end facilities in early stages.
Vietnam	No current commercial reactors, but a number of full-scale reactors planned, with agreements signed recently with Russia, Japan, ROK for reactor construction and finance.[211] Enthusiasm for nuclear power in Vietnam seems to have waned in recent years.[212]	Some U resources, but no production; no enrichment.	Consideration of back-end facilities in early stages.

[209] World Nuclear Association (2012), "Australia's Uranium", updated 14 November 2012, and available as http://www.world-nuclear.org/info/inf48.html. Note that 2010 and 2011 production was substantially lower than the average of over 8000 t U per year in the previous decade (2000-2009).
[210] See, for example, Platts (2012), "Taiwan mulls conversion of under-construction nuclear power plant to gas-fired", dated November 1, 2012, and available as http://www.platts.com/RSSFeedDetailedNews/RSSFeed/ElectricPower/7213676.
[211] See, for example, World Nuclear Association (2012), "Nuclear Power in Vietnam" updated November 2012, and available as http://www.world-nuclear.org/info/vietnam_inf131.html.
[212] David von Hippel, personal communication with Vietnamese officials. The Vietnamese economy has not performed as well as hoped, and although nuclear plants remain of interest in Vietnam, it appears that the cost of the plants may become more of a barrier to large-scale adoption of the technology.

6.1 Current Status of Electricity Consumption and Nuclear Generation

Recent growth in electricity generation and use in East Asia has been remarkable. As an example, Figure 6-1: Electricity Generation in Northeast Asia, 1990-2011 shows total electricity generation in the Northeast Asia region more than tripled between 1990 and 2014, with generation in China increasing by more than a factor of nine, generation in Taiwan increasing by a factor of nearly three, and generation in the ROK increasing by a factor of 4.4. Even though electricity production in Japan—which in 1990 had the highest generation in the region—grew by only 28 percent (an average of 1.1 percent annually), the fraction of global generation accounted for by the Northeast Asia region grew from just over 15 percent in 1990 to over 32 percent in 2011, even as electricity generation in the rest of the world grew at an average rate of 2.0 percent annually.

Figure 6-1: Electricity Generation in Northeast Asia, 1990-2011



Sources: Data from British Petroleum "Statistical Review of World Energy 2015" workbook[213] for all countries except the DPRK (based on updated Nautilus Institute results not yet published[214]), Mongolia (based on data from USDOE/EIA[215]), and RFE (estimated from paper by Gulidov and Ognev[216]). Generation figures shown are for gross generation (that is, including in-plant electricity use), except for Mongolia and the RFE.

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[213] File downloaded 3/8/15 from http://www.bp.com/content/dam/bp/excel/energy-economics/statistical-review-2015/bp-statistical-review-of-world-energy-2015-workbook.xlsx.

[214] See D. von Hippel and P. Hayes (2012), Foundations of Energy Security for the DPRK: 1990-2009 Energy Balances, Engagement Options, and Future Paths for Energy and Economic Redevelopment, Nautilus Institute Special Report, dated September 13, 2012, and available as http://nautilus.wpengine.netdna-cdn.com/wp-content/uploads/2012/12/1990-2009-DPRK-ENERGY-BALANCES-ENGAGEMENT-OPTIONS-UPDATED-2012_changes_accepted_dvh_typos_fixed.pdf, for an earlier version of the updated DPRK electricity generation results used for this figure.

[215] United States Department of Energy, Energy Information Administration (2016), "International Energy Statistics, Mongolia", with data on net electricity generation available as http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=2&pid=2&aid=12&cid=MG,&syid=1980&eyid=2012&unit=BKWH. .

[216] Gulidov R. and A. Ognev (2007), "The Power Sector in the Russian Far East: Recent Status and Plans", prepared for the 2007 Asian Energy Security Project Meeting "Energy Futures and Energy Cooperation in the Northeast Asia Region", Tsinghua University, Beijing, China, October 31 – November 2, 2007. Presentation available at http://nautilus.wpengine.netdna-cdn.com/wp-content/uploads/2011/12/Russia-Energy-Changes.ppt.

Against this backdrop of growth in electricity needs—existing "business as usual" projections call for continuing strong increases in electricity use in the countries of East Asia (with the possible exception of Japan)—many of the countries of the region face significant energy resource constraints. The industrialized economies of Taiwan, the ROK, and Japan import over 90 percent of their energy needs. Vietnam and Indonesia, though they have been net energy exporters for several decades, are at or near the point where they will become net importers. China, though endowed with large reserves of coal and significant oil and gas reserves, is obliged to meet the energy needs of an increasingly affluent 1.3 billion people, and the economy that sustains them. As a result, China is increasingly an energy importer as well. The sparsely settled Russian Far East has a vast resource endowment—including hydraulic energy, coal, oil, and natural gas—that could potentially be harnessed for export to its neighbors. A combination of severe climatic conditions, politics, and huge financial requirements for the infrastructure needed to accomplish oil, gas, and power exports have slowed development of these resource sharing schemes. Even massive international pipelines and powerlines, however, will only make a modest contribution to the energy needs of Russia's energy-hungry neighbors.[217]

The resource constraints faced by most of the nations of the region, together with the technical allure of nuclear power, have made East Asia a world center for nuclear energy development, and—news reports of a global nuclear renaissance notwithstanding—one of the few areas of the world where significant numbers of nuclear power plants are being added. Nations have chosen nuclear power because they wish to diversify their energy portfolios away from fossil fuels (especially oil) and thus improve their energy supply security, because nuclear power provides a stable sources of baseload power with low air pollutant emissions (particularly compared with coal), and for the less practical but still significant reason that being a member of the nuclear energy "club" is seen as offering a certain level of status in the international community.

6.2 Future Nuclear Capacity Scenarios

Table 6-2 and Table 6-3 summarize the nuclear capacity included for each the three nuclear capacity expansion paths (Business as Usual, Maximum Nuclear, and Minimum Nuclear) for each country for the years 2010, 2030, and 2050. Figure 6-2 shows the capacity trend by year and country for the Business as Usual path. For the years through 2030 or 2035, assumptions for China, the DPRK, and the ROK are as described in the relevant sections of Chapters 3 and 5 of this Report. Results for years from 2030 or 2035 through 2050 in those nations are either taken from work by country teams or extrapolated from work by country teams. Assumptions for Japan are based on recent work by Nautilus, but informed by the data in the Japan subsections of Chapters 3 and 5 of this Report.[218] Key assumptions and results by

[217] See, for example, von Hippel, D.F., and P. Hayes (2008), Growth in Energy Needs in Northeast Asia: Projections, Consequences, and Opportunities. Paper prepared for the 2008 Northeast Asia Energy Outlook Seminar, Korea Economic Institute Policy Forum, Washington, DC, May 6, 2008, and available as http://s3.amazonaws.com/zanran_storage/www.keia.org/ContentPages/44539229.pdf.

[218] The three nuclear generation paths for Japan are based on three "Nuclear Restart" paths, the development and evaluation of which are described in the forthcoming Nautilus Institute Special Report David F. von Hippel and

country used to determine nuclear capacity and output for the other nations of East Asia and the Pacific are as follows:

- The **Russian Far East** adds some capacity between about 2020 and 2050 in the BAU case to its very small existing reactors in the far north. This capacity is mostly to serve export markets and/or to provide power for producing export commodities such as aluminum. In the MAX case, future capacity is approximately twice that in the BAU case, reflecting a stronger market for RFE power and/or minerals exports. In the MIN case, only one new (larger) reactor is added in the RFE by 2030, and no more thereafter.
- In **Taiwan**, as in Japan and the ROK, limited space for new reactors and a declining population limit the extent to which nuclear capacity can increase. In the BAU case, capacity increases by 2 GW, as a result of finally completing the reactors now under construction, but remains at the resulting 7 GW level through 2050. In the MAX case, larger reactors are added at existing sites when older reactors are decommissioned, pushing capacity to nearly 11 GW by 2050. In the MIN case, older reactors are not replaced, and the reactors now under construction are not completed, resulting in Taiwan's nuclear generation capacity falling to zero by 2036.
- For **Indonesia, Vietnam**, and **Australia**, which do not have and are not yet building nuclear power capacity, the BAU case includes first reactors that come on line between 2020 and 2030 in Vietnam and Indonesia, with Vietnam's program being much more aggressive than in the other two nations[219]. The MAX path includes greater use of nuclear power for each nation by both 2030 and 2050. Australia is assumed not to adopt nuclear power in the BAU path. In the MIN path only Vietnam adopts nuclear power, but builds only its first two reactors, which come on line several years later than expected. Neither Indonesia nor Australia ultimately adopts nuclear power in the MIN path.

Peter Hayes (2016), *Japan's Post-Fukushima Choice: Future Nuclear Fuel Cycle Paths and Their Implications*, dated March, 2016.

[219] For Vietnam, the "BAU" path is based roughly on a combination of projections from Pham, K.T. (2007), "Vietnam Energy Review and Power Development Plan: Period 2006 - 2015 with outlook to 2025", prepared for the "Asian Energy Security Project Meeting", Beijing, PRC, October 31-November 2, 2007, and available as http://nautilus.wpengine.netdna-cdn.com/wp-content/uploads/2011/12/Vietnam-Energy.ppt; and World Nuclear Association (2012) "Nuclear Power in Vietnam", dated November, 2012, and available as http://www.world-nuclear.org/info/vietnam_inf131.html. For Indonesia, we assume that the first set of reactors referenced in Indriyanto A.R.S., B. T. Wattimena, and F. V. C. Mulia (2007), "Indonesia Energy Overview" (prepared for the "Asian Energy Security Project Meeting", Beijing, PRC, October 31-November 2, 2007, and available as http://nautilus.wpengine.netdna-cdn.com/wp-content/uploads/2011/12/Indonesian-Energy.ppt), are delayed but ultimately built in the BAU case in 2023/2024. For Australia, the MAX path includes about 50 percent of the additions suggested by the "Zwitkowski taskforce", as quoted in Falk, J. (2007), "Energy in Australia", prepared for the 2007 Asian Energy Security Project Meeting "Energy Futures and Energy Cooperation in the Northeast Asia Region", Tsinghua University, Beijing, China, October 31 - November 2, 2007, and available at http://nautilus.wpengine.netdna-cdn.com/wp-content/uploads/2011/12/Australia-Nuclear.ppt.

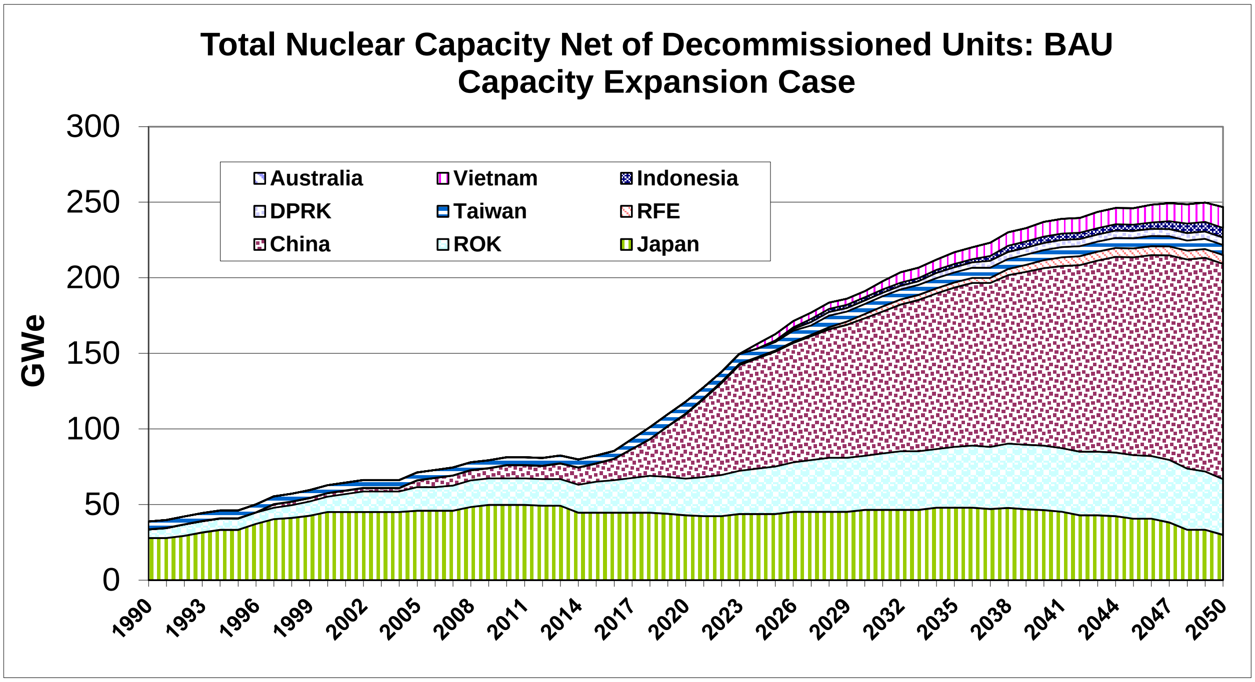
Table 6-2: Table 2: Regional Nuclear Generation Capacity, Summary of BAU, MAX, and MIN Paths

	Total Nuclear Capacity Net of Decommissioned Units (GWe)								
	BAU (Reference) Case			Maximum Nuclear Case			Minimum Nuclear Case		
Nation	2010	2030	2050	2010	2030	2050	2010	2030	2050
Japan	49	46	26	49	56	33	49	26	2
ROK	18	39	34	18	39	50	18	29	26
China	10	100	150	10	150	286	10	80	110
RFE	0	3	6	0	6	11	0	1	1
Taiwan	5	7	7	5	4	-	5	3	3
DPRK	-	2	5	-	5	11	-	0.13	0.33
Indonesia	-	2	6	-	4	13	-	-	-
Vietnam	-	7	14	-	12	24	-	2	2
Australia	-	-	-	-	3	13	-	-	-
TOTAL	82	207	247	82	279	442	82	141	144

Table 6-3: Regional Nuclear Electricity Output, Summary of BAU, MAX, and MIN Paths

	Total Nuclear Electricity Output (TWhe)								
	BAU (Reference) Case			Maximum Nuclear Case			Minimum Nuclear Case		
Nation	2010	2030	2050	2010	2030	2050	2010	2030	2050
Japan	288	206	162	288	304	219	288	69	6
ROK	141	307	266	141	307	396	141	230	203
China	71	776	1,168	71	1,155	2,231	71	623	857
RFE	0	23	41	0	41	77	0	6	6
Taiwan	40	50	50	40	29	-	40	21	21
DPRK	-	16	35	-	34	89	-	1	2
Indonesia	-	16	47	-	31	94	-	-	-
Vietnam	-	51	103	-	88	177	-	17	17
Australia	-	-	-	-	24	102	-	-	-
TOTAL	541	1,444	1,871	541	2,013	3,385	541	966	1,111

Figure 6-2: Trends in Regional Nuclear Generation Capacity, BAU Path



As noted above, Nautilus has worked with colleagues in the region to analyze four cooperation "scenarios" for nuclear fuel enrichment and for spent fuel management. The scenarios, and some (but hardly all) of the key policy issues they suggest, are as follows:

1. "**National Enrichment, National Reprocessing**": In this scenario the major current nuclear energy users in East Asia (Japan, China, and the ROK), and perhaps others as well, each pursue their own enrichment and reprocessing programs. Disposal of high-level nuclear wastes from reprocessing would be up to each individual country, with attendant political and social issues in each nation. Security would be up to the individual country, and as a result, transparency in the actions of each country is not a given.
2. "**Regional Center(s)**": This scenario features the use of one or more regional centers for enrichment and reprocessing/waste management, drawn upon and shared by all of the nuclear energy users of the region. We avoid identifying particular country hosts for the facilities, but China and Russia are obvious candidates.
3. "**Fuel Stockpile/Market Reprocessing**": Here, the countries of the region purchase natural and enriched uranium internationally, but cooperate to create a fuel stockpile that the nations of the region can draw upon under specified market conditions. Reprocessing services are purchased from international sources, such as France's AREVA or from Russia, while some spent fuel continues to be stored in nations where nuclear generation is used.

4. "**Market Enrichment/Dry Cask Storage**": In this, likely the least expensive of the four scenarios for participants, countries in the region (with the possible exception of China) would continue to purchase enrichment services from international suppliers such as URENCO in Europe, the USEC in North America, and Russia. All spent fuel, after cooling in ponds at reactor sites, would be put into dry cask storage either at reactor sites or at intermediate storage facilities.

In section 6.1, below, we summarize some of the key results of these scenarios, and briefly explore some of the ramifications of the scenarios with regard to radiological risk of accident at or attack on nuclear facilities, as well as other risks associated with the nuclear fuel cycle. Sections 6.2 and 6.3 present, respectively, key assumptions used in the evaluation of the cooperation scenarios, and the results of the analysis of the scenarios. Section 6.4 provides additional summary results and conclusions.

6.3 Summary of Cooperation Scenario Findings

The results of the regional scenario evaluation indicates that Scenario 4, which focuses on at-reactor dry cask storage and coordinated fuel stockpiling, but largely avoids reprocessing and mixed-oxide fuel use, results in lower fuel-cycle costs, and offers benefits in terms of social-cultural and military security. These results are consistent with broader studies by other research groups.

Scenario 1, by using much more domestic enrichment and reprocessing than the other scenarios, arguably improves energy supply security (narrowly defined) for individual nations, but results in higher technological risk due to national reliance on one or a small number of enrichment and reprocessing plants, rather than the larger number of plants that constitute the international market. Scenario 1 would also raise significant proliferation concerns, not the least of which would be the DPRK's, and to some extent, Japan's reaction to ROK enrichment and reprocessing, were the United States to allow the ROK to move forward with pyroprocessing. Scenario 1 also results in the build-up of stockpiles of plutonium (or minimally-adulterated Pu) in each of the nations pursuing reprocessing. Though the magnitude of the plutonium stockpiles, and the rate at which they are used, varies considerably by nuclear path and scenario, the quantities accrued, in the range of 100 to over 200 tonnes of Pu at a maximum in Scenarios 1 through 3 in the years around 2040, are sufficient for tens of thousands of nuclear weapons, meaning that the misplacement or diversion of a very small portion of the stockpile becomes a serious proliferation issue, and thus requires significant security measures in each country where plutonium is produced or stored. Scenario 4, without additional reprocessing, maintains today's stockpile of about 70 tonnes of Pu, mostly from the Japanese reprocessing (domestic and contracted) program to date. This still represents a serious proliferation risk, but at least does not add to existing stockpiles or create stockpile in new places.

Scenarios 1 through 3, which include reprocessing, result in higher annual costs—about $3 billion per year higher in 2050 relative to Scenario 4—over the entire region. Scenarios 1 through 3 reduce the amount of spent uranium oxide fuel to be managed substantially, but imply additional production of many thousands of cubic meters of high-level waste that must be managed instead (versus about 300 cubic meters in Scenario 4). This in addition to medium- and low-level wastes from reprocessing, and wastes from MOx fuel fabrication that must be managed in significant quantities in Scenarios 1 through 3, but not in Scenario 4. Scenarios 1 through 3 offer a modest reduction—less than10 percent in for the BAU nuclear capacity paths case—in the amount of natural uranium required region-wide, and in attendant needs for enriched uranium and enrichment services. This reduction is not very significant from a cost perspective unless uranium costs rise much, much higher in the next four decades, and recent trends in both raw uranium and enrichment costs have been much in the opposite direction in the post-Fukushima era.

Scenarios 2 and 3, though they include reprocessing, place more of the sensitive materials and technologies in the nuclear fuel cycle in regional and international facilities, and as a consequence, are likely to be superior to Scenario 1 in terms of reducing proliferation opportunities, reducing security costs, and increasing the transparency of (and thus international trust in) fuel cycle activities. Scenarios 2 and 3 result in significantly more transport of nuclear materials—particularly spent fuel, enriched fuel, MOx fuel, and possibly high-level wastes around the globe, likely by ship, than Scenario 1, though there would be somewhat more transport of those materials inside the nations of East Asia in Scenario 1.

6.3.1 Implications of Cooperation Scenarios in Consideration of Other Project Findings

Some of the key implications of the cooperation scenario analyses summarized in this Chapter, when combined with the other findings of this project, has a number of ramifications.

First, it is clear that the costs of fuel cycles including reprocessing will be higher than those including alternative methods of spent fuel storage, including dry cask at-reactor or centralized storage unless the costs of raw uranium and enrichment services rise far higher than levels of the recent past. Using base-case assumptions, scenarios involving reprocessing by 2050 are projected to cost several billion dollars per year, region-wide, more than "once through" scenarios in which spent fuel is simply placed in dry cask storage after a period of cooling in spent fuel pools.

That said, even several billion in the full context of the region's electricity system as of 2050 is a trivial sum of money. All of the fuel-cycle costs tracked in this analysis amount to on the order of one percent of overall power costs, and are thus dwarfed by uncertainties in the future costs of electricity provision. Future electricity costs are rendered uncertain by potential changes in costs of generation technologies, costs associated with climate change mitigation (for example, carbon taxes) and pollution reduction, or costs related to regulatory compliance, particularly as civil society becomes more active in scrutinizing infrastructure plans in the region.

These findings with regard to the relative overall direct financial cost of different cooperation options suggest that decisions with regard to how spent fuel is managed, and whether cooperation is attractive for spent fuel management, largely boil down to political decisions that weigh proliferation and radiological risks with other, largely non-cost factors. This is not to say that certain nuclear sector actors—including nuclear plant operators, nuclear technology vendors, government regulators, and, ultimately, consumers, may be affected economically in different ways, but the overall unit costs of nuclear electricity generation to society are affected relatively little by spent fuel management decisions.

If the conclusion holds that management of spent fuel will, or should, if incentives are properly structured, be decided by non-economic criteria, actual and perceived radiological risk from spent fuel management approaches becomes a more critical factor in the overall calculus, as does proliferation concerns. Both considerations point toward expanded use of dry cask storage in the near-term to reduce dense-packing in spent fuel pools in Japan and the ROK (and Taiwan), and to avoiding reprocessing. Getting spent fuel out of dense-packed pools and into much more attack- and accident-resistant dry casks is a key to reducing the radiological risk associated with accidents or non-state attack at nuclear energy facilities. Potential radiological risks associated with reprocessing facilities, though not a central topic of this project, would also be reduced by not moving forward with reprocessing, and by placing the spent fuel now in inventory at reprocessing plants into dry-cask storage.

Further, an emphasis on dry-cask storage in the near- and medium-term provides time for technologies for long-term storage and/or disposal of spent fuel and other similarly radioactive wastes (including HLW from reprocessing and wastes from the Fukushima accident) to mature. This could include both geologic storage/disposal and deep borehole disposal, both of which will require decades for research, design, and siting.

Regional cooperation in the nuclear fuel cycle could include shared uranium provision and enrichment services, but regional cooperation in spent fuel management pertains more directly to the current project. Regional cooperation could contribute to spent fuel management by establishing or strengthening regimes for the oversight of nuclear fuel cycle activities and accounting for nuclear materials. Given the difficulties that some nations, most notably Japan and the ROK (and Taiwan) face in siting interim or out-of-pool at-reactor storage of spent fuel, it is possible that regional cooperation could help to facilitate the establishment of intermediate, shared away-from-reactor storage facilities. Further, international cooperation will, as noted in Chapter 4 of this Report, be very helpful in undertaking deep borehole disposal of nuclear spent fuels, as it will both help to spread the costs of R&D, and help to overcome reluctance on the part of nuclear sector actors in individual countries to explore new options for spent fuel management.

Additionally, in the long run, if deep borehole disposal is to be undertaken, it may be that its operation on a regional scale will offer benefits in terms of accounting for nuclear materials disposed of, and thus build confidence between the nations of the region in the transparency of nuclear sector activities in other nations. This will likely be particularly critical if, ultimately, existing (or, if reprocessing starts/continues in nations of the region, new) stocks of plutonium are disposed of by blending with other materials, followed by deep borehole disposal. The process of accounting for plutonium disposal is particularly critical because diversion of even a small fraction of existing stocks poses the threat of proliferation of nuclear weapons and/or "dirty bombs", thus clear and open accounting for all of the nuclear materials disposed of in deep boreholes (or, for that matter, by other means) is crucial for maintaining the integrity of disposal practices from a non-proliferation perspective.

6.4 Regional Scenarios for Cooperation on Spent Fuel Management

Cooperation on nuclear fuel cycle activities could take place between all of the countries of East Asia and the Pacific, or a narrower group of several countries within the region, or a broader group of countries that could include nations outside the region. At their least demanding (in terms of costs and institutional arrangements between nations), cooperation options can involve relatively modest types of activities such as straightforward scientific, educational, and technical exchanges, or collaborations—for example, through the International Atomic Energy Agency (IAEA) or other international agencies—on sharing of information on nuclear "best practices". More complex options include consortiums for purchasing of raw uranium or of enriched fuel. More complex still are arrangements to share enrichment and spent-fuel management facilities. An IAEA Expert Group in 2005 produced a generic review of multilateral approaches to the nuclear fuel cycle, and some of that group's observations and suggestions are reflected in the proposals by other groups summarized below, as well as in the regional cooperation scenarios elaborated and evaluated in this paper[220]. A few of the benefits—and challenges—of regional cooperation on nuclear fuel cycle issues are listed below[221].

6.4.1 Potential Benefits and Challenges of Cooperation

Some of the benefits of cooperation on nuclear fuel cycle issues could include:

- Scientific, educational, and technical exchanges on nuclear fuel cycle issues help to assure that countries have a common understanding and knowledge base with regard to fuel cycle issues.
- Sharing nuclear facilities, whether enrichment, reprocessing, or spent-fuel facilities, provides viable alternative for countries that may, due to political, social, geological, or other concerns, have few positive prospects for domestic siting of such facilities.
- Achieving economies-of-scale for enrichment facilities, reprocessing centers, or geologic repositories, though economies of scale likely are stronger for some types of facilities—such as enrichment plants or mined geologic repositories—than for others, such as spent-fuel storage based on dry-cask technologies[222] (Bunn and et al., 2001).
- Creating a new revenue source for a host country.
- Sharing nuclear facilities may help to assure that all countries maintain consistent practices and quality control standards in working with nuclear materials, as well as consistent levels

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[220] International Atomic Energy Agency (IAEA, 2005), *Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report submitted to the Director General of the International Atomic Energy Agency*. Document # INFCIRC/640, dated 22 February 2005, and available as http://www.iaea.org/Publications/Documents/Infcircs/2005/infcirc640.pdf.

[221] Kang, J. (2007), *Regional Spent Fuel Management in Northeast Asia: Status, Initiatives, and Issues*. Prepared for the Nautilus Institute East Asia Science and Security Collaborative project

[222] Bunn, M. and et al. (2001), *Interim Storage of Spent Nuclear Fuel: A Safe, Flexible, and Cost-Effective Near-Term Approach to Spent Fuel Management*. A Joint Report from the Harvard University Project on Managing the Atom and the University of Tokyo Project on Sociotechnics of Nuclear Energy. June 2001. Available as http://www.whrc.org/resources/publications/pdf/BunnetalHarvardTokyo.01.pdf.

of safeguards, monitoring, and verification in nuclear fuel cycle activities, helping to build confidence between nations.

- Sharing of spent-fuel and reprocessing facilities can help to reduce proliferation risks by avoiding unnecessary accumulation of separated plutonium.

Implementing regional or international facilities, including those for spent fuel/radioactive waste storage/disposal, also will likely involve overcoming obstacles such as:

- Ethical issues in the region. There is some public perception that countries that have the benefits of nuclear power generation should bear the burden of storing and disposing of their radioactive wastes. This argument raises ethical and fairness issues that would oppose the concept of a regional/international repository. To obtain public and political support, an arrangement for the regional/international repository should be based on a fair and equitable sharing of benefits between a repository host and other participating countries.
- Complicating national policies in the management of spent fuel and high-level waste (HLW). A regional/international repository could distract national spent fuel and radioactive waste management programs with hopes for an international facility.
- Increasing transportation requirements in the region. The regional/international repository will involve frequent transportation of spent fuel/radioactive waste from participating countries to a host country, and increasing concern over nuclear accidents during the transportation that may lead radioactive release to the environment. Proliferation risks due to diversion of materials during transport are also a concern.

6.4.2 Previous Global Nuclear Fuel Cycle Cooperation Proposals in East Asia

Regional (East Asia), and indeed, global nuclear fuel cycle cooperation proposals have been offered by a number of groups and individuals over the past two decades and earlier. Below we provide brief descriptions of selected prior proposals. Other authors have reviewed these and other proposals in greater detail than is possible here.[223]

- Interest in regional/international spent fuel/radioactive waste storage/disposal increased significantly in the 1970s and early 1980s. In 1977, the IAEA reported that regional fuel cycle centers were feasible and would offer considerable nonproliferation and economic advantages. In 1982, the IAEA concluded a project of the International Fuel Cycle

[223] See Yudin, Y. (2009), *Multilateralization of the Nuclear Fuel Cycle: Assessing the Existing Proposals,* United Nations Institute for Disarmament Research, report # UNIDIR/2009/4, available as http://www.unidir.ch/pdf/ouvrages/pdf-1-978-92-9045-195-2-en.pdf; Yudin, Y. (2011), *Multilateralization of the Nuclear Fuel Cycle: A Long Road Ahead*, United Nations Institute for Disarmament Research, available as http://unidir.org/pdf/ouvrages/pdf-1-978-92-9045-201-0-en.pdf; Suzuki, T. (1997), "Nuclear Power in Asia: Issues and Implications of "ASIATOM" Proposals", in: *United Nations Kanazawa Symposium on Regional Cooperation in Northeast Asia*, Kanazawa, Japan. June 2-5, 1997; and Tanabe, T. and Suzuki, T. (1998). "Institutional and Policy Issues for Cooperation Schemes in the Asia-Pacific Region", in *Pacific Basin Nuclear Conference*, Banff, Canada, May 3-7, 1998.

Evaluation (INFCE) in which IAEA expert groups suggested an establishment of international plutonium storage and international spent fuel management.[224]

- In the mid-1990s, the concept of the International Monitored Retrievable Storage System (IMRSS) was proposed by Wolf Hafele. The IMRSS envisioned international sites where spent fuel, and possibly also excess separated plutonium, could be stored under monitoring for an extended period but could be retrieved at any time for peaceful use or disposal.[225]

- In the mid-1990s through the late 1990s, a number of proposals for nuclear power sector cooperation in the Asia-Pacific region, on topics ranging from safety to proliferation to waste management, were developed. Tatsujiro Suzuki[226] prepared a comparison of various proposals for regional nuclear cooperation offered during the period, and concluded that there are potential areas of cooperation where common needs and interests exist among the countries of Northeast Asia. At present, however, none of these proposals have been implemented to a significant degree.

- The past decade has seen a number of additional proposals for cooperation on uranium enrichment, management of nuclear spent fuels, or both, many involving East Asian and Pacific countries. Brief summarizes of just some of the cooperation proposals on international enrichment and/or low-enriched uranium (LEU) fuel supply and spent fuel management that have come forth in the last 10 years or so follow.[227]

- The **Global Nuclear Energy Partnership (GNEP)**, proposed by the United States during the George W. Bush administration (in 2006), had as its enrichment component a proposal to establish a group of enriched fuel supplier states, and a requirement that those states provide enriched fuel to non-supplier nations at a reasonable cost, while reducing the potential for proliferation of sensitive technologies, in part through cooperation with the IAEA on nuclear safeguards.[228] GNEP proposed coupling these fuel supply guarantees and with spent fuel "take back" arrangements. GNEP has received when the U.S. Congress cut funding to the program in 2008, and eliminated funding (except for a parallel but related "Advanced Fuel Cycle Initiative" that funds reprocessing research and development) for 2009. GNEP has, however, been recast as the **International Framework for Nuclear Energy Cooperation (IFNEC)**, which "is a partnership of countries aiming to ensure that new nuclear in

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[224] Bunn et al., (2001), ibid.
[225] Hafele, W. (1996), "The Concept of an International Monitored Retrievable Storage System". In: *Uranium Institute Symposium*, London, UK, August 1996.
[226] Suzuki (1997), ibid.
[227] Suzuki, T. and T. Katsuta (2009), "A Proposal of Multilateral Nuclear Fuel Cycle Approach: 'International Nuclear Fuel Management Arrangements (INFA)'", presentation prepared *for A-MAD Project Mini Workshop on Policy Recommendations for Nuclear Disarmament and Non-proliferation*, September, 2009, and available as http://a-mad.org/download/MNA_Suzuki_Katsuta_AMAD_090930.pdf.
[228] Tomero, L., (2008), "The future of GNEP: The international partners", *Bulletin of the Atomic Scientists* web edition, dated 31 July 2008, available as http://www.thebulletin.org/web-edition/reports/the-future-of-gnep/the-future-of-gnep-the-international-partners.

initiatives meet the highest standards of safety, security and non-proliferation" and "involves both political and technological initiatives, and extends to financing and infrastructure". [229]

- The **International Uranium Enrichment Center (IUEC) and LEU Nuclear Fuel Bank**, was proposed by Russia in 2006, and initiated by Russia shortly thereafter. The concept is for Russia to host the IUEC at its existing Angarsk Electrolytic Chemical Combine[230]. Membership in the enrichment center, intended to be on an "equal and non-discriminatory basis", requires charter states to forego developing their own enrichment facilities, and be in compliance with their nonproliferation obligations (including membership in the Treaty on the Non-Proliferation of Nuclear Weapons). Reserves of LEU were placed at Angarsk in late 2010, and the IUEC Agreement went into force in early 2011, after which "the LEU reserve in Angarsk has been available for IAEA Member States", constituting "the first proposals on nuclear fuel supply assurances to have been put into practice".[231]

- In 2006, **NTI (the Nuclear Threat Initiative)** pledged $50 million toward an **International Fuel Bank** to be run by the IAEA. Since then, $100 million in matching contributions have been pledged by other countries. Similar to the Russian proposal, but not affiliated with a specific enrichment center, the goal of the Fuel Bank concept by NTI "…is to help make fuel supplies from the international market more secure by offering customer states, that are in full compliance with their nonproliferation obligations, reliable access to a nuclear fuel reserve under impartial IAEA control should their supply arrangements be disrupted. In so doing, it is hoped that a state's sovereign choice to rely on this market will be made more secure"[232]. As of early 2010, the IAEA was planning to site the LEU repository at a remote site in Kazakhstan, at a metallurgical factory with existing storage infrastructure. IAEA member states voted in favor of the fuel bank in late 2010.[233]

- In April of 2007, **Germany** proposed to the IAEA the creation of **a multilateral enrichment facility**, established by a group of interested states, to be placed in a host states but on an

[229] World Nuclear Association (2012), "International Framework for Nuclear Energy Cooperation (formerly Global Nuclear Energy Partnership)", updated July 2012, and available as http://www.world-nuclear.org/info/inf117_gnep.html.

[230] Loukianova, A. (2008), "The International Uranium Enrichment Center at Angarsk: A Step Towards Assured Fuel Supply?", NTI Issue Brief, updated November, 2008, available as http://www.nti.org/e_research/e3_93.html.

[231] See International Atomic Energy Agency (IAEA, 3011), "Assurance of Supply for Nuclear Fuel: IUEC and the LEU Guaranteed Reserve", dated 31 October, 2011, and available as http://www.iaea.org/OurWork/ST/NE/NEFW/Assurance-of-Supply/iuec.html.

[232] Nuclear Threat Initiative (NTI, 2009), "NTI/IAEA Fuel Bank Hits $100 Million Milestone; Kuwaiti Contribution Fulfills Buffett Monetary Condition", NTI press release dated March 5, 2009, available as http://www.nti.org/c_press/release_Kuwait_Fuel_Bank_030509.pdf; NTI (2010), "IAEA to Pursue Nuclear Fuel Bank in Kazakhstan". Global Security Newswire, dated Jan. 11, 2010, available as http://gsn.nti.org/gsn/nw_20100111_3105.php; and Horner, D. (2010), "IAEA Board Approves Russian Fuel Bank Plan", *Arms Control Today* January/February 2010, available as http://www.armscontrol.org/act/2010_01-02/FuelBank.

[233] Nuclear Threat Initiative (NTI, undated, but probably 2011), "International Nuclear Fuel Bank", available as http://www.nti.org/about/projects/international-nuclear-fuel-bank/.

"extraterritorial basis".[234] Like the Russian proposal, and similar to the Fuel Bank NTI proposal, the facility would help assure supplies of enriched fuels to nations that qualify based on adherence to their non-proliferation treaty commitments and related IAEA safeguards.[235]

- The so-called **"Six-Country" Proposal of a Nuclear Fuel Assurance Backup System**, offered in 2006 by the enriched fuel supplier nations France, Germany, the Netherlands, Russia, the United Kingdom, and the United States, proposed that enrichment suppliers would substitute enrichment services for each other to cover supply disruptions for enriched fuel consumers that have "chosen to obtain suppliers on the international market and not to pursue sensitive fuel cycle activities". Further, the proposal would provide "physical or virtual" reserves of LEU fuel for use in the event that other fuel assurances fail.[236]

- Also in 2006, **Japan** proposed an **IAEA Standby Arrangements System for the Assurance of Nuclear Fuel Supply**. This system would be managed by the IAEA and would offer information, provided voluntarily by nuclear fuel supplier countries, on the status of uranium ore, reserves, conversion, enrichment, and fuel fabrication in each country. The goal of this system is to help prevent disruption in international fuel supplies by acting as a kind of "early warning" system of impending supplier shortfalls for states purchasing fuel or fuel services. If a disruption in supply takes place, under this system, the IAEA acts as intermediary in helping a consumer country find a new supplier country.[237]

- In the 1990s, a commercial group called **Pangea** was looking for an **international geologic repository for both spent fuel and radioactive wastes**. Envisioning a facility for disposing of 75,000 MT heavy metal of spent fuel/HLW, Pangea initially selected Australia for its proposed repository, but is seeking other sites around the world after confronting political opposition in Australia.[238]

- During the late 1990s to early 2000s, two proposals involving depository sites in Russia were presented. One was a concept of the **Nonproliferation Trust** (NPT) that called for establishing a dry cask storage facility in Russia that would accept 10,000 MT heavy metal of spent fuel from abroad, and would include eventual spent fuel disposal. The other was a concept offered by **MINATOM (**Ministry for Atomic Energy of Russia) that suggested a plan for an international spent fuel service involving offering temporary storage with later

[234] Rauf, T., and Z. Vovchok (2007), "Fuel for Thought". *IAEA Bulletin* 49-2, March 2008, pages 59-63, available as http://www.iaea.org/Publications/Magazines/Bulletin/Bull492/49204845963.pdf.
[235] International Energy Agency (IAEA, 2007*), Communication received from the Resident Representative of Germany to the IAEA with regard to the German proposal on the Multilateralization of the Nuclear Fuel Cycle*, IAEA document # INFCIRC/704, dated 4 May 2007, and available as http://www.iaea.org/Publications/Documents/Infcircs/2007/infcirc704.pdf.
[236] United Nations Institute for Disarmament Research (2009), UNIDIR project "Multilateral Approaches to the Nuclear Fuel Cycle". Available as www.unidir.org/pdf/activites/pdf3-act396.pdf
[237] Rauf and Vovchok,(2007), ibid; Yudin (2009), ibid.
[238] Bunn and et al. (2001), ibid.

return of the spent fuel, or reprocessing of spent fuel without return of plutonium or radioactive wastes for customer countries.[239]

- In 2003, Dr. Mohamed El Baradei suggested multinational approaches to the management and disposal of spent fuel and radioactive waste[240]. In 2005, commissioned at Dr. M. El Baradei's suggestion in 2003, the IAEA published a report on Multilateral Approaches to the Nuclear Fuel Cycle in which the IAEA concluded that such approaches are needed and worth pursuing, on both security and economic grounds.[241]
- In January 2006, Russian President Vladimir Putin announced a **Global Nuclear Power Infrastructure** (GNPI) initiative to provide the benefits of nuclear energy to all interested countries in strict compliance with nonproliferation requirements, through a network of international nuclear fuel cycle centers (INFCC). INFCC are conceived as being related to the provision of enrichment services and to spent fuel management issues through the provision of reprocessing and the disposal of residual waste within the framework of INFCC, under IAEA safeguards.[242]
- In 2008, Tatsujiro Suzuki and Tadahiro Katsuta proposed the idea of an "**International Nuclear Fuel Management Association** (INFA)" as a multilateral nuclear fuel cycle approach[243]. The central principles of the INFA are universality, meaning avoiding discrimination between nuclear "haves" and "have nots", transparency, meaning that the IAEA "Additional Protocol" or equivalent safeguards arrangements should be applied for all facilities, and demand should come first before supply, and economic viability, meaning that the activities of the Association should be consistent with global nuclear fuel market activities, and that the economic rationale of the Association should be clearly defined to support nuclear fuel cycle programs.

6.4.3 Scenarios for Nuclear Fuel Cycle Cooperation in Northeast Asia

The descriptions below update earlier Nautilus analyses of four cooperation "scenarios" for nuclear fuel enrichment and for spent fuel management. These generic scenarios borrow many concepts from earlier enrichment and spent-fuel management cooperation proposals, some of which are summarized above. Each scenario includes specific assumptions by country for each of several fuel-cycle "nodes": uranium mining and milling, uranium transport, uranium conversion and enrichment, fuel fabrication, transportation of fresh reactor fuel, electricity

[239] Bunn and et al. (2001), ibid.
[240] El Baradei, M. (2003), "Toward a Safer World". *The Economist*, October 16, 2003.
[241] International Atomic Energy Agency (IAEA, 2005), *Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report submitted to the Director General of the International Atomic Energy Agency*. Document # INFCIRC/640, dated 22 February 2005, and available as http://www.iaea.org/Publications/Documents/Infcircs/2005/infcirc640.pdf.
[242] Ruchkin, S.V. and Loginov, V.Y. (2006), "Securing the Nuclear Fuel Cycle: What Next?". *IAEA Bulletin* 48/1, September 2006.
[243] Suzuki, T. and T. Katsuta (2009), ibid.

generation, spent fuel management (including reprocessing), spent fuel transport, and permanent disposal of nuclear wastes. Key attributes of the scenarios are as follows:

1. "**National Enrichment, National Reprocessing**": In this scenario the major current nuclear energy users in East Asia (Japan, China, and the ROK) each pursue their own enrichment and reprocessing programs, with all required enrichment in those countries accomplished domestically by 2025 or 2030. Other countries may also pursue domestic enrichment, though this scenario assumes that other countries import enrichment services through 2050. Reprocessing, using 60 percent of newly cooled spent fuel (SF) in the ROK in each path, 60 percent of newly cooled spent fuel in the BAU path and 80 percent in the MAX path in China,[244] and operating at 85 percent of reprocessing capacity in the MAX path, 55 percent in the BAU path, but not at all in the MIN path is in place in Japan by 2020, and in ROK/China by 2030. Nuclear fuel is assumed to be fabricated where uranium is enriched and/or fuel is reprocessed. Half of the reactors in China and the ROK eventually use 20% mixed oxide fuel (fuel including mixed uranium and plutonium oxides, or MOx), with half of the reactors in Japan using 30 percent MOx fuel in the MAX and MIN paths, and 40 percent of reactors using MOx in the BAU path, but MOx use starts earlier in Japan than in the other nations. Japan and the ROK import uranium; other nations in the region eventually produce half of their U needs domestically except Australia, which produces all of its needs, and the Russian Far East, which imports all of its modest needs from elsewhere in Russia. Arrangements for disposal of high-level nuclear wastes from reprocessing would be up to each individual country, with attendant political and social issues in each nation. Security would be up to the individual country, and as a result, transparency in the actions of each country is not a given. Disposal of spent fuel and of high-level nuclear wastes from reprocessing is assumed to be carried out in each individual country, with interim storage or dry cask storage use assumed through 2050.

2. "**Regional Center(s)**": This scenario features the use of one or more regional centers for enrichment and reprocessing/waste management, drawn upon and shared by all of the nuclear energy users of the region. We avoid identifying particular country hosts for the facilities, but China and Russia are obvious candidates, though the potential involvement of other countries, including Mongolia, has been suggested. The centers are assumed to be operated by an international consortium, and drawn upon and shared by all nuclear energy users in region. The consortium imports uranium for enrichment from the international market, and shares costs between participants. China limits its own production of uranium to current levels. Nuclear fuel (including MOx) is fabricated at the regional center(s), with use of MOx by country the same as in Scenario 1. Reprocessing of spent fuel from the ROK, and China also occurs in the same amounts as in Scenario 1, but is accomplished in regional center(s) starting in 2025, with phase-in complete by 2030, and with reprocessing of half of the spent

[244] The growth in China's nuclear generation, particularly in the MAX path, is such that without a higher fraction of the reprocessing of newly cooled (eight-year-old) spent fuel, insufficient plutonium will be available to supply MOx for Chinese reactors. In practice, it is likely that older cooled spent fuel and/or spent fuel from other nations (the latter in Scenarios 2 and 3) would be used to make up any gap between the amount of separated Pu needed to meet MOx fuel demand and Pu produced via reprocessing.

fuel from other nations carried out in regional centers by 2050. Japan's domestic reprocessing is initially the same by path as in Scenario 1, but transitions to regional centers starting in 2025 and ending in 2030. Disposal of spent fuel and high-level nuclear wastes from reprocessing is done in coordinated regional interim storage facilities, pending development of permanent regional storage in the post-2050 period.

3. "**Fuel Stockpile/Market Reprocessing**": Here, the countries of the region purchase natural and enriched uranium internationally, but cooperate to create a fuel stockpile (the equivalent of one year's consumption of natural uranium and enriched fuel) that the nations of the region can draw upon under specified market conditions. Enrichment is purchased from international sources except for the existing modest Japanese and Chinese capacity. Reprocessing services are purchased from international sources, such as France's AREVA or from Russia, while some spent fuel continues to be stored in nations where nuclear generation is used. Nuclear fuel (**excluding** MOx) is fabricated where uranium is enriched. Reprocessing of spent fuel is done in the same amounts as in Scenario 2, but is carried out at international center(s), where MOx fuel is fabricated for use in the region (with MOx use is as in Scenarios 1 and 2). Management of spent fuel and high-level nuclear wastes from reprocessing is accomplished using international interim storage facilities, possibly including facilities in the region, pending development of permanent regional storage post-2050.
4. "**Market Enrichment/Dry Cask Storage**": In this scenario, countries in the region (with the possible exception of China) would continue to purchase enrichment services from international suppliers such as URENCO in Europe, the USEC in North America, and Russia except that existing Chinese capacity enrichment capacity would continue to be used, and existing Japanese capacity would be used until it is closed after 2020. Uranium and enrichment services purchases would be through an international consortium, as in scenarios 2 and 3. Japan and China cease reprocessing in 2015, and no other countries reprocess spent fuel after that point either at international or in-region facilities. Japan's MOx use would be phased out by 2013 and no MOx use would occur elsewhere in the region. All spent fuel, after cooling in ponds at reactor sites, would be put into dry cask storage either at reactor sites or at intermediate storage facilities. High-level wastes from reprocessing (before 2016) would also be placed in interim storage facilities.

These scenarios are not by any means intended to exhaust the universe of possible nuclear fuel cycle cooperation (or non-cooperation) options for the region, but do, we believe, represent a reasonable range of the different options that might be adopted.

6.4.4 Key Analytical Approaches and Assumptions

In order to the estimate the relative costs and benefits of the four nuclear fuel cycle cooperation scenarios summarized above, the following analytical approach was taken. What is presented here is necessarily a condensed description of the methods and data used; please see our more detailed 2010 report[245] for further details.

[245] von Hippel, D., T. Suzuki, T. Katsuta, J. Kang, A. Dmitriev, J. Falk, and P. Hayes (2010), *Future Regional Nuclear Fuel Cycle Cooperation in East Asia: Energy Security Costs and Benefits*, Nautilus Institute Report, June,

As a first step, nuclear paths specified by EASS country working groups, in some cases modified as noted above by the authors, served as the basis for calculating nuclear fuel requirements, and spent fuel arisings (including arisings from decommissioned plants). To these estimates of fuel requirements, calculated for each of the three nuclear "paths" in each country, as presented above, we overlaid the four scenarios of regional cooperation on nuclear fuel cycle issues over a timeline of 2000 through 2050. Simple stock and flow accounting was used to generate estimates of major required inputs to and outputs of the nuclear reactor fleet in each country, and of other nuclear facilities such as enrichment and reprocessing facilities. The fuel cycle nodes modeled were uranium mining and milling, uranium transportation and enrichment, fuel fabrication and reactor fuel transport, and reprocessing and spent fuel management. Key inputs at each (applicable) node included the mass of uranium (in various forms) and plutonium, energy, enrichment services, transport services, and money, accounted for by country and by year. Key outputs at each node included uranium and plutonium, spent UOx (uranium oxide) and MOx fuel, and major radioactive waste products, again by country and year. Costs are presented and calculated in approximately 2009 dollars, except where noted.

Using this approach, quantitative results for 12 different regional cooperation scenario and nuclear power development path combinations were generated. These quantitative results were coupled with qualitative considerations to provide a side-by-side comparison of the energy security—broadly defined to include not just energy supply and price security, but technological, economic, environmental, social/cultural, and military security aspects as well[246]— attributes of four cooperation scenarios. As such, we used the energy security comparison methodology developed by Nautilus Institute and its partners under a series of initiatives starting in 1998.

Many of the parameters incorporated in the analysis described here are uncertain, with the future costs of nuclear materials and facilities perhaps the most uncertain. As such, numerous assumptions informed by a variety of literature sources were used in this analysis. Some of the key assumptions used in the analysis are as follows:

- Uranium Cost/Price: $86/kg in 2015,[247] escalating at 2.9%/yr. Uranium prices "spiked" in 2007 at over $260/kg, fell to about the $120/kg level by 2009-2010, rose again in early 2011, then began to fall, particularly after the Fukushima accident, with continued decline over 2012 through early 2014 to about $86 per kg by mid-2014, rising somewhat thereafter.
- Average uranium (U) concentration in ore purchased from international market sources: 2.5%: Note that this estimated average, based mostly on 2011 output data, is heavily influenced by the uranium concentration of a single highly productive mine in Canada with

2010, available as http://nautilus.wpengine.netdna-cdn.com/wp-content/uploads/2012/01/EASS_Report_6-2010_rev.pdf. An update to this report is in progress, and will be provided to MacArthur when it is complete.

[246] See, for example, von Hippel, David F., Suzuki, Tatsujiro, Williams, James H., Savage, Timothy, and Hayes, Peter (2011), "Energy Security and Sustainability in Northeast Asia", Asian Energy Security special section of *Energy Policy*, 39(11), 6719–6730; and von Hippel, David F., Suzuki, Tatsujiro, Williams, James H., Savage, Timothy, and Hayes, Peter (2011), "Evaluating the Energy Security Impacts of Energy Policies", in Benjamin K. Sovacool (Ed.), *The Routledge Handbook of Energy Security* (pp. 75–95), Oxon, UK: Routledge.

[247] Recent historical prices from Cameco "URANIUM PRICES, Uranium Spot Price History, though July, 2015, available as http://www.cameco.com/invest/markets/uranium-price.

an ore concentration of on the order of 20 percent. Excluding this mine, the global average U concentration in ore is about 0.1%, though in practice uranium concentrations in ore vary widely.[248]

- Enriched uranium from the international market is produced 30 percent in gaseous diffusion plants in 2007, with the remainder in centrifuge-based plants, with all enrichment sourced from centrifuge-based plants by 2030 as gaseous diffusion capacity, mostly in the United States, is retired.
- Enrichment costs have fallen by nearly a 40 percent in the last five years, from about $160/kg per separative work unit (SWU) in 2008 through early 2010 to about $72 per kg in 2015, likely as a result of the combination of the global economic recession and the impacts on the nuclear industry of the Fukushima accident. We assume, for the BAU nuclear generation capacity expansion case, that costs per SWU rise at 1 percent annually in real terms from the 2015 level, meaning that real 2050 costs per SWU will be substantially lower than they were at the cost peak in 2008/2009. Since the MAX nuclear capacity expansion case results in higher demand for SWU, we assume that the costs per SWU will rise faster than for BAU capacity expansion, at an average rate of 2.5 percent annually. Conversely, a low rate of nuclear generation capacity expansion reduces SWU demand, so we assume no real escalation of costs per SWU is associated with scenarios in based on the MIN capacity expansion case.
- Raw uranium transport costs are set at roughly container-freight rates.
- The cost of U_3O_8 conversion to UF_6 (uranium hexafluoride, which is processed by enrichment plants) is $14/kg U.[249]
- The cost of UOx fuel fabrication is $270/kg heavy metal (HM, meaning uranium and plutonium).[250]
- The cost of MOx fuel blending and fabrication is $1800/kg heavy metal.[251]
- The fraction of plutonium (Pu) in (fresh) MOx fuel is 7%.[252]

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[248] World Nuclear Association (2012), "World Uranium Mining", last updated August, 2012, and available as http://www.world-nuclear.org/info/inf23.html.

[249] The World Nuclear Association (2012), in "The Economics of Nuclear Power" (updated December, 2012, and available as http://www.world-nuclear.org/info/inf02.html), lists costs for UF_6 conversion as of March 2011 as $13 per kg UO_2. This is more than twice the cost listed in the earlier study Deutch, J., C. W. Forsberg, A.C. Kadak, M.S. Kazimi, E. J. Moniz, J.E. Parsons, Y. Du, and L. Pierpoint (2009), *Update of the MIT 2003 Future of Nuclear Power Study*. MIT Energy Initiative, available as http://web.mit.edu/nuclearpower/pdf/nuclearpower-update2009.pdf.

[250] World Nuclear Association (2012), in The Economics of Nuclear Power" (updated December, 2012, and available as http://www.world-nuclear.org/info/inf02.html), lists costs for fuel fabrication as of March 2011 as $240 per kg UO_2.

[251] Bunn, M., S. Fetter, J. P. Holdren, B. van der Zwaan (2003), *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel: Final Report*, 8/12/1999-7/30/2003. Project on Managing the Atom, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, dated December 2003, Report number DE-FG26-99FT4028, and available as http://belfercenter.ksg.harvard.edu/files/repro-report.pdf.

- Spent fuel transport costs by ship are about $40/tHM-km.[253]
- The cost of reprocessing is $1200/kg HM[254] except in Japan, where it is $3400/kg HM based on the costs of the existing Rokkasho plant.[255]
- The effective average lag between placement of nuclear fuel in-service (in reactors) and its removal from spent fuel pools at reactors is 8 years.
- The cost of treatment and disposal of high-level wastes is $150/kg HM reprocessed, the mass of Pu separated during reprocessing is 11 kg/t HM in the original spent fuel, and the cost of storage and safeguarding of separated plutonium is $3000/kg Pu-yr.[256]
- The average capital cost of dry casks (for UOx or MOx spent fuel) is $0.8 million/cask and the operating cost of dry cask storage is $10,000 per /cask-yr.[257]
- The cost of interim spent fuel storage (total) is $360/kg HM placed in storage, and the cost of permanent storage of spent fuel is assumed to be $1000/kg HM placed in storage.[258] Permanent storage, however, is not implemented, and its costs are not charged, in any of the scenarios above by 2050.
- The annual cost of storing cooled spent fuel, including both UOx and MOx spent fuel, in pools is $11,700 per tHM.[259] Note that this cost does not apply to spent fuel before it has cooled, as costs for at-reactor cooling for 8 years are assumed to be part of reactor operating and maintenance costs.

6.5 Spent Fuel Management Cooperation Scenario Results

Results for the spent fuel management cooperation scenarios described above are provided in this section of this Project Summary Report. These results update Nautilus' previous work on the topic, but further updates are ongoing.

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[252] Massachusetts Institute of Technology (MIT, 2003), *The Future of Nuclear Power, An Interdisciplinary MIT Study*. Available as http://web.mit.edu/nuclearpower/pdf/nuclearpower-full.pdf.
[253] Organization for Economic Cooperation and Development Nuclear Energy Agency (OECD/NEA, 1994), *The Economics of the Nuclear Fuel Cycle*.
[254] MIT, 2003, ibid.
[255] Katsuta, T. (2010), personal communications.
[256] OECD/NEA, 1994, ibid.
[257] Capital and operating costs based very roughly on United States Department of Energy (US DOE, 1994), *Multi-purpose Canister Evaluation: A Systems Engineering Approach*, Report DOE/RW-0445, September, 1994l and TRW Environmental Safety Systems, Inc. (TRW, 1993), *At Reactor Dry Storage Issues*, Report # E00000000-01717-2200-00002, September, 1993..
[258] Based roughly on OECD/NEA, 1994, ibid.
[259] A recent estimate for the operating costs of spent fuel pools was not immediately available, but an older (1991) US study, S.R. Rod (1991), *Cost Estimates of Operating Onsite Spent Fuel Pools After Final Reactor Shutdown*, Report Number PNL-7778, dated August, 1991, and available as http://www.osti.gov/scitech/servlets/purl/5349359/, lists an average (mean) cost of operating spent fuel pools of $7.41 per kg U-yr, presumably in 1991 dollars or similar, which implies $11.71 per kg U-yr in 2009 dollars.

6.5.1 Uranium Production and Enrichment

Over the period from 2000 through 2050, the countries of East Asia and the Pacific included in this study are projected to use a cumulative 1.5 to somewhat under 1.6 million tonnes of natural uranium in the BAU capacity expansion case, with usage under Scenario 4 about 7 percent higher than in Scenarios 1 and 2. Producing these quantities of uranium will require the extraction of about 70 (Scenarios 2 through 4) to 300 million tonnes (Scenario 1)[260] of uranium ore, with extraction in Scenario 1 being much higher because more of the ore is mined domestically, rather than being sourced from higher-grade Canadian (and other) deposits. As large as these figures seem, they are dwarfed by the annual volume of coal extracted in China alone in a single year (over 3.5 billion tonnes in 2011,[261] though of course Chinese coal-fired power plants generated on the order of 10 times as much power during 2011 than did all of the reactors in the region combined). This comparison is, of course, inexact, because coal ash and other wastes have different disposal attributes and environmental impacts—and thus costs for disposal—than do uranium tailings. Milling the uranium needed for reactors in the region will require about 1.5 to 1.6 billion cubic meters of water over the period from 2000 through 2050, which, to put the level of resource use in perspective, is about half of one day's discharge of water from the Yangtze River to the ocean, or about a tenth of annual domestic water use in Japan.

The enrichment services requirements for the BAU paths across scenarios are about 34 to 35 million kg SWU in 2050 in Scenarios 1-3, and about 38 M for Scenario 4 (which includes no MOx use). For the MAX generation capacity expansion path, needs rise to about 71 M SWU/yr in 2050 in scenarios without substantial MOx use, and are about 8 to 15 percent less in scenarios with MOx use. For the MIN path, requirements are about 18-20 million SWU in the 2020s, rising slowly (on the strength of continued growth in the Chinese nuclear sector, offsetting declines elsewhere in the region to 20-22 million SWU in 2050.

Under Scenario 1, additional enrichment capacity in the countries of the region will be required under all nuclear capacity expansion paths. Under other scenarios, global enrichment capacity by 2015 would need to be expanded to meet 2050 regional plus out-of-region enrichment demand under the BAU or MAX expansion paths. Under the MAX expansion path and Scenario 1, China alone would need to build new enrichment capacity by 2050 approximately equal to half of today's global capacity. Under the MIN expansion path, however, international enrichment facilities extant as of 2015 are likely sufficient to meet regional and out-of-region demand without significant expansion, assuming existing facilities (or replacement facilities) continue to operate. Figure 6-3 summarizes the required regional volume of enrichment service required, both in-country and out-of-country (that is, from regional or international facilities), for the period from 2000 through 2050 for each of the four scenarios. Figure 6-4 shows enrichment requirements over time by country. Though the ROK and Japan account for almost all enriched

[260] In the MAX capacity expansion case, cumulative 2000 through 2050 uranium ore extraction is about 510 million tonnes in Scenario 1.

[261] British Petroleum (2012), Excel workbook "BP Statistical Review of World Energy June 2012", available as http://www.bp.com/assets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/spreadsheets/statistical_review_of_world_energy_full_report_2012.xlsx.

uranium needs pre-Fukushima, the rapid growth of China's nuclear power sector and the slow process of restarting Japan's reactors means that China's demand for enrichment will outstrip needs in the rest of the region well before 2020.

Figure 6-3: Requirements for Enriched Uranium by Scenario, Adjusted for MOx Use, BAU Nuclear Capacity Expansion Path

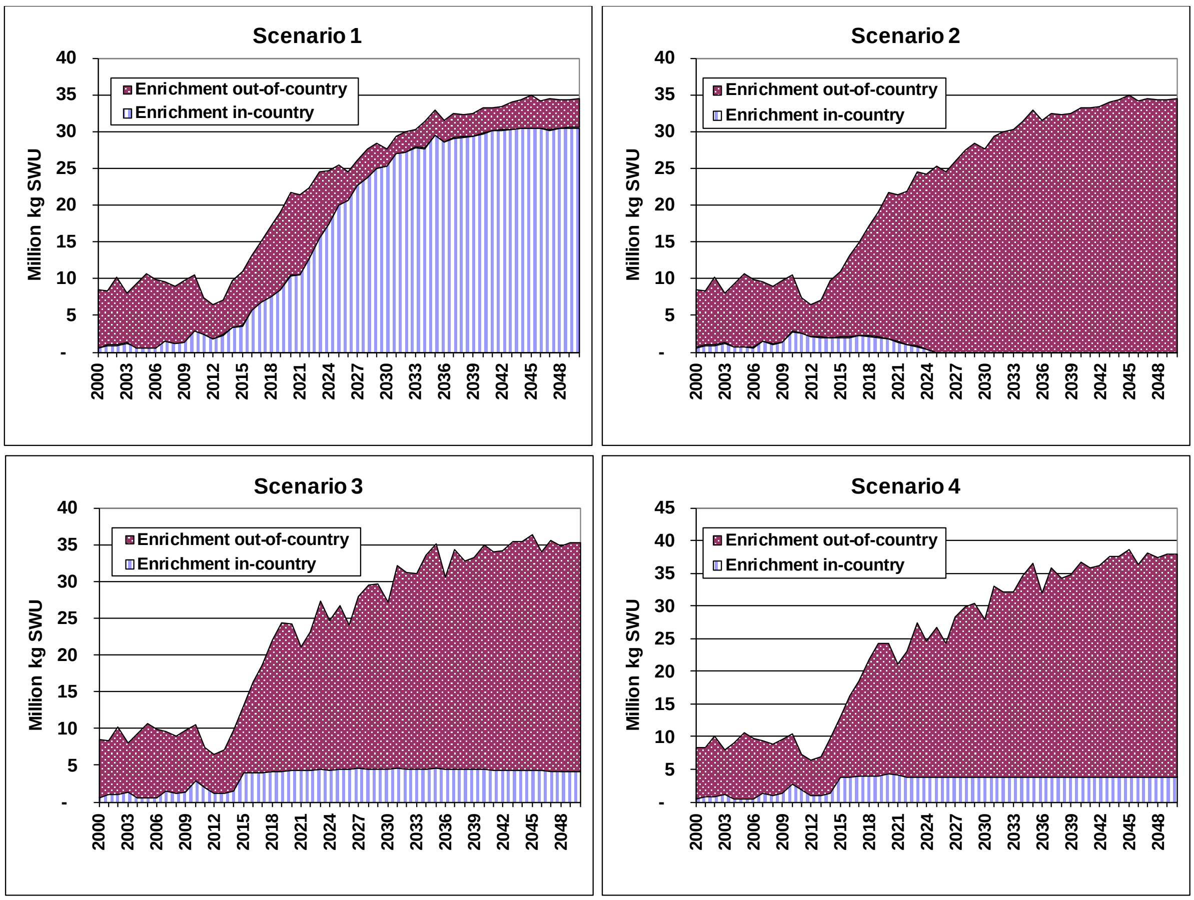
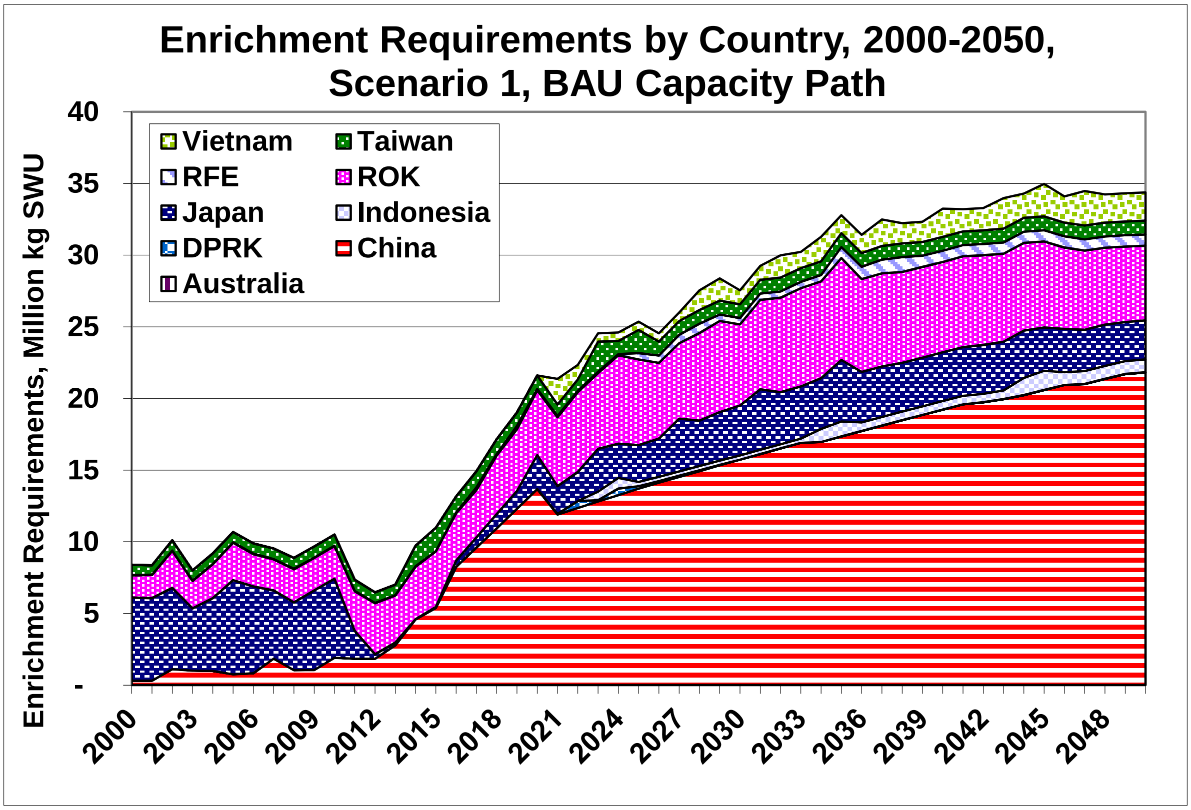


Figure 6-4: Requirements for Enriched Uranium by Country, Scenario 1, Adjusted for MOx Use, for the BAU Nuclear Capacity Expansion Path

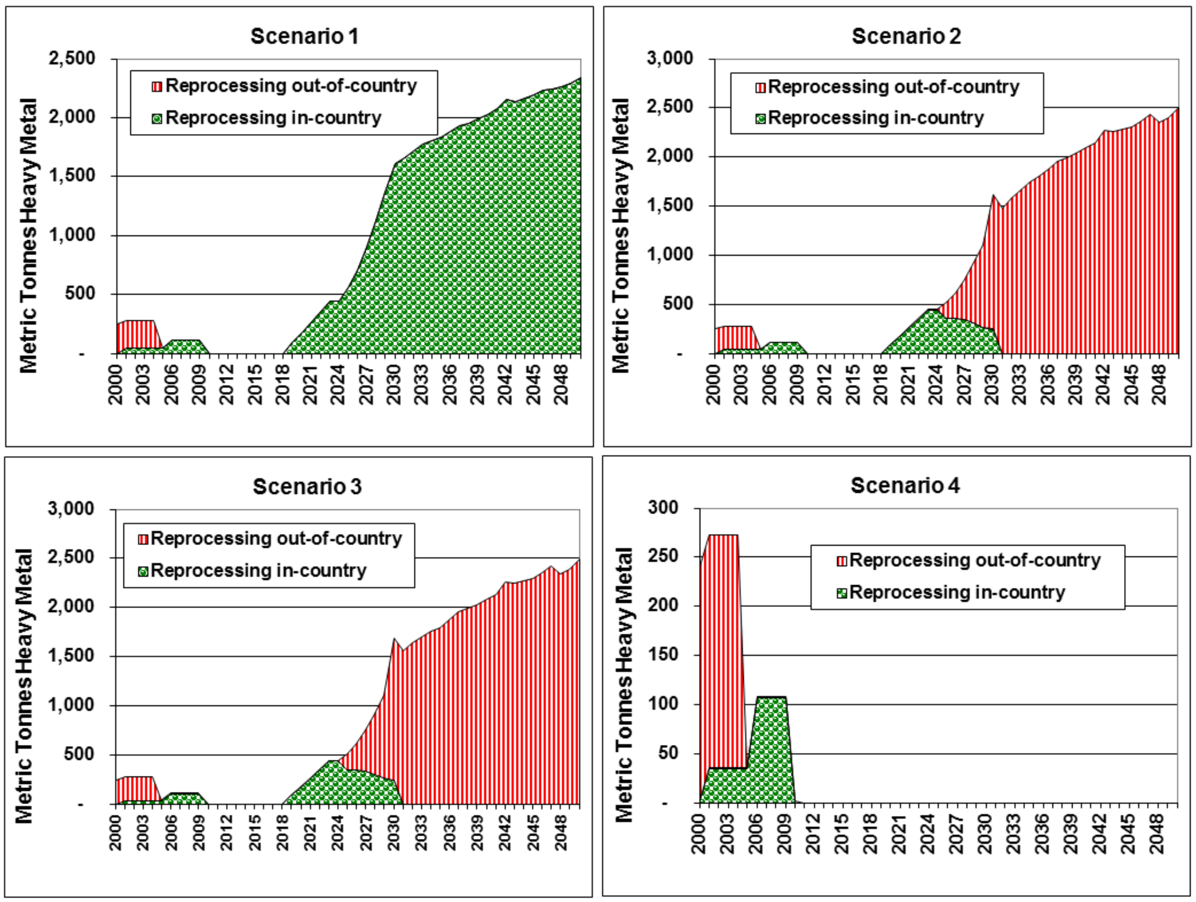


6.5.2 Spent Fuel Management

The increase in production of spent fuel has implications for the sufficiency of space for storage of spent fuel at reactors (spent fuel pools) and other facilities. In Scenario 1 under the BAU nuclear capacity expansion path, China, Japan, and the ROK will require new spent fuel storage capacity by the early 2020s or sooner (the ROK and possibly Japan, depending on whether spent fuel pools remain dense-racked, and the timeline for starting the Mutsu dry cask storage facility in Japan), and the mid-2030s (China). By 2050, in the BAU case, storage, disposal, or reprocessing for about 3200 THM of spent fuel will need to be added annually, with nearly two-thirds of that requirement in China. In the absence of regional cooperation on spent fuel management, the countries of East Asia, and in particular Japan, the ROK, and China, will in the next 10 to 20 years need to begin opening a large amount of out-of-reactor-pool spent fuel storage or disposal space, or develop the same equivalent amount of storage space in reprocessing facilities. This result is based, as noted above, on the assumption that new reactors will (mostly) be designed with 15 years of spent fuel storage capacity. Though it may be that new nuclear plants will be designed with larger spent fuel pools, this tendency may be tempered by consideration of the risks of at-reactor pool storage of large quantities of spent fuel, particularly when, as in many existing plants in Northeast Asia, spent fuel pools are “dense packed" with fuel rod assemblies. These risks were underscored by the damage to spent fuel in pool storage that occurred during the Fukushima Daiichi Plant accident in Japan starting in March 2011. Given the recent history of public opposition to new nuclear sites in Japan and the ROK, one would expect the process of developing new storage/disposal/reprocessing facilities to be difficult. China, with more lightly-populated area than the ROK or Japan, and less of a tradition of civic involvement, may find an easier path to siting such facilities. On the other hand, in the twenty years between now and when China will need such facilities, and given the recent trend of a growing civil society voice in key issues, spent fuel management facilities may also become progressively harder to site in China as well.

Figure 6-5 summarizes the region-wide use of reprocessing over time in each of the four Scenarios. A similar amount of reprocessing takes place in each of Scenarios 1 through 3, rising to about 1900 tonnes of heavy metal annually by 2050, but reprocessing in Scenario 1 takes place mostly in the countries of the region, while in Scenarios 2 and 3 reprocessing is mostly done either outside the region, or in shared reprocessing facilities in the region. In Scenario 4, as a result of the scenario assumptions, no reprocessing takes place after about 2016. Note that the scale in the graph for Scenario 4 is much smaller than the scale in the other three panels of Figure 6-5. Combinations of active reprocessing programs and high or medium growth in nuclear generation capacity yield large, though transitional, inventories of plutonium—on the order of 90 to 130 tonnes. Scenario 1 coupled with the "MAX" capacity expansion path produces a maximum regional inventory of plutonium, at nearly 130 tonnes in 2038, but most of that inventory is used in MOx fuel by 2050, with only about 13 tonnes by that time. Two scenario/path combinations, Scenario 3 MAX and Scenario 2 MIN, actually result net negative plutonium stocks regionwide, implying that Pu from other international separation programs—or, perhaps, conversion of Plutonium originally produced for weapons—would be used to produce MOx fuel in the last year or two before 2050. Plutonium inventories remain at about 53 tonnes in all Scenario 4 capacity variants from about 2015 on. Placed in perspective, in almost all years any of these quantities of Pu are sufficient that diversion of even a few hundredths of one percent of the total regional stocks would be enough to produce one or more nuclear weapons.

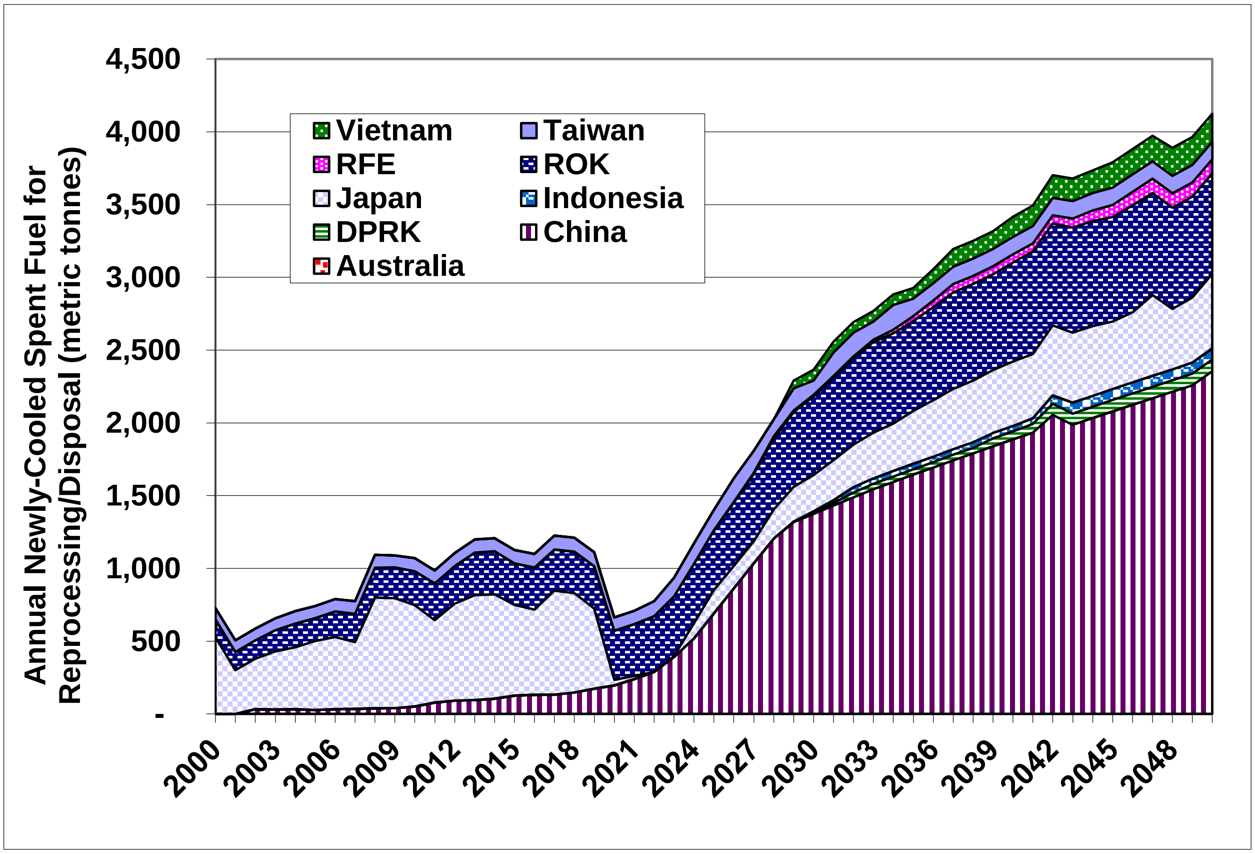
Figure 6-5: Region-wide Quantities of Spent Fuel Reprocessed by Year by Scenario, BAU Nuclear Capacity Expansion Path



6.5.3 Spent Fuel Production

Figure 6-6 summarizes cooled spent fuel (UOx fuel only) production by country in Scenario 1 for the BAU capacity expansion path. By 2050, an annual volume of about 4000 tonnes of spent fuel regionwide will be cooled and ready for storage, reprocessing, or disposal. An additional 300 tonnes per year of MOx spent fuel will be cooled and require further management—but likely somewhat different management than UOx fuel, due to its different radiological properties) in 2050, with all cooled MOx fuel coming from Japan, China, and the ROK. Note, in Figure 6-6, the dip in cooled spent fuel production corresponding to the very low capacity factors for nuclear power in Japan in the aftermath of the Fukushima accident. The actual spent fuel production may be even lower, as the capacity factors used in this study for the post-Fukushima years in Japan may well prove to be overstated.

Figure 6-6: Production of Cooled Spent UOx Fuel by Year and by Country, Scenario 1 and BAU Nuclear Capacity Expansion Path



6.5.4 Relative Costs of Scenarios

Along with the inputs to and outputs of nuclear fuel cycle facilities, the estimated costs of key elements of the nuclear fuel cycle have been evaluated for each combination of scenario and nuclear capacity expansion path. In general, though not in every case, "levelized" costs have been used, expressed, for example, on a per-tonne-heavy metal processed basis, to include a multitude of operating and maintenance as well as capital costs, often for very long-lived facilities. In other cases market trends in prices have been extrapolated, for example, for uranium prices and enrichment services, while providing for the option of modeling different price trends. All costs in the figures in this section are provided in 2009 dollars. The figures below focus on the results of the BAU nuclear capacity expansion path. As with other parameters, cost estimates are in many cases by their very nature quite speculative, as they often specify costs for technologies that have not yet been commercialized (permanent waste storage, for example), or are commercialized but practiced in only a few places in the world (reprocessing and high-level waste vitrification, for example), or are subject to regulatory oversight with the potential to considerably change costs, or for which specific costs were not immediately available for this analysis (such as most nuclear materials transport costs). As such, the costs estimates provided here should be taken as indicative only, for use primarily in comparing regional scenarios.

Not yet included in the cost analysis summarized here are the costs of nuclear generation, apart from fuel-related costs. These costs have been omitted (capital costs and O&M costs, for example) in analyses thus far because a full comparison of different nuclear paths also requires inclusion of the capital costs of other electricity generation sources and of other methods of providing energy services (such as energy efficiency improvements) that might be included in a given energy sector development path for a given country. It should be noted, however, that using MOx fuel in some of the region's reactors will require modifications in reactor design and operation that will vary in cost by plant, but will likely be in the range of tens of millions of dollars in capital costs and tens of millions of dollars in annual operations costs, per reactor (see, for example, Williams, 1999).[262] These costs would accrue to scenarios with substantial MOx use, but not to scenarios where reprocessing (and MOx use) is avoided.

Highlights of the cost results summarized as annual costs in 2050 for the BAU path (Figure 6-7) include:

- Uranium mining and milling costs for the region are estimated at $4.3 to $4.7 billion per year by 2050, with the inclusion of reprocessing in Scenarios 1 through 3 reducing costs only modestly (a few percent) relative to Scenario 4.
- Natural uranium transport costs, at an estimated 2 to 6 million dollars per year in 2050, are a negligible fraction of overall costs.
- Uranium conversion costs range from 620 to 690 million dollars per year by 2050 for the countries of the region.
- Uranium enrichment costs for the region are on the same order of magnitude as mining and milling costs, at an estimated at $3.5 to $3.9 billion per year by 2050, with the inclusion of reprocessing in scenarios again reducing costs only modestly.
- UOx fuel fabrication costs are estimated at $1.3 to $1.5 billion annually by 2050.
- Though the quantity of MOx fuel used is much lower than that of UOx fuel, MOx fabrication costs are estimated at about $720-740 million annually by 2050 in Scenarios 1 through 3 where MOx is used.
- Reprocessing costs range from about $3.0 to 3.7 billion per year in those Scenarios (1 through 3) that feature reprocessing, with Scenario 1, with more (and more expensive) reprocessing in Japan having the highest reprocessing costs.
- Treatment of high-level wastes from reprocessing adds $350 to 380 million per year to the costs of Scenarios 1 through 3, with treatment of medium-level, low-level, and solid wastes

[262] See, for example, Williams, K.A. (1999), *Life Cycle Costs for the Domestic Reactor-Based Plutonium Disposition Option*. Oak Ridge National Laboratory Report ORNL/TM-1999-257, Dated October, 1999, and available as http://www.ornl.gov/~webworks/cpr/rpt/105050.pdf.

from reprocessing, and of uranium separated from spent fuel during reprocessing (less uranium used for MOx fuel) adding an aggregate $220 to 240 million per year to costs by 2050.

- Plutonium storage costs range from about $60 to $160 million/yr in 2050, with those scenarios that result in higher Pu inventories by 2050 (those where Pu is not substantially used up in MOx fuel) showing higher costs.
- Interim storage of non-reprocessed spent fuels (and of MOx fuel), in Scenarios 1 through 3, has estimated costs in 2050 of $830 to $870 million per year. In Scenario 4, using Dry Cask Storage, estimated costs in 2050 are about $700 million per year, or somewhat lower, though the amount of spent fuel being handled in Scenario 4 does not include the fuel sent to reprocessing in the other scenarios. Estimated costs for transportation of spent fuel in are about $80 million annually in 2050 in Scenario 1, about $230 million/yr in Scenarios 2 and 3, and $23 million/yr in Scenario 4.

Overall, the conclusion from the above—similar to the conclusion that a number of other researchers have reached using per-unit costs (not from regional scenarios), is that reprocessing of spent fuel results in much higher costs—higher by on the order of $4 to 5 billion per year (about 25 percent), region-wide, in 2050—than using dry-cask storage and avoiding reprocessing of spent fuel, as shown in Figure 6-7. Figure 6-8 shows net present value costs from 2010 through 2050 (calculated with three different discount rates) for the nuclear fuel cycle elements. Scenario 1 through 3 yields total costs that about 14 to 23 (at a discount rate of 5.0 percent/yr) to 23 to 29 percent (at a zero discount rate) higher overall than in the least expensive scenario (Scenario 4). The absolute cost difference between scenarios declines somewhat as the discount rate used increases. Results at three different real discount rates are shown to reflect a range of potential perspectives as to the time value of money in nuclear investments. Present interest rates in Japan, for example, are near zero (and in the negative range in real terms). In addition, one could argue that as investments with decidedly intergenerational implications, nuclear fuel cycle costs should be evaluated with a near-zero, zero, or even negative discount rate.[263]

[263] See, for example, Hellweg, S., T. B. Hofstetter, and K. Hungerbühler (2003), "Discounting and the Environment: Should Current Impacts be Weighted Differently than Impacts Harming Future Generations?". *International Journal of Life-Cycle Analysis* Volume 8 (1), pages 8 – 18. Available as http://www.lcaforum.ch/Portals/0/DF_Archive/DF22/Steffi.pdf.

Figure 6-7: Annual Regional Nuclear Fuel Cycle Costs in 2050

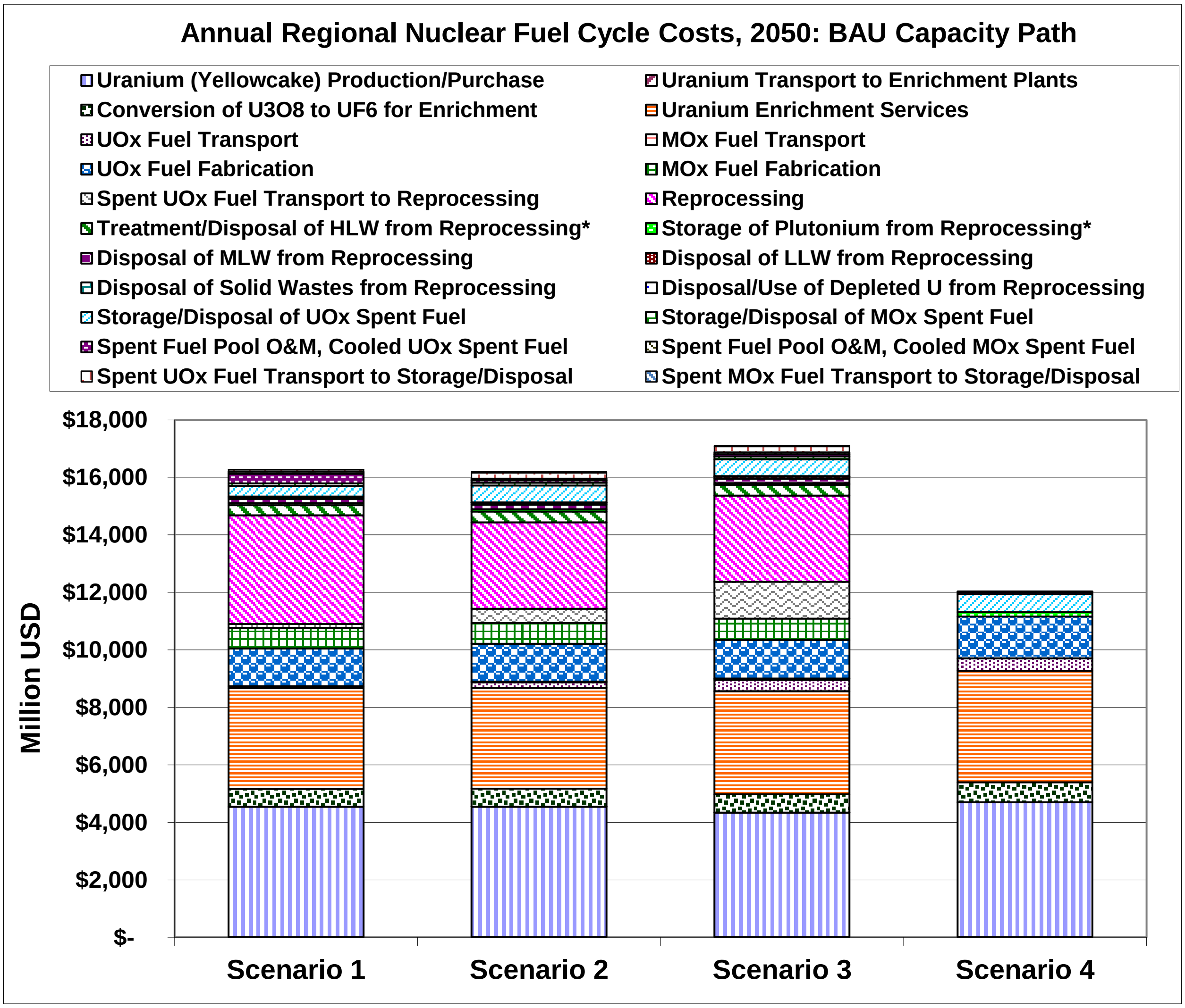
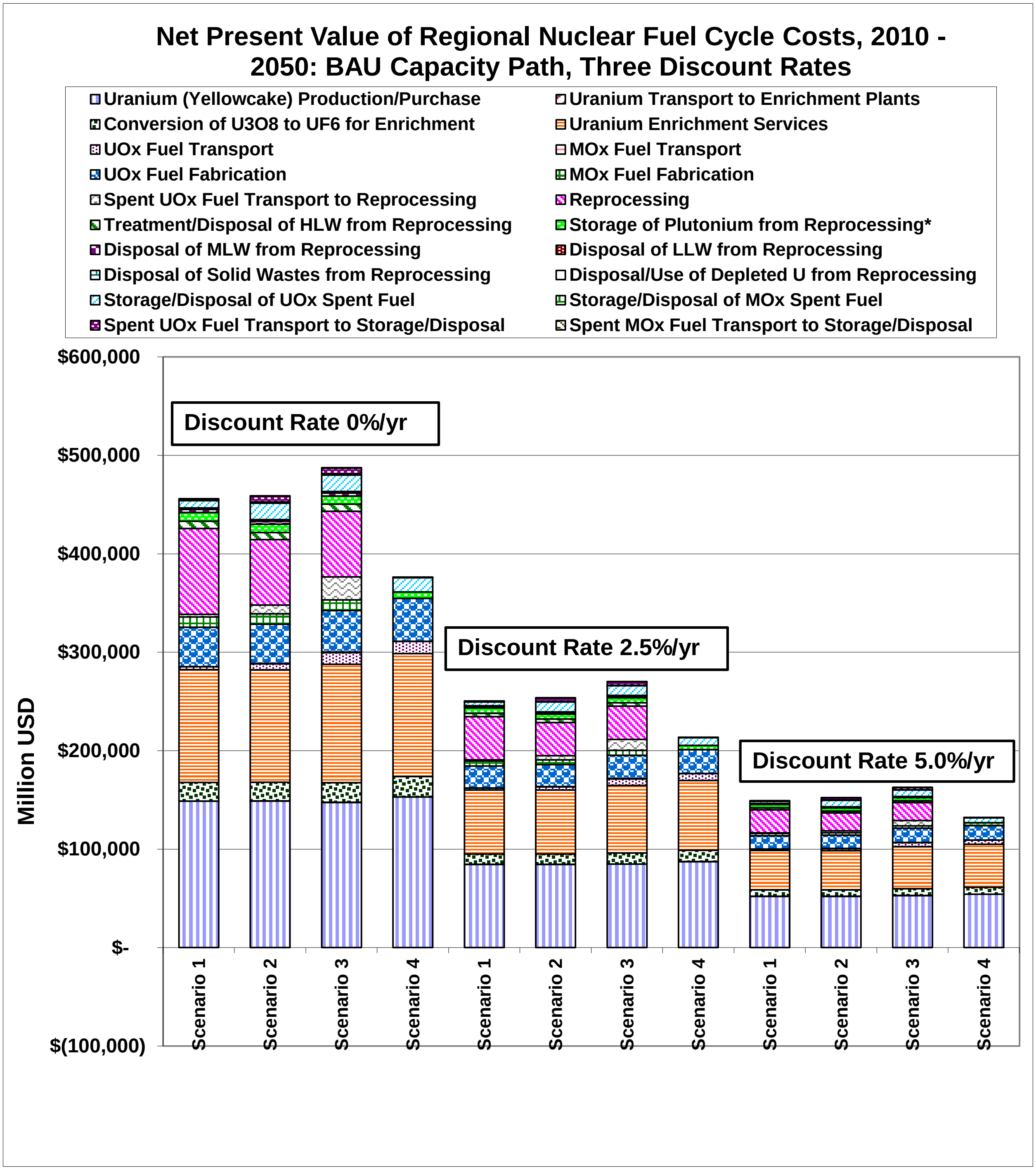


Figure 6-8: Net Present Value of Regional Nuclear Fuel Cycle Costs



6.5.5 Energy Security Attributes Comparison of Scenarios

The broader energy security definition referred to earlier in this Chapter was used to develop a multiple-attribute method of compare national energy policy scenarios. This method was adapted to compare the energy security attributes of the four regional nuclear fuel cycle scenarios developed and evaluated as described above. It should be emphasized that while many different attributes and measures could be chosen for this analysis, the approach taken here has generally been to focus on attributes that are significantly different between scenarios, in order to provide guidance on the key policy trade-offs involved in choosing one scenario over another. Key results of this comparison are as follows:

Energy supply security: Arguably, Scenario 1, in which the major current nuclear energy nations of the region own and run their own enrichment and reprocessing facilities, provides greater energy supply security on a purely national level. On a regional level, depending on the strength of the agreements developed to structure regional cooperation on nuclear fuel cycle issues, Scenarios 2 and 3, and possibly 4, may offer better energy supply security. Scenarios 3 and 4 also offer the added security of shared fuel stockpiles.

Economic security: Scenarios including reprocessing have significantly higher annual costs, when viewed over the entire fuel cycle, than the scenario without reprocessing. The additional cost is still, however, only a relatively small fraction of the cost of nuclear power as a whole. The use of reprocessing and related required waste-management technologies may, however, expose the countries of the region to additional economic risks if the technologies have costs that are unexpectedly high (as has been the case, for example, with Japan's Rokkasho reprocessing plant). In addition, the required additional investment, probably by governments or backed by governments (tens of billions of dollars, at least) in facilities related to fuel reprocessing may divert investment from other activities, within the energy sector and without, of potentially more benefit to the long-term health of the economies of the region. On the other hand, development of in-country and in-region nuclear facilities will have its own job-creation benefits in the nuclear industry and some related industries.

Technological security: Scenario 4, which depends on proven dry-cask storage, depends the least on the performance of complex technologies, but implicitly also depends on future generations to manage wastes generated today. Since all of the other scenarios, however, depend on interim storage of spent fuels, plutonium, and high-level wastes from reprocessing, and thus imply dependence on a future means of safe disposal, the scenarios are not so different in this long-term outlook.

Environmental security: Scenarios 1 through 3 evaluated offer a trade-off between somewhat (on the order of several to 10 percent) less uranium mining and processing, with its attendant impacts and waste streams, relative to scenario 4, balanced by the additional environmental burden of the need to dispose of a range of solid, liquid, and radioactive reprocessing wastes. Differences between the scenarios with regard to generation of greenhouse gases and more conventional air and water pollutants are likely to be relatively small, and are inconsequential when compared with overall emissions of such pollutants from the economies of the region.

Social-Cultural security: To the extent that some of the countries of the region have growing civil-society movements with concerns regarding nuclear power in general, reprocessing in particular, and local siting of nuclear fuel-cycle facilities, Scenario 4 arguably offers the highest level of social-cultural security. This advantage has likely been exacerbated by the social/political fallout from the Fukushima accident, although the different countries of the region are finding and will find that the Fukushima accident has impacts of different types and magnitudes on social and cultural issues related to Fukushima. In some cases current laws—in Japan, for example—would have to be changed to allow the long-term at-reactor storage included in Scenario 4, and changing those laws has its own risks.

Military security: From a national perspective, safeguarding in-country enrichment and reprocessing facilities in Scenario 1, including stocks of enriched uranium and (especially) plutonium, puts the largest strain on military (or police) resources. Those responsibilities are shifted largely to the regional level in Scenario 2, and to the international level in Scenario 3, with less stress on national resources, but more on the strength of regional and international agreements. The level of military security (guards and safeguard protocols) required of Scenario 4 is arguably considerably less than in the other scenarios.

6.6 Summary of Results and Conclusions

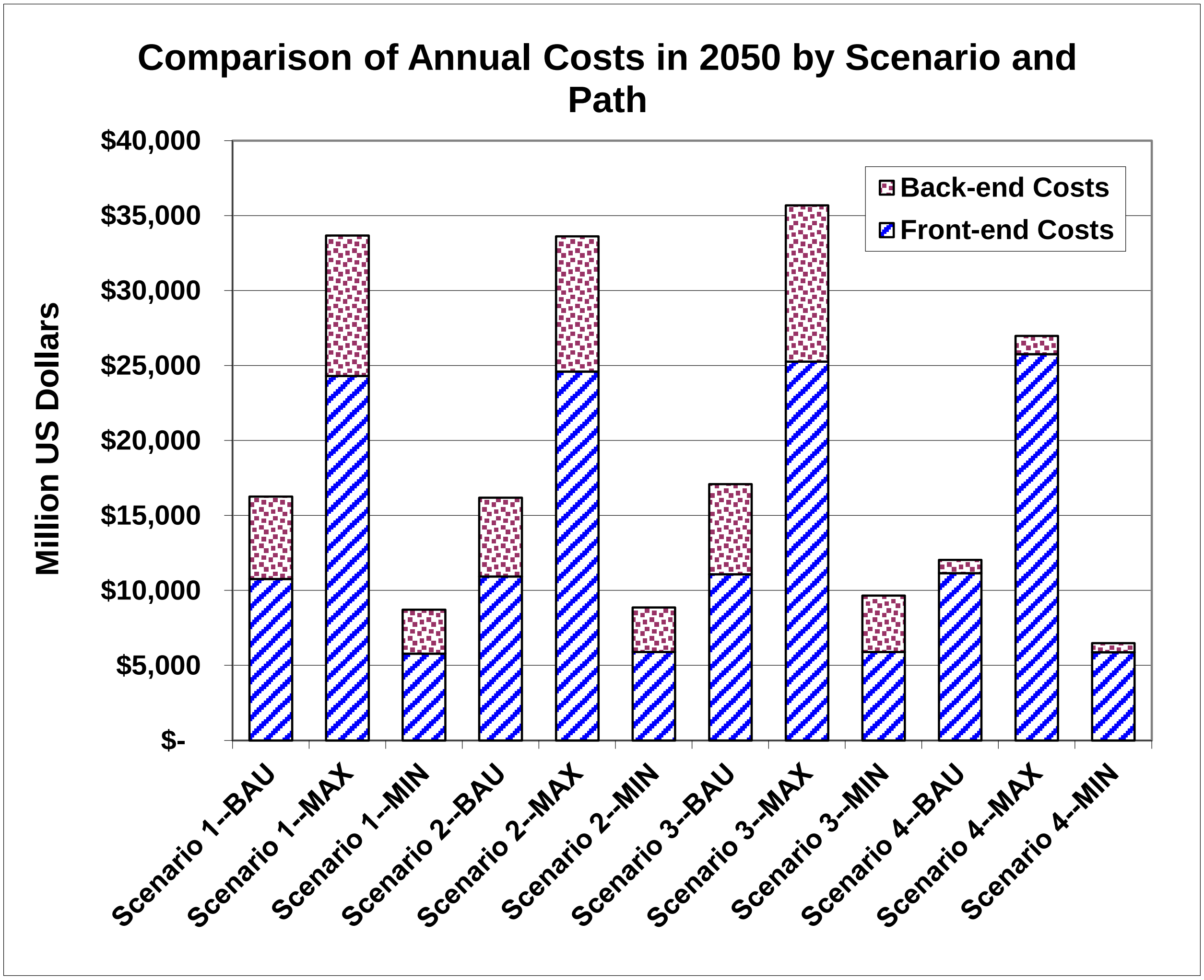
6.6.1 Results

The results of the regional scenario evaluation above indicate that Scenario 4, which focuses on at-reactor dry cask storage and coordinated fuel stockpiling, but largely avoids reprocessing and mixed-oxide fuel (MOx, that is, reactor fuel that uses a mixture of plutonium reprocessed from spent fuel and uranium and as its fissile material) use, results in lower fuel-cycle costs, and offers benefits in terms of social-cultural and military security. These results are consistent with (and, indeed, draw ideas and parameters from) broader studies by other research groups, including, for example, the joint work by the Harvard University Project on Managing the Atom and the University of Tokyo Project on Sociotechnics of Nuclear Energy.

That said, there are definite trade-offs between scenarios. Scenario 1, by using much more domestic enrichment and reprocessing than the other scenarios, arguably improves energy supply security for individual nations, but results in higher technological risk due to national reliance on one or a small number of enrichment and reprocessing plants, rather than the larger number of plants that constitute the international market. Scenario 1 would also raise significant proliferation concerns (not the least of which would be the DPRK's reaction to ROK enrichment and reprocessing). Scenario 1 also results in the build-up of stockpiles of plutonium (Pu) in each of the nations pursuing reprocessing. Though the magnitude of the plutonium stockpiles, and the rate at which they are used, varies considerably by nuclear path and scenario, the quantities accrued, ranging from about 90 to about 200 tonnes of Pu at a maximum in Scenarios 1 through 3 in the years around 2040, are sufficient for tens of thousands of nuclear weapons, meaning that the misplacement or diversion of a very small portion of the stockpile becomes a serious proliferation issue, and thus requires significant security measures in each country where plutonium is produced or stored. Scenario 4, without additional reprocessing, maintains a stockpile of about 70 tonnes of Pu from about 2010 on. This still represents a serious proliferation risk, but does not add to existing stockpiles or create stockpile in new places.

Scenarios 1 through 3, which include reprocessing, result, as noted above, in higher annual costs-about \$3 to \$5 billion per year higher in 2050 relative to Scenario 4, over the entire region. Scenarios 1 through 3 reduce the amount of spent fuel to be managed substantially—by 50 percent or more over the period from 2000 through 2050, relative to Scenario 4—but imply additional production of about 20-fold more high-level waste that must be managed instead (thousands versus hundreds of cubic meters). This in addition to medium- and low-level wastes from reprocessing, and wastes from MOx fuel fabrication that must be managed in significant quantities in Scenarios 1 through 3, but not in Scenario 4. Scenarios 1 through 3 offer a modest reduction—less than10 percent in for the BAU nuclear capacity paths case—in the amount of natural uranium required region-wide, and in attendant needs for enriched uranium and enrichment services. This reduction is not very significant from a cost perspective unless uranium costs rise much, much higher in the next four decades. The quantities of electricity and fuel used for uranium mining and milling, as well as production of depleted uranium, are generally somewhat lower under Scenarios 1 through 3 than under Scenario 4, though results for Scenario 1 differ from Scenarios 2 and 3 because of the emphasis on sourcing uranium from domestic mines in the region. Figure 6-9 shows aggregated front-end (fuel preparation) and back-end (spent fuel management) costs by Scenario and for each of the three nuclear capacity paths for the region.

Figure 6-9: Summary of Year 2050 Annual Costs by Scenario and by Nuclear Capacity Expansion Path



Scenarios 2 and 3, though they include reprocessing, place more of the sensitive materials and technologies in the nuclear fuel cycle in regional and international facilities, and as a consequence, are likely to be superior to Scenario 1 in terms of reducing proliferation opportunities, reducing security costs, and increasing the transparency of (and thus international trust in) fuel cycle activities. The costs of Scenarios 2 and 3 shown in this analysis are not significantly different, overall, from those of Scenario 1, but a more detailed evaluation of the relative costs of nuclear facilities (particularly, enrichment and reprocessing facilities) in different countries, when available, might result in some differentiation in the costs of these three scenarios. Overall, however, although the total costs of the scenarios may vary by several billion dollars per year, it must be remembered that these costs are inconsequential to the overall annual costs of electricity generation in general. In round terms, if one assumes that the total electricity demand in East Asia in 2050 is on the order of 20,000 TWh, or about three times electricity demand in the countries in the region as of 2011, and that the per-unit total cost of electrical energy at that time is on the order of 10 US cents/kWh (perhaps somewhat greater than the average in the region today, but possibly an underestimate for 2050), then the implied total cost of electricity supplies in 2050 in the countries under consideration in this Working Paper is on the order of $2 trillion per year. The nuclear-related costs considered here are therefore just a percent or so of the total, and the differences between scenarios is a just fraction of a percent. Both of these values are easily lost in the margin of uncertainty regarding future power costs.

Scenarios 2 and 3 result in significantly more transport of nuclear materials—particularly spent fuel, enriched fuel, MOx fuel, and possibly high-level wastes around the globe, likely by ship, than Scenario 1, though there would be somewhat more transport of those materials inside the nations of East Asia in Scenario 1.

The scenarios described and evaluated above have, of necessity, to a certain extent suspended consideration of national and international political and legal constraints in order to focus on alternatives for regional fuel cycle management. It is more than clear, however, that there are substantial legal and political constraints to regional cooperation on nuclear fuel cycles, and that these constraints will either limit the opportunities for cooperation, or need to be overcome in some way, in order to allow regional arrangements to proceed. These constraints include (but are unlikely to be limited to) legal and/or political constraints on regional spent fuel management, enrichment, and integrated facilities. Specific discussion of these issues is beyond the scope of this article, but will play a crucial role in determining the practicality of specific cooperation schemes, as discussed briefly in the next and final Chapter of this Report.

6.6.2 Conclusions

Nuclear power will certainly continue to play a significant role in the economies of the countries of the East Asia and Pacific region for decades to come, but the extent of that role, and how the various cost, safety, environmental, and proliferation-risk issues surrounding nuclear power are and will be addressed on the national and regional levels, is not at all certain, and, in the wake of both the Fukushima accident and a host of recent leadership changes, is perhaps more uncertain than it has been in decades. The analysis summarized above indicates that different policy choices today, particularly with regard to cooperation between nations on nuclear fuel cycle issues, can lead to very different outcomes regarding the shape of the nuclear energy sector—and of related international security arrangements—over time. Regional cooperation on nuclear fuel cycle issues can help to enhance energy security for the participating countries, relative to a scenario in which several nations pursue nuclear fuel cycle development on their own. From a number of energy security perspectives, however, a regional nuclear fuel cycle approach (such as that modeled in Scenario 4) that rapidly phases out reprocessing and MOx fuel use, and uses interim spent fuel storage in dry casks (or similar technologies) to manage spent fuel until indefinite storage facilities—potentially including "deep borehole disposal"[264]—has significant advantages. An approach that avoids reprocessing and MOx fuel use would be less expensive as well, though placed in perspective, the $3 billion or so saved annually in 2050 under Scenario 4 relative to other scenarios is just a small fraction of the overall cost of nuclear power, and a tiny fraction of the overall costs of power in general. What this means is that relative fuel cycle costs, at least for the range of LWR-based fuel cycles cooperation/non-cooperation options explored here, should in most cases play a trivial role in decisions about nuclear spent fuel management, and the other considerations described here should thus dominate the policy development process. Of these, it is likely to be the least quantifiable considerations—social and cultural factors, preventing nuclear weapons proliferation, nuclear safety, and military security issues—that are the most important to decisions regarding nuclear spent fuel policy. Unfortunately, these are the very issues that are some of the most difficult to address, particularly in the many instances where addressing those issues require a coordinated international, and intercultural, response.

Nuclear power choices intersect strongly with other energy policies and with security policy issues. As such, the exploration of the implications of different nuclear fuel cycle cooperation (or non-cooperation) options and opportunities in East Asia informs issues such as deployment of new nuclear technologies, climate change, and non-proliferation, but needs to be expanded to more fully address those issues.

A number of new types of reactors—including, for example, small, modular reactors, "fast" reactors using and producing plutonium fuels, and reactors based on a Thorium fuel cycle, to name just a few—have been proposed for implementation in the coming decades (typically after 2030, and often later). In addition, variants on the existing LEU/MOx fuel cycle, including a version of reprocessing called "pyroprocessing", have been proposed by various groups, including, recently, in the ROK. How might the implementation of these new nuclear technologies affect the form or prospects of nuclear fuel cycle cooperation in East Asia? Given that, for example, small and medium reactors and "Gen IV" reactor designs are likely to be at least 20 years from commercialization[265], it seems clear that such reactors will play only a small role in the overall reactor fleet by 2050, or perhaps at most a moderate role in a "MAX" nuclear capacity expansion path. There is considerable uncertainty as to which next-generation reactors will be deployed, how much they will cost, and as to the implications their deployment may have for the region's nuclear fuel cycle. Given these uncertainties, consideration of the impact of next-generation reactors has been beyond the scope of this Working Paper, but should be included in future work.

Climate change is a major and growing concern worldwide, with countries and sub-national jurisdictions making plans not just for reducing GHG emissions, but for adapting to impacts of

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[264] See, for example, von Hippel, D., and P. Hayes (2010), *Engaging the DPRK Enrichment and Small LWR Program: What Would it Take?* Nautilus Institute Special Report, dated December 23, 2010, and available as http://nautilus.wpengine.netdna-cdn.com/wp-content/uploads/2011/12/Deep-Borehole-Disposal-von-Hippel-Hayes-Final-Dec11-2010.pdf.

[265] See, for example, Goldberg, S.M, and R. Rosner (2011), *Nuclear Reactors: Generation to Generation*. American Academy of Arts and Sciences, available as http://www.amacad.org/pdfs/nuclearReactors.pdf.

climate change that seem inevitable. Nuclear power is enjoying a resurgence of interest worldwide—though as yet, with the exception of China, relatively little new reactor construction is underway. A part of this interest is related to nuclear power's potential role in meeting energy needs without substantial GHG emissions. Some of the major issues associated with the linkages between nuclear power and climate change include the environmental implications of a "nuclear renaissance" for GHG emissions reduction, the economic, social, and political implications of a broad program of nuclear power development, relative to other GHG mitigation strategies, and the benefits and challenges posed by nuclear power in terms of adaptation to a changing climate.

Finally, there is a substantial link between nuclear fuel cycle choices and the risk of nuclear weapons proliferation, as indicated above. The presence of the DPRK in East Asia makes the proliferation issue especially pertinent in the region, as does the history of conflict between many of the region's nations, including ongoing territorial disputes among virtually all pairs of parties one could name (with the possible exception of Mongolia). Choices of nuclear fuel cycle approaches will affect national and international security arrangements. Specifically, if a Nuclear Weapons Free Zone in the region is to be developed, the future of nuclear fuel cycle development and cooperation in the region will be an integral part of the discussion[266].

[266] See, for example, Morton H. Halperin (2012), *Promoting Security in Northeast Asia: A New Approach*, presented at "A New Approach to Security in Northeast Asia: Breaking the Gridlock", October 9-10, 2012, Washington, DC, and available as http://nautilus.wpengine.netdna-cdn.com/wp-content/uploads/2012/10/Halperin-New-approach-to-Northeast-Asian-Security-Oct8-2012.pdf.

7 Overall Conclusions and Next Steps

In this Chapter we summarize the overall conclusions and key findings of the project to date, and offer ideas as to the next steps in moving forward with the key topics—radiological risk reduction, deep borehole disposal of nuclear materials, and spent fuel management cooperation—covered in the project. These next steps include both activities that are candidates for further work by Nautilus and its partners, and activities that might be pursued by the international community more broadly.

7.1 Summary of Key Findings

Key findings of the project to date include the following:

- The Fukushima accident has had a profound impact on the nuclear sector in each of the three countries included in this Project, but the response to the accident has been different in each country with respect to both the modes of response and the degree of response. Japan has shut down its reactors for extensive safety checks and, according to Japan country team member Tomoko Murakami, extensive retrofits related to back-up and other systems that were implicated in the Fukushima accident. In the ROK, reactors were also checked for safety, although a more recent scandal that has come to light regarding falsification of certifications for reactor parts has added to concerns raised by Fukushima. In China, the Fukushima incident has caused authorities to revisit ambitious reactor construction plans, and to somewhat slow the pace of nuclear plant construction, including reconsideration of some plants, notably those to be located inland. Inland plants are on rivers where reactor cooling, at times, and particularly in consideration of potential changes in water availability due to climate change impacts, may be problematic.
- The results of the Fukushima accident have shown, and findings of this project have underlined, the need for key power and cooling water provision systems at reactors and in spent fuel pools to be both multiply backed-up and also sufficiently separate that an accident in one element (such as a reactor) does not cascade to pose a threat to another unit (another reactor or a spent fuel pool). As noted above, increasing the redundancy of key systems has been a key feature of the response of the nuclear industry in Japan to the Fukushima accident.
- The project has shown that some modes of management of spent fuel—non-dense racking in spent fuel pools vs. dense racking, and dry cask storage of cooled spent fuel, including centralized, below-ground storage—are superior to current methods of spent fuel management. Some of these alternative methods are under investigation in the region, but the pace of adopting these methods of risk reduction is slow, in part due to a combination of a lack of independence between the authorities regulating nuclear power in each nation from those planning and implementing nuclear power facilities, and in part because of existing laws regarding the siting of nuclear facilities, particularly in Japan and the ROK, that make it

difficult for reactor operators to store spent fuel on site in dry casks, but do not affect the storage of spent fuel in pools.

- Each of the nations involved in the project has at least a general interest in international collaboration on spent fuel issues, but because of asymmetries between the nations, collaboration has been difficult to start. These asymmetries include China being a nuclear weapons state, while Japan and the ROK are not, and Japan having a reprocessing program and uranium enrichment capability, while the ROK does not (although it wishes to pursue a lightly-modified form of reprocessing called "pyroprocessing). In addition, longstanding regional rivalries likely impede the potential for cooperation on this sensitive issue.
- Dry-cask storage of spent fuel appears much less vulnerable to release of radiation through accident or attack than storage in spent fuel pools. Release of radiation from fuel stored in dry casks essentially requires a concerted effort targeted specifically at the dry cask to not only break it open—requiring high explosives detonate essentially on the cask or physically drilling into the cask, requiring proximity of attackers—but to ignite the spent fuel assemblies stored in the cask. Zircaloy-clad fuel assemblies in dense-racked spent fuel pools, on the other hand, can ignite if water from the pool is lost, as dense-racked pools lack the ability to passively release sufficient heat through the air when coolant is lost, leading to rising temperatures and, eventually, ignition of fuel cladding, resulting in releases of radioactivity.
- Deep borehole disposal of nuclear spent fuel and high-level waste seems likely to be an attractive possibility, and there are areas within the Korean peninsula and China, as well as in other countries of the region, though possibly not in Japan, that would make good hosts for deep borehole facilities from a geological point of view. Deep borehole disposal facilities may well even have cost advantages over other forms of disposal (such as mined repositories). Deep borehole disposal, however, will require both technological advances to assure that key operational elements, such as emplacement of wastes, can be done safely and in a reliable manner, as well as domestic and possibly international policy agreements to allow the siting of deep borehole facilities. In addition, materials stored in deep boreholes should likely be considered essentially irretrievable, as a huge effort will be required to remove emplaced materials from boreholes. This can well be considered a significant advantage, from a risk-of-diversion-of-nuclear materials point of view, but it brings up significant design considerations, and is of concern to those who see spent fuel as a potential future resource for energy production. Dr. Neil Chapman summarized the status of readiness of deep borehole technologies, despite their potential simplicity and low cost relative to mined repositories as probably being 30 or so years from full-scale implementation, or about the same as other disposal options (or, for that matter, the closed nuclear fuel cycle options involving the use of fast reactors that are under consideration in all three of the nations involved in this project). What this means is that it is inevitable that intermediate spent fuel storage, and most likely dry cask storage, must be employed by all three nations in advance of any final disposal option.

- Our preliminary calculations have indicated that the costs of spent fuel management in general are very modest when compared to the full cost of nuclear generation, and particularly when compared with the cost of electricity in Japan, the ROK, and China (Japan especially). Costs of nuclear cooperation (or non-cooperation) scenarios that include reprocessing are higher than those without reprocessing if any reasonable estimates of future uranium prices are assumed, and costs for dry-cask storage are likely to be a tiny part of overall nuclear fuel cycle costs.

7.2 Next Steps in Reduction of Radiological Risk, and Follow-on Activities

Reducing spent fuel density at existing and future reactors would require changes in design and operation, especially in BWRs (boiling water reactors). The resulting incremental cost of these changes per unit of electricity is highly likely to be tiny, but the benefits in terms of avoided risk of radiological emissions and damage could be huge, as could the benefits of avoided public anxiety. Conversely, the risks of not changing spent fuel pool practices could be catastrophic. Moreover, reducing pool density implies choices with regard to dry cask storage versus surface or underground spent fuel pools outside existing secure reactor containment buildings, posing different and new risks of technological accident and/or malevolent attack (in the ROK, DPRK missile or bomb attack; in the PRC, of non-state actor attack, in particular).

It is clear that further work is needed to identify technical means of reducing the risks associated with current common practices of spent fuel storage, to more rigorously estimate the relative costs and benefits of adopting risk-reduction approaches, to communicate the results of those assessments to decisionmakers, and to work with decisionmakers to develop policies that work toward risk reduction. One approach to accomplishing these tasks might be to convene an expert group on spent fuel management that includes both advocates of changed spent fuel management and critics and skeptics of the case that spent fuel pool density should be reduced. This might start in one country, probably Japan. Subsequently, the expert group could be broadened by convening a regional workshop involving representatives from the ROK, Taiwan, and China, as well as US and Japanese experts to address this issue, and ways to mitigate the different hazard events (natural disasters, aerial bombardment, non-state attack). In addition to expert meetings, synthesis, analysis, and summarizing of findings for policy input would be carried out.

In Japan, there is now a strong civil society and business constituency, as well as a well-informed nuclear-expert community, able and willing to address this issue in policy contexts, as part of the overall battle to reform the "nuclear village", and to reconstitute the social pact that sustains the LWR-reprocessing-breeder reactor strategy in Japan. In Korea, there is less public interest, but keen political and bureaucratic interest given the issue's salience of the US-ROK nuclear cooperation "123" negotiations.[267] There are key political and social constraints on fuel storage options in both nations that need further exploration in light of recent events. Policy options are less constrained and therefore more open in China, and we believe that Chinese experts and policymakers will respond to new data and analysis.

[267] See, for example, World Nuclear News (2013)," US-Korea 123 extension is passed", dated September 19, 2013, and available as http://www.world-nuclear-news.org/NP-US-Korea_123_extension_is_passed-1909137.html.

In short, it is critical to nuclear security to clarify whether reducing spent fuel pool density is justified to reduce the possible risk of inadvertent or malevolent radiological release from spent fuel pools and reactor sites.

Particularly in Japan and the ROK, dry cask storage at or away from reactor sites is clearly an attractive option for reducing radiological risks associated with spent fuel pools in the short-to-medium-term. There are, however, a host of legal, political, and institutional barriers preventing the wider use of this technology in both countries. Better understanding these barriers, and how to overcome them in each nation, is therefore a key need. To that end, working with colleagues and civil society groups in the region to better understand the challenges to siting at-reactor or away-from-reactor dry cask storage options that would reduce risks associated with spent fuel pools is an attractive activity that would build on the results of the current project, as well as other research efforts in the region.

7.3 Next Steps on Deep Borehole Disposal of Nuclear Materials, and Follow-on Activities

Among the perceived favorable characteristics of deep borehole disposal of nuclear materials are its inherently modular nature, potentially lower costs, and widespread applicability. As a results, there is the possibility of sharing international R&D, and ultimately, of separately licensing the borehole technology and the disposal facility that allows nuclear waste to be disposed of in boreholes, analogous to generic reactor design licensing of different technologies.

Discussions on borehole operations focus on the need to understand drilling damage (extent and properties of the disturbed zone close to the borehole) and on the need for high integrity, low permeability seals to assure long-term isolation. Characteristics of the interface between the seals and the borehole wall will be particularly important. Potential operational problems during emplacement, including damage to canisters and waste during the trip down the borehole, should be minimized, and it may be desirable to line the hole for its entire length with steel casing. A reference design concept to provide a baseline for evaluating performance and impacts of alternative approaches may be useful.

Section 4.7 of this Summary Report reviewed a list of R&D questions, generated during a 2009 US workshop on the topic, that ranged from the design of pilot tests through investigations into particular technical aspects of borehole technology. These questions remain pertinent, and could be the topics of a series of further collaborative workshops and/or investigations on DBD topics.

In summary, for DBD to move forward, work will be required on a number of topics – in particular:

- Large-scale testing/demonstration is essential if further progress is to be made;
- A more comprehensive operational and post-closure safety evaluation for DBD is essential – this is not an obstacle, as it can be done readily today, with available international expertise and data.

International cooperation, including, perhaps, cooperation between the countries of Northeast Asia, could help to move the concept forward through evaluation of the generic aspects of the technology. Such an effort would be amenable to an international co-operation project, and there is potentially sufficient interest from a number of countries to consider such a shared multinational project. The project would ultimately need a host country for the engineering trials. A first step in consideration of DBD by the countries of Northeast Asia, however, might be convening a regional meeting, attended by researchers and officials responsible for designing and managing nuclear waste disposal in the countries of the region, at which DBD concepts are described, and discussions are held on the specific barriers, especially institutional barriers, to DBD in the countries of the region.

In the China-Japan-ROK region, the amounts of radioactive material to be disposed of make shared disposal facilities look less attractive, for many reasons, but shared R&D could be highly appropriate, particularly given some of the potential institutional resistance to DBD (due to nuclear sector priorities) in many of the countries of the region. That is, it may be easier for a country to participate in a multi-nation project exploring DBD in than to negotiate internally for funding and support for a national DBD program.

Ultimately if DBD proves to be an attractive and acceptable means of spent fuel disposal, the location of a shared site remains a key question. Several countries of the region, including nuclear weapons states Russia and China, almost certainly have suitable geology suitably remote from population centers. Mongolia has been mentioned as a potential participant in the nuclear fuel cycle, likely has suitable sites for DBD, and is considered a neutral party, though indications are that substantial nuclear sector development in Mongolia appears to be off the table from a political perspective.[268] As a consequence, a regional DBD facility, as with other shared nuclear facilities, would likely require years of patient international negotiation and institution building, as well as the types of technical R&D mentioned above, to come to fruition. Convening of an international workshop to begin to discuss these issues would therefore be a significant first step in this direction.

7.4 Next Steps on Spent Fuel Cooperation, and Follow-on Activities

The scenarios on nuclear fuel cycle cooperation, including on spent fuel management, as summarized in Chapter 6 of this Report, have of necessity, to a certain extent suspended consideration of national and international political and legal constraints in order to focus on alternatives for regional fuel cycle management. It is more than clear, however, that there are substantial legal and political constraints to regional cooperation on nuclear fuel cycles, and that these constraints will either limit the opportunities for cooperation, or need to be overcome in some way, in order to allow regional arrangements to proceed. These constraints include (but are unlikely to be limited to) legal and/or political constraints on regional spent fuel management, enrichment, and integrated facilities. These issues will play a crucial role in determining the practicality of specific cooperation schemes. As such, the development of cooperation arrangements will need to be built through follow-on activities that include a

[268] Personal communications from a Mongolian official to D. von Hippel, 2013.

combination of expert analysis and input, through development of, for example, a report laying out the possible organization and activities of institutions for nuclear fuel cycle cooperation in the region, plus one or more workshops, attended by representative from the region, to discuss the political, organizational, institutional, and economic challenges that might be faced. The report on the potential organization of fuel cycle cooperation would build on previous work on the topic, but would also extend Nautilus' existing quantitative analysis to further describe the physical flows of materials and costs that would be involved, as well as use sensitivity analysis to examine the response of results to changes in key parameters. The workshop on barriers and challenges likely to be faced by nuclear sector cooperation would look at challenges faced on a national level in each country, as well as regionally and internationally, and would explore ways of overcoming those challenges.

The underpinnings of Nautilus' work on nuclear fuel cycle cooperation in general, and spent fuel management in particular, has been our work since 2000 with Country Teams on energy sector status, policy, and futures in the countries of the region. Continuing and deepening this work, including advanced full energy-sector and national/regional energy futures modeling, will continue to provide the full economic, environmental, political and social context for nuclear energy, and thus, nuclear spent fuel management and nuclear cooperation scenarios. Deepening this work to include more detailed non-nuclear (for example, renewable energy and energy efficiency) greenhouse gas emissions mitigation scenarios to compare and combine with nuclear scenarios will help to round out the consideration of nuclear energy paths, and to set the relative context for nuclear power and nuclear spent fuel management. A potential simultaneous activity could be to broaden, as Nautilus has done in years past (but has not been funded to do in recent years), the group of participating nations to include those in the East Asia and Pacific region with nascent or proposed nuclear energy programs, both to gain the insights of those groups and to explore the particular issues associated with building and operating the elements of a nuclear energy system (including spent fuel management) in nations without nuclear experience. The combination of representatives from nations with long nuclear experience and those from nations seeking to join the "nuclear club" offers significant opportunities for sharing of knowledge and perspectives, and for uncovering both challenges to and opportunities for cooperation in nuclear fuel cycle management.

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ANNEX 1: Selected Inputs, Assumptions, and Additional Results of Radiological Risk Estimates for Daya Bay and Ling'Ao Nuclear Power Plants (China)

ANNEX 1A: Selected Inputs and Assumptions: Daya Bay Analysis

APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

CASE STUDY: China's Daya Bay Reactor Complex
David von Hippel, Date Last Revised: 2/3/2015

Nominal thermal capacity of reactor	2905	MWth http://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=63
Electricity generation capacity of reactor	984	MWe (Gross--944 MWe net, source for net output, http://www.nti.org/facilities/779/ and IAEA website above)
Level of enrichment in U235	4.45%	
Mass of Uranium in reactor core	72.4	te heavy metal (HM)
which implies	24.92	kg/MWth
Number of fuel assemblies per core	157	
Implied tHM per assembly	0.461	

Lifetime performance through 2013 from IAEA website above

	Electricity Supplied (TWh)	Energy Availability Factor	Operation Factor	Energy Unavailability Factor	Load Factor
Daya Bay Unit 1	**138.44**	**84.40%**	**86.60%**	**15.60%**	**84.40%**
Daya Bay Unit 2	**137.15**	**84.70%**	**86.50%**	**15.30%**	**84.60%**

Following from http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China--Nuclear-Fuel-Cycle/:
"A standard 18-month fuel cycle is the normal routine for Daya Bay, Ling Ao, and early M310 to CPR-1000 reactors. This has average burn-up of 43 GWd/t, with maximum of 50 GWd/t."

We therefore assume a burn-up of: 43 GWd/tonne Heavy Metal

Based on reports below, we assume that 40% of fuel is replaced every
18 months, which implies that the fuel that is
removed has been in the reactor for about 45 months.
GW-th-days of burnup in fuel removed from core 1,342
Total GW-th-days of burnup in core at refuel 2,282

The website http://nuclear-power-plants.findthedata.com/l/598/Daya-Bay-Nuclear-Power-Plant-Unit-1
lists the spent fuel pool inventory at Daya Bay Unit 1 as 282 tHM, and
http://nuclear-power-plants.findthedata.com/l/599/Daya-Bay-Nuclear-Power-Plant-Unit-2
lists the spent fuel pool inventory at Daya Bay Unit 2 as 284 tHM.

Implied annual average discharge per reactor: 19.31 tHM/yr
or, by an alternative calculation 20.81 tHM/yr
Some of the references below and elsewhere list the annual spent fuel production at 50 tHM,
which likely either corresponds to both reactors and/or to the lower level of enrichment and more rapid fuel replacement used in earlier years of reactor operation.

From the data below, the spent fuel pool capacity of 690 assemblies appears to correspond to
about 318.19 tHM
The comparison of this result with the inventories reported above suggests that typical operations leave room for about
1.18 fuel replacement cycle (for one reactor), which implies
less free space is left in these pools than typically would be the case (a full core plus one refueling).
Some references below (and elsewhere) list the design capacity of the spent fuel pools as 10 years, and
other references list the capacity as 8 years. The former seems closer to current practice based on 19.31
tHM/yr discharge per reactor.
We assume that the reactors have operated for 36 months from the most recent refuel as of the time of this radiological risk calculation.

We assume that the transport casks used for Daya Bay spent fuel transport to Lanzhou or another storage location are of the NAC-STC type
(see Liu Xuegang (2012), *China's Nuclear Energy Development and Spent Fuel Management Plans* ,
Nautilus Special Report available as http://nautilus.org/napsnet/napsnet-special-reports/chinas-nuclear-energy-development-and-spent-fuel-management-plans/
These casks hold 26 assemblies each, meaning that they hold 11.99 tHM each, and
that to hold a refuelings' worth of cooled spent fuel from the spent fuel pool for 2 reactors will require 4.83 casks
This is somewhat less than the 104 assemblies per year (apparently) estimated in Zhou, 2011 (see below), but is
on the same order of magnitude.

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We consider two main scenarios for incidents involving the Daya Bay reactors and spent fuel pool. For the first scenario, which we call "Worst-case Reactor Incident" (or "S1"), one of the reactors is assumed to suffer a core breach and subsequent loss of coolant due to an extreme seismic event or attack. In this case, the spent fuel pool may or may not suffer a loss of coolant, either through being breached by the same event or by losing cooling capacity when utilities (power and/or water) are lost as a result of the incident, but because the spent fuel pool is not dense-packed, the spent fuel in the pool is able to cool in air and a zirconium cladding fire does NOT ensue. We assume, in scenario 1, since the two Daya Bay units are physically separated, that the second reactor core remains intact, and standard or emergency cooling can be maintained, even if there is damage to the second reactor. This scenario therefore does not include common mode failures--such as the interruption of pumping and water utilities affecting both units, coupled with radiation or other conditions that prevent emergency cooling measures from being undertaken.
For the second scenario, which we call "Worst-case Spent Fuel Pool Incident" (or "S2"),we assume that as a result of a seismic event, catastrophic operational accident (such as dropping a transport cask into the pool), or terrorist attack, the pool suffers a coolant loss and cooling cannot be restored before cooling water mostly or completely evaporates. Further, those regions of the stored spent fuel that have been most recently (within the past few months) have been off-loaded from the two reactors are assumed to reach temperatures high enough for cladding failure and ignition, resulting in a zirconium fire that engulfs an amount of spent fuel equal to the most recent off-loading.

The "Participation Fraction" ("PART FRAC") of the material in the spent fuel pool is assumed to be a function of the density of racking in the pool. We assume that the racking continues to be low-density in both scenarios.
In S1 we assume that even if the incident focused on a reactor does cause a loss of coolant in a spent fuel pool, passive cooling in air is sufficient that the cladding does not reach ignition temperature, and thus the Participation Fraction for each of the spent fuel pools in S1 is 0, and the release fraction is similarly 0
In S2, however, we assume that the most recently off-loaded spent fuel, a total of
28.96 teHM, does participate in a pool fire
The Participation Fraction for the spent fuel pool (assumed to be unit 2) in scenario 2 would therefore be 0.10
In this scenario involving cladding failure and significant Cs-137 emissions (S2), a release fraction of 0.3 is assumed.
We assume that in this scenario only the spent fuel pool for the first unit is affected, and thus the participation and release fractions for the spent fuel pool for the first unit are both 0.

For one of the reactors, for S1, we assume that it experience a core melt, and thus its participation fraction is 1, though the participation fraction for the second reactor is assumed to be 0, and the release fraction is similarly 0.
Based on consideration of Table II.3-7 in the Handbook, as well as estimates of fraction of the Cs-137 inventory in the Fukushima reactor cores that were released to the atmosphere (see, for example, Stohl et al, 2012 (http://www.fukushimaishere.info/AtmosphereRprt_mar12.pdf) and Koo et al, 2014 (abstract at http://www.sciencedirect.com/science/article/pii/S0149197014000444),
we assume a release fraction of 0.05 for one of the reactors for S1,
which assume an incident that would breach containment and the reactor vessel, and severely damage the reactor and the fuel within.

For the both of the reactors, for S2, we assume that the incident involving one of the spent fuel pools does not affect the reactors enough to cause a core melt (or emergency procedures are sufficient to prevent a core melt if the reactors is damaged, and thus the participation fraction for both reactors is by definition 0.
The release fraction ("REL FRAC") for S2 for the reactors is assumed to be 0, since the neither reactor is assumed to undergo a core melt.

In either scenario, though dry casks or transport casks are present at the time of the incident (and transport casks, at least, may well be), we assume that the casks will be sufficiently distant from the reactor and spent fuel pool and/or sufficiently robust that their participation and release fractions are all 0. An possible exceptional case might be if the incident (accident or attack) occurs the period when transport casks are being loaded, in which case, depending on where they are physically located near the spent fuel pool and how much fuel is in them at the time of the incident, there could be additional complications. The spent fuel placed in transport casks, however, has been cooled for several years, and is thus likely to be passively cooled if coolant is lost. The spent fuel in a not-yet-closed transport cask might be vulnerable to terrorist attack with an incendiary device that would ignite the cladding in the spent fuel in the cask, but this eventuality is not explicitly considered in our scenarios.

We assume an average wind speed of 3.4 meters/second, based very roughly on considerations of recent annual windspeed values for the spring and fall (when prevailing winds are mostly East to West from http://www.windfinder.com/windstatistics/ for Shanwei, which is East along the coast from Daya Bay, and Hong Kong, which is West and South from Daya Bay. An older document entitled "Environmental Radiation Monitoring in Hong Kong, Technical Report No. 3, Surface Meteorological Conditions in Daya Bay, 1984-1988, available as http://www.hko.gov.hk/publica/rm/rm003.pdf, dated July, 1991, by B.Y. Lee, M.C. Wong and W.Y. Chan of the Royal Observatory, Hong Kong,
suggests that average wind speeds in Daya Bay are more likely to be similar to those in Shanwei than in Hong Kong.
This wind speed is equivalent to 12.07 km/hour

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Given the approximate nature of this modeling effort, we use a deposition velocity ("DEP VEL") of 1 cm/second, or 0.01
which is a typical value used with the wedge model.
Alternatively, we could have chosen a deposition velocity by applying the figure below from Figure II.4-2 in the Handbook, along with the table at right from http://yosemite.epa.gov/oaqps/eogtrain.nsf/b81bacb527b016d785256e4a004c0393/c9862a32b0eb4f9885256b6d0064ce2b/$FILE/Lesson%206.pdf, which defines the Pasquill-Gifford categrories of atmospheric stability (A-G in the Figure II.4-2. For the Daya Bay site, data in the 1991 document above indicates that atmospheric stability is (or was as of the late 1980s) largely in category D, which assumes that insolation is not, on average, strong.
Reading a DV off the graph below for an average wind speed of 3.3528 meters/second and category D, we get a DV of 0.78 cm/second, which is close to the typical value adopted as above.

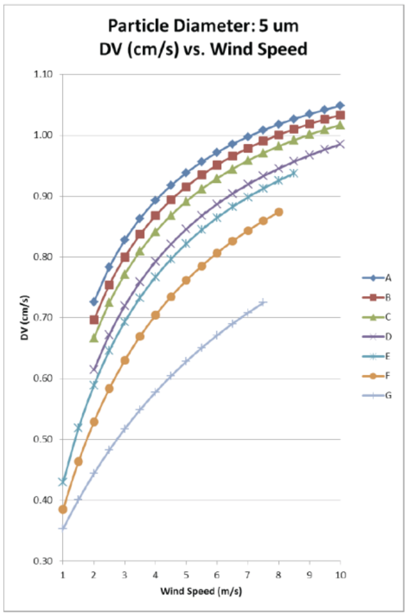


Table 6-1. Key to stability categories

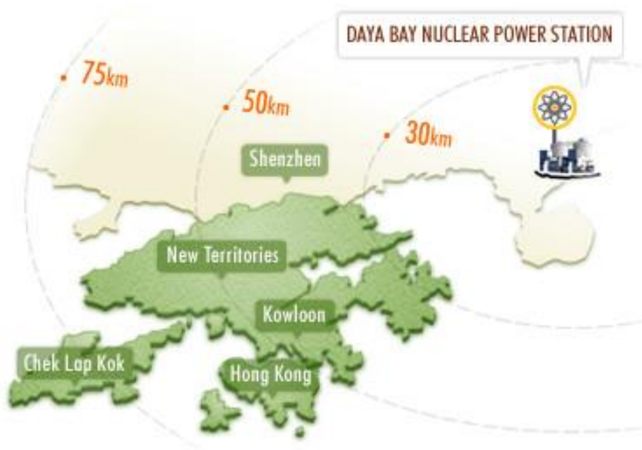
Surface wind Speed (at 10 m) (m/s)	Insolation			Night	
		Moderate	Slight	≥ 4/8 low cloud cover*	≤ 3/8 cloud cover
< 2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
> 6	C	D	D	D	D

* Thinly overcast
Note: Neutral Class D should be assumed for overcast conditions during day or night.

Notes:
(a) This figure is from: Rishel and Napier, 2012.
(b) The letters A through G refer to Pasquill-Gifford (Pasquill) categories of atmospheric stability.

For the variable Mixing Height ("MIX HT"), we use the default value from Table II.4-1 in the Handbook, 1000 meters, or 1 km
We also use the handbook defalut value for the wedge angle ("WEDGE ANG"), 0.25 radians, as well as for the
Shield Factor ("SHLD FAC"), set equal to 0.33
We make a first calculation with an exposure time of 1 year

Following from https://www.hknuclear.com/dayabay/location/pages/locationsiteselection.aspx



Following from https://www.hknuclear.com/dayabay/waste/pages/spent.aspx

"The nuclear fuel that has been expended in the reactor during the fission process is known as spent fuel. Spent fuel assemblies are removed from the reactor during refuelling and held underwater in a fuel storage pool in the fuel building. Daya Bay produces about 50 tonnes of spent nuclear fuel each year and the station has the capacity to store for at least 10 years' worth of spent nuclear fuel."

Following from https://www.hknuclear.com/dayabay/plant/pages/plantandequipment.aspx

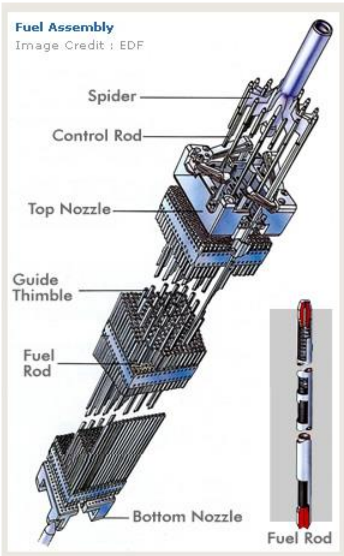
"Daya Bay comprises two identical 984 MW (gross) pressurised water reactor type electricity generating units adopting French reactor design and manufacture."

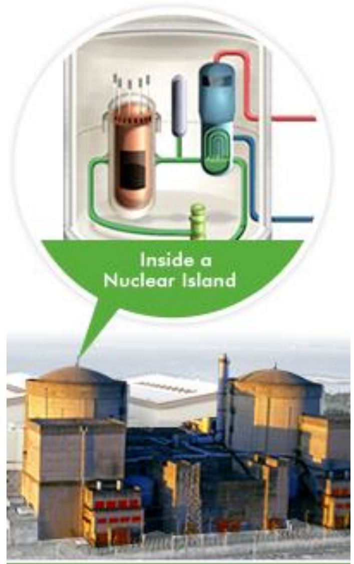
Following from https://www.hknuclear.com/dayabay/plant/features/pages/basicfeatures.aspx

Each generating unit at Daya Bay consists of a "nuclear island" (left picture (1)) w here the steam is produced and a "conventional island" (left picture (2)) w here the steam is used to produce electricity. These tw o generating units are supported by various other station facilities (left picture (3)).

Following from https://www.hknuclear.com/dayabay/plant/nuclearisland/reactor/pages/nuclear.aspx

"The reactor contains nuclear fuel which undergoes a fission process - the splitting of atoms -- to produce heat. At Daya Bay, uranium 235 with an enrichment of 4.45% is used as nuclear fuel. It is loaded as sintered fuel pellets of uranium oxide inside fuel rods to make up a fuel "assembly". Each square prismatic assembly is about half a tonne in weight and its 17 X 17 grid contains 264 fuel rods, 24 guide tubes for control rods and a tube for instrumentation. An assembly is about 4.4 metres tall and just over 20 centimetres wide." "Each reactor uses 157 fuel assemblies grouped into a core of about 3.7 metres high and 3 metres in diameter, producing just under 3,000 MW of heat. Although each fuel assembly has a set of 24 guide tubes for the control rods that help control the reaction process, not all of the 157 sets of guide tubes are used. At Daya Bay, 61 sets of control rods are enough to maintain the safe operation of the reactor and the unused guide tubes are plugged." "A fuel assembly stays inside the reactor for between three and four-and-a-half years. A change of fuel, known as refuelling, takes place roughly every 18 months and each time about 40% of the fuel assemblies are replaced.
Refuelling can be done in slightly over a week, but the opportunity is usually taken to conduct maintenance of the power station. This period typically takes 30 days, although more time may be taken if additional inspection and maintenance are considered necessary."





Following from http://www.nti.org/facilities/779/

"The Guangdong Nuclear Power Station produces roughly 50 tons of spent nuclear fuel each year and "has the capacity to store… at least 10 years' worth of spent nuclear fuel."[5] However, most of the onsite storage at GNPS is full so spent high-level waste is being transported over 2,500 km to the Lanzhou Nuclear Fuel Complex.[6]"

Other references
Stephen Vines (2010), "Daya Bay leak exposes a culture of secrecy", *South China Morning Post* , PUBLISHED Friday, 18 June, 2010
http://www.scmp.com/article/717376/daya-bay-leak-exposes-culture-secrecy

Nuclear Engineering International (2012), "Chinese nuclear fuel", dated 1 June 2012
http://www.neimagazine.com/features/featurechinese-nuclear-fuel/

The follow suggests that dense-packing of the spent fuel pool is NOT being practiced in Daya Bay, but is being practiced at other Chinese plants.
https://www.amacad.org/content/publications/pubContent.aspx?d=1011

Following from http://www.weather.gov.hk/radiation/tidbit/201103/safe_e.htm

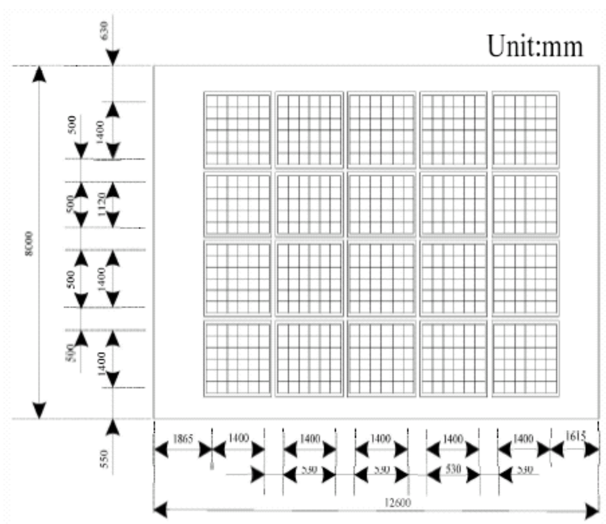
Following is from By Xuegang LIU (2014), *Spent Nuclear Fuel Management in China* , March, 2014, available as
http://nautilus.org/napsnet/napsnet-special-reports/spent-nuclear-fuel-management-in-china/

"Spent fuel discharged from M310/CPR1000 reactors is stored in fixed racks arrayed in a storage pool. The total volume of wate r in the spent fuel pool for these reactor models is approximately 1300 cubic meters, with the overall dimensions and configuration as shown in Table 3 and Figure 3, below[11]. The storage pool can hold twenty racks, each of which can store 30 or 36 spent fuel assemblies. The maximum capacity of the spent fuel pool is 690 assemblies, equivalent to about 10 years of spent fuel generation. The thermal output of the spent fuel is transferred via circulation of the water in the pool through forced external heat exchangers. The decay heat is exchanged by two horizont al tube heat exchangers. The heating load of the external heat exchangers is 4.2MW."

Table 3: Spent Fuel Pool Parameters for M310/CPR1000 Reactor Types

Parameters	Value
Size of pool	12.6 m* 8.0 m
Depth of water	12.5 m
Max. number of assemblies in pool	690 assemblies
Grid flow area	1.50 m^2
Heat load of exchanger	4.2 MW

Figure 2: Spent Fuel Pool Cross Section for M310/CPR100 Reactors



Following from Nuclear Division of The Hong Kong Institution of Engineers (HKIE) (2008), "Guangdong Nuclear Power Base"
available as http://home.pacific.net.hk/~nuclear/info0211.htm

	Guangdong Daya Bay Nuclear Power Station	Ling Ao Nuclear Power Station	
Reactor Type	PWR	PWR	
Reactor Model	Framatome M310	Framatome M310	
No of generating units	2	2	

16.480892

Power			
NSSS thermal power	2905	2905	
Gross electrical power	984	990	
Net electrical power	944	950	

Reactor core and fuel			
Active core height/ length	3.66m	2.9m	
Active core diameter	3.04m	3.04m	
Fuel inventory t Heavy Metal	72.4	72.4	
Number of assemblies/ bundle	157	157	
Fuel	UO_2	UO_2	
Fuel enrichment, initial core	1.8%, 2.4%, 3.1%	1.8%, 2.4%, 3.1%	
Fuel enrichment, reload	4.45%	3.70%	
Number of fuel rods per assembly/bundle	264	264	
Fuel rod configuration	17X17 square	17X17 square	
Fuel cycle length	18 months	12 months	

Following from Yun Zhou, "China's Spent Nuclear Fuel Management: Current Practices and Future Strategies",
Working Paper, Center for International and Security Studies at Maryland, dated March 2011
"Since then [2003], the plant has transported 104 assemblies of spent fuel twice a year to the interim storage pool."

Valuation of Excess Deaths

Values below are from p. 27 of W. Kip Viscusi and Josepth E. Aldy (2003), "The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World",
The Journal of Risk and Uncertainty, 27:1; 5–76, 2003, one version of which is available as http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0483-09.pdf/$file/EE-0483-09.pdf.

	Value in 2000 dollars (million)	Value in 2012 dollars (million)
Japan	$ 9.70	$ 12.90
ROK	$ 0.80	$ 1.06
US		$ 10.00

Inflator, 2000 to 2012 dollars, from http://www.bls.gov/data/inflation_calculator.htm	1.33

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APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

CASE STUDY: China's Daya Bay Reactor Complex
David von Hippel, Date Last Revised: 2/3/2015

Data and Assumptions on Weather and Population for Plume Modeling

Following from http://www.citypopulation.de/China-Guangdong.html

Guangdong Province

Province

The population development of Guangdong Province according to census results and latest official estimates.

Name	Abbr.	Status	Native	Capital	Area A (km²)	Population Census (C) 7/1/1982	Population Census (C) 7/1/1990	Population Census (C) 11/1/2000	Population Census (C) 11/1/2010	Population Estimate (E) 12/31/2013
China	**CHN**		**中华人民共和国**	**Beijing**	**9,572,900**	**1,008,175,288**	**1,130,822,993**	**1,242,612,226**	**1,339,724,852**	**1,360,720,000**
Guangdong	GD	Prov	广东省	Guangzhou	197,100	59,299,220	62,829,741	85,225,007	104,320,459	106,440,000

(1990) China Dimensions Data Collection (sedac.ciesin.org)
(2000) (2010) (2013) China National Bureau of Statistics (web).

Major Cities

	Name	Population Census (C) 11/1/2010
1	Guangzhou	10,641,408
2	Shenzhen	10,358,381
3	Dongguan	7,271,322
4	Foshan	6,771,895
5	Shantou	3,644,017
6	Zhongshan	2,740,994
7	Huizhou	1,807,858
8	Jiangmen	1,480,023
9	Zhuhai	1,369,538
10	Chaozhou	1,256,268
11	Jieyang	1,226,848
12	Zhanjiang	1,038,762
13	Maoming	1,033,196

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Cities & Counties

The urban population of all cities and counties in Guangdong Province with more than 75,000 urban inhabitants by census years.

The presented urban population is counted on district or county level; therefore it may refer to more than one settlement. Population changes may result from population growth, migration, or boundary changes.

Name	Status	Native	Population Census (C) 7/1/1990	Population Census (C) 11/1/2000	Population Census (C) 11/1/2010
Boluo	Cnty	博罗县	104,236	240,550	471,902
Chaozhou (incl. Chao'an)	City	潮州市	*333,390*	708,368	1,256,268
Dabu	Cnty	大埔县	43,715	139,040	161,014
Deqing	Cnty	德庆县	40,067	66,553	85,086
Dongguan	City	东莞市	552,328	3,870,036	7,271,322
Dongyuan	Cnty	东源县	...	38,406	94,751
Enping	City	恩平市	107,570	151,626	244,257
Fengkai	Cnty	封开县	59,051	71,803	116,798
Fengshun	Cnty	丰顺县	48,477	144,908	207,417
Fogang	Cnty	佛冈县	27,958	58,343	118,429
Foshan (incl. Gaoming, Nanhai, Sanshui, Shunde)	City	佛山市	901,455	4,006,681	6,771,895
Gaoyao	City	高要市	65,117	157,139	224,755
Gaozhou	City	高州市	106,366	393,675	352,006
Guangning	Cnty	广宁县	40,034	60,743	156,304
Guangzhou (incl. Conghua, Huade, Panyu, Zengcheng) [Canton]	City	广州市	3,509,726	8,090,976	10,641,408
Haifeng	Cnty	海丰县	146,032	325,859	489,304
Heping	Cnty	和平县	36,312	72,103	103,233
Heshan	City	鹤山市	55,532	201,043	282,580
Heyuan	City	河源市	99,463	200,230	450,953
Huaiji	Cnty	怀集县	57,192	93,434	161,544
Huazhou	City	化州市	97,132	319,850	320,418
Huidong	Cnty	惠东县	146,667	289,034	473,147
Huilai	Cnty	惠来县	105,092	286,581	434,958
Huizhou (incl. Huiyang)	City	惠州市	302,636	1,057,659	1,807,858
Jiangmen (incl. Xinhui)	City	江门市	379,397	876,531	1,480,023
Jiaoling	Cnty	蕉岭县	16,934	85,575	98,287
Jiexi	Cnty	揭西县	87,567	116,397	247,236
Jieyang (incl. Jiedong)	City	揭阳市	*176,421*	936,485	1,226,848
Kaiping	City	开平市	135,341	343,233	371,019
Lechang	City	乐昌市	97,845	210,108	191,457
Leizhou (Haikang)	City	雷州市	137,771	463,820	344,043
Lianjiang	City	廉江市	156,383	369,365	359,225
Lianping	Cnty	连平县	32,276	66,559	110,851
Lianzhou (Lianxian)	City	连州市	59,455	159,936	161,667
Longchuan	Cnty	龙川县	53,734	113,049	190,368
Longmen	Cnty	龙门县	50,043	74,932	90,831
Lufeng	City	陆丰市	274,727	569,299	579,527
Luhe	Cnty	陆河县	17,747	76,327	150,902
Luoding	City	罗定市	88,395	248,035	263,338
Maoming (incl. Dianbai)	City	茂名市	310,455	971,469	1,033,196
Meizhou (incl. Meixian)	City	梅州市	129,285	440,397	612,551
Nanxiong	City	南雄市	50,631	143,912	140,017
Pingyuan	Cnty	平远县	22,867	86,569	106,250
Puning	City	普宁市	75,593	646,327	874,954
Qingyuan (incl. Qingxin)	City	清远市	167,892	350,545	916,453
Raoping	Cnty	饶平县	204,539	334,188	418,709
Renhua	Cnty	仁化县	38,282	72,669	73,858
Ruyuan	ACnty	乳源瑶族自治县	25,553	56,557	73,580
Shantou (incl. Chaoyang, Chenghai)	City	汕头市	1,750,256	3,070,364	3,644,017
Shanwei	City	汕尾市	169,985	318,422	370,608
Shaoguan (incl. Qujiang)	City	韶关市	313,801	693,731	726,267
Shenzhen (incl. Bao'an)	City	深圳市	1,081,621	6,480,340	10,358,381
Shixing	Cnty	始兴县	26,490	72,996	76,313
Sihui	City	四会市	69,703	209,261	355,709
Suixi	Cnty	遂溪县	94,895	208,458	252,792
Taishan	City	台山市	168,560	293,725	394,855
Wengyuan	Cnty	翁源县	37,537	98,794	103,372
Wuchuan	City	吴川市	129,026	317,602	332,672
Wuhua	Cnty	五华县	52,264	136,661	245,631
Xinfeng	Cnty	新丰县	29,386	49,358	99,897
Xingning	City	兴宁市	80,273	381,745	392,000
Xinxing	Cnty	新兴县	41,906	141,213	160,209
Xinyi	City	信宜市	62,934	276,419	333,965
Xuwen	Cnty	徐闻县	94,312	145,844	238,246
Yangchun	City	阳春市	98,346	270,309	287,391
Yangdong	Cnty	阳东县	...	118,078	193,487
Yangjiang	City	阳江市	341,985	415,784	499,053
Yangshan	Cnty	阳山县	42,353	92,912	125,246
Yangxi	Cnty	阳西县	52,372	105,001	153,771
Yingde	City	英德市	119,580	277,261	346,927
Yunan	Cnty	郁南县	64,167	135,538	152,342
Yunfu	City	云浮市	61,610	193,582	242,040
Zhanjiang	City	湛江市	485,833	832,273	1,038,762
Zhaoqing	City	肇庆市	247,256	438,157	559,887
Zhongshan	City	中山市	393,353	1,434,251	2,740,994
Zhuhai (incl. Doumen)	City	珠海市	269,457	1,056,169	1,369,538
Zijin	Cnty	紫金县	42,203	110,703	231,072

(1990) China Dimensions Data Collection (sedac.ciesin.org)
(2000) China National Bureau of Statistics (web).
(2010) China National Bureau of Statistics: Tabulation of the 2010 Population Census of the People's Republic of China by County.

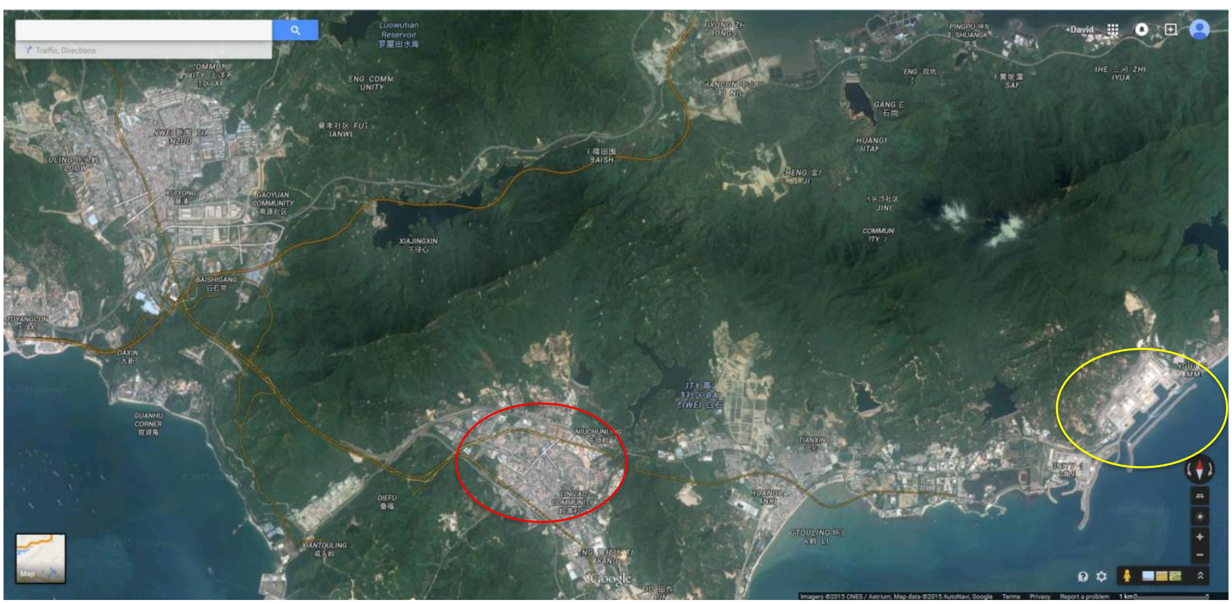
1/2/2015
WWW.CITYPOPULATION.DE

Closest town to power plants is Ling'Ao Community. Following information on Ling'Ao from http://www.fallingrain.com/world/CH/30/Lingao.html:

Latitude	22.6267	**Longitude**	114.5606	**Altitude (feet)**	495
Lat (DMS)	22° 37' 36N	**Long (DMS)**	114° 33' 38E	**Altitude (meters)**	150
	Time zone (est)				
Approximate population for 7 km radius from this point: 104228					

1.4 nm	S	Ling Ao Nuclear Power Plant
1.7 nm	S	Daya Bay Nuclear Power Plant

D. von Hippel estimate from the Google Earth Image below is that the "Ling'Ao Community" has a population of about 50,000 in a radius of approximately 1 km from its center.
The community (red oval below) seems to be centered about 7.2 km from the Daya bay and Ling'Ao nuclear plants (yellow oval).



The next town in the same direction (largely East) is in Starling Inlet and identified by various names Google Maps. It is about 30 km from the nuclear plants, and D. von Hippel estimates its population as 50,000 . It appears to be home to a major container shipping terminal.

Continuing East, the next major population center is Shenzhen, about 55 km from the nuclear plants, and with a population of 10,358,381 in late 2010.
Shenzhen's city area is 2050 square kilometers (Google maps, after UN data), which means its population density is about 5,053 persons per square km.
Wikipedia (http://en.wikipedia.org/wiki/Shenzhen) estimates Shenzhen's population at 15,000,000 in an area of just under 2,000 square kilometers, for a population density of 7,500 persons per square kilometers. We use the latter, as it seems more up-to-date, and probably includes resident workers, official and unofficial, not counted in the official census.
Further East, Zhongshan is about 115 km from the nuclear plants, and with a population of 2,740,994 in late 2010.
Wikipedia (http://en.wikipedia.org/wiki/Zhongshan) estimates Zhongshan's population at 3,142,300 in 2012, with a population density of 1800 per km.
Based on the satelite image below, we increase this population density by a factor of 2 to account for the high-density population centers that the plume encounters on an eastward trajectory, as suggested by the Google Earth image below.
Jiangmen is about 160 km from the nuclear plants, and with a population of 1,480,023 in late 2010.

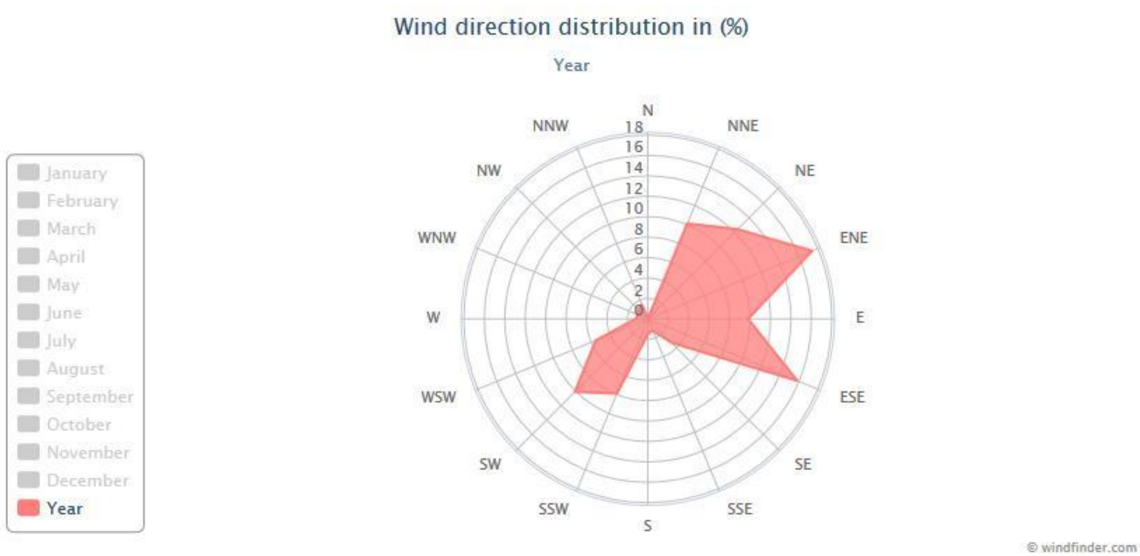
If prevaling winds are from the Northeast, as they sometimes are in the late fall/early winter, then a plume from the Daya Bay area could go over Hong Kong. Wikipedia (http://en.wikipedia.org/wiki/Hong_Kong) lists a population density for Hong Kong of 6544 per square kilometer as of 2014. We increase this value by a factor of 5 to account for the high-density population centers that the plume encounters on this trajectory, as suggested by the Google Earth image below. (That is, most of Hong Kong's population of about 7,200,000 live in an area of about 214 square kilometers, suggesting a more representative density for this analysis would be on the order of 33,668 persons per square km when using radii from Daya Bay that bracket population centers.

Wind statistics for Shanwei from http://www.windfinder.com/windstatistics/shanwei
Shanwei is about 70 km ENE of the Daya Bay plants

Wind statistics | Report | Forecast | Maps

Statistics based on observations taken between 08/2009 - 12/2014 daily from 7am to 7pm local time. You can order the raw wind and weather data in Excel format from our historical weather data request page.

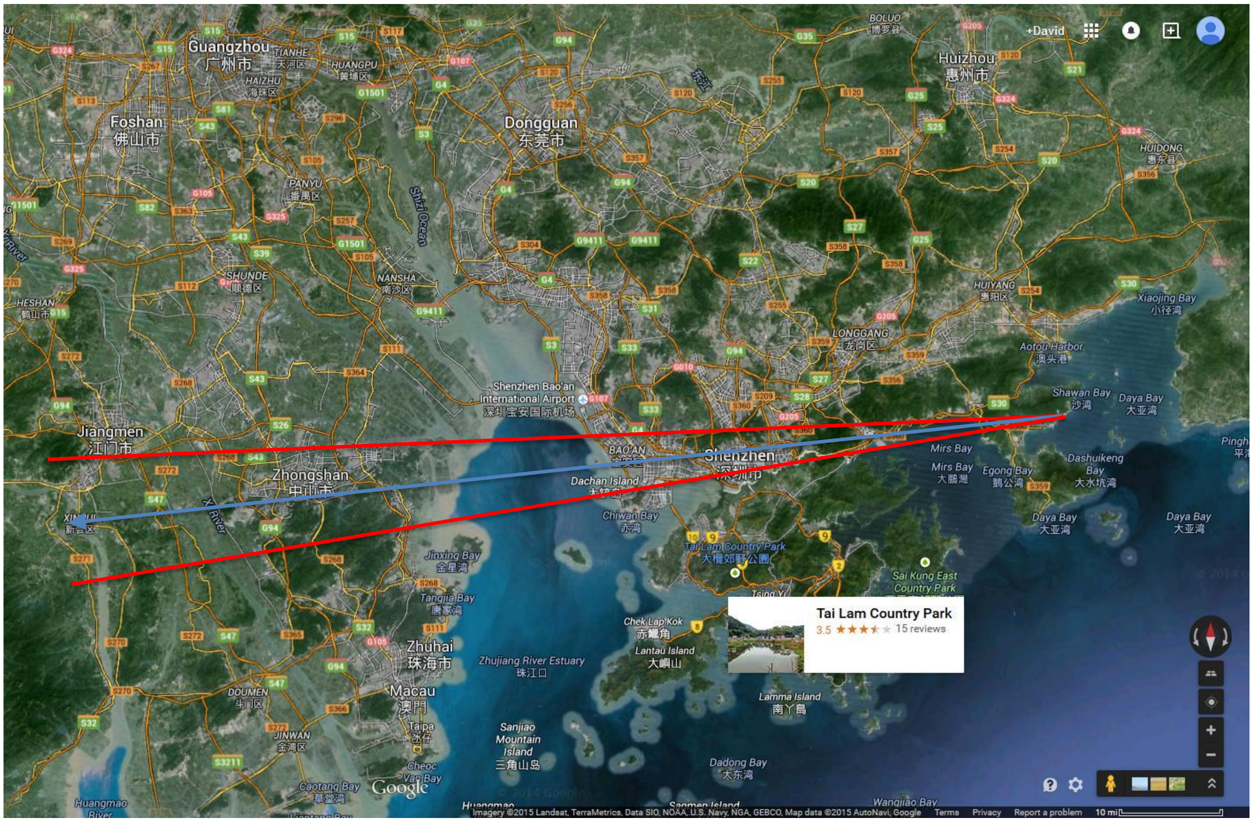
Month of year	Jan 01	Feb 02	Mar 03	Apr 04	May 05	Jun 06	Jul 07	Aug 08	Sep 09	Oct 10	Nov 11	Dec 12	Year 1-12
Dominant Wind dir.													
Wind probability >= 4 Beaufort (%)	1	2	3	4	5	9	5	2	5	2	2	2	3
Average Wind speed (mph)	6	6	6	7	7	8	7	7	7	7	7	6	6
Average air temp. (°F)	59	62	66	71	78	82	84	86	84	78	71	62	73



0.414213562 -1.995200412

Conversions:

One mile per hour equals 0.44704 meters per second.
One radian equals 57.30 degrees, therefore a wedge angle of 0.25 radians equals 14.32 degrees.
For every 10 units of distance from the source, the width of the arc is approximately 1.26 units


Guangzhou
广州市
Foshan
佛山市
Dongguan
东莞市
Huizhou
惠州市
Jiangmen
江门市
Zhongshan
中山市
Shenzhen
Zhuhai
珠海市
Macau
澳門
Shenzhen Bao'an International Airport
Tai Lam Country Park
3.5 ★★★★★ 15 reviews
Lantau Island
大嶼山
Lamma Island
南丫島
Zhujiang River Estuary
珠江口
Mirs Bay
Daya Bay
大亚湾
Dashuikeng Bay
大水坑湾
Shawan Bay
沙湾
Aotou Harbor
澳头港
Xiaojing Bay
小径湾
Chiwan Bay
赤湾
Dachan Island
Jinxing Bay
金星湾
Tangjia Bay
唐家湾
Sanjiao Mountain Island
三角山岛
Dadong Bay
大东湾
Sai Kung East Country Park
Google
Imagery ©2015 Landsat, TerraMetrics, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Map data ©2015 AutoNavi, Google

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From http://www.windfinder.com/windstatistics/hong_kong_airport
Hong Kong is about 50 km SW of the Daya Bay plants

Wind & weather statistics Hong Kong Airport

Spot profile		Current weather	Top webcam
Sunrise: 7:03 am Sunset: 6:11 pm	Local time: 10:45 am (UTC +8) **Homepage weather**	59° F 9 mph	

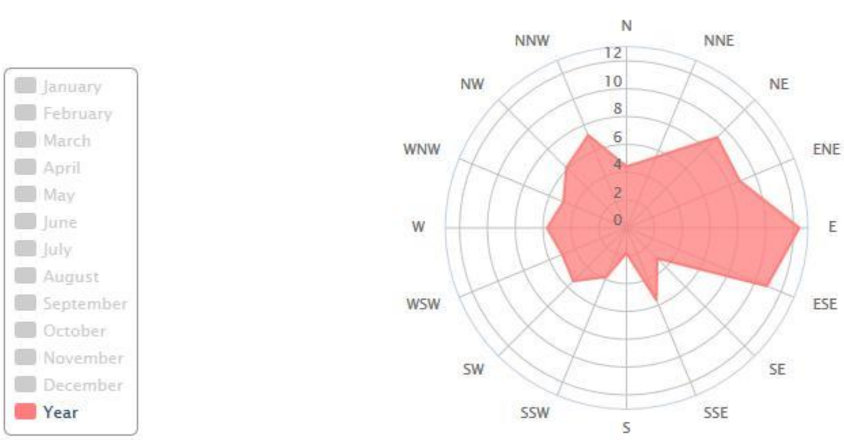
Wind statistics | Report | Forecast | Webcams | Maps

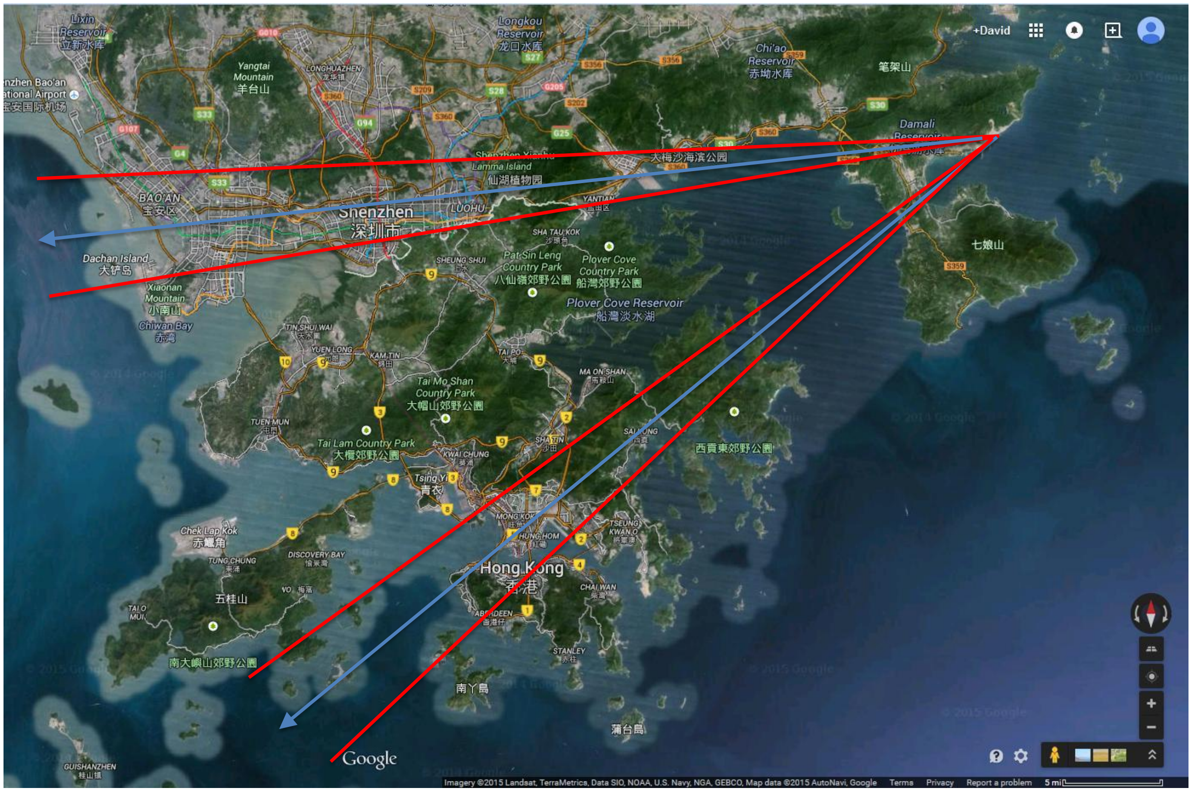
Statistics based on observations taken between 12/2005 - 12/2014 daily from 7am to 7pm local time. You can order the raw wind and weather data in Excel format from our historical weather data request page.

Month of year	Jan 01	Feb 02	Mar 03	Apr 04	May 05	Jun 06	Jul 07	Aug 08	Sep 09	Oct 10	Nov 11	Dec 12	Year 1-12
Dominant Wind dir.													
Wind probability >= 4 Beaufort (%)	33	38	39	45	46	44	38	29	34	31	34	29	36
Average Wind speed (mph)	12	12	12	13	13	13	12	10	12	12	12	10	12
Average air temp. (°F)	62	66	69	77	82	86	87	87	86	82	75	66	77

Wind direction distribution in (%)

Year




Shenzhen
深圳市
Hong Kong
香港
Dachan Island
大铲岛
Tai Mo Shan Country Park
大帽山郊野公園
Tai Lam Country Park
大欖郊野公園
Plover Cove Reservoir
船灣淡水湖
Plover Cove Country Park
Pat Sin Leng Country Park
Chek Lap Kok
赤鱲角
西貢東郊野公園
南大嶼山郊野公園
五桂山
七娘山
南丫島
蒲台島
Tsing Yi
青衣
Yangtai Mountain
羊台山
Longkou Reservoir
Chi'ao Reservoir
Damali Reservoir
Xiaonan Mountain
Chiwan Bay
Google

The Nautilus Institute
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ANNEX 1B: Selected Inputs and Assumptions: Ling'Ao Analysis

APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

CASE STUDY: China's LingAo Phase I Reactor Complex

David von Hippel, Date Last Revised: 2/12/2015

Nominal thermal capacity of reactors (each of 2 units)	2905	MWth	http://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=63http://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=67
Electricity generation capacity of reactor	990	MWe (Gross--950 MWe net, source for net output, IAEA website above)	
Level of enrichment in U235	4.45%	Assumed same as currently used in Daya Bay--consistent also with http://nuclear-power-plants.findthedata.com/l/601/Ling-ao-Nuclear-Power-Plant-Unit-1	
Mass of Uranium in reactor core	72.4	te heavy metal (HM)	
which implies	24.92	kg/MWth	
Number of fuel assemblies per core	157		
Implied tHM per assembly	0.461		

Lifetime performance through 2013 from IAEA website above

	Electricity Supplied (TWh)	Energy Availability Factor	Operation Factor	Energy Unavailability Factor	Load Factor
LingAo Phase I Unit 1	**84.16**	**88.40%**	**89.70%**	**11.60%**	**87.80%**
LingAo Phase I Unit 2	**80.56**	**89.10%**	**89.80%**	**10.80%**	**88.90%**

Following from http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China--Nuclear-Fuel-Cycle/:
"A standard 18-month fuel cycle is the normal routine for Daya Bay, Ling Ao, and early M310 to CPR-1000 reactors. This has average burn-up of 43 GWd/t, with maximum of 50 GWd/t."

We therefore assume a design burn-up of: 43 GWd/tonne Heavy Metal

Based on reports below for the nearly identical Daya Bay plants, we assume that 40% of fuel is replaced every 18 months, which implies that the fuel that is removed has been in the reactor for an average of about 45 months.

GW-th-days of burnup in fuel removed from core	1,396
THM of fuel removed from core in each cycle	28.96
Total GW-th-days of burnup in core at refuel	2,374

The website http://nuclear-power-plants.findthedata.com/l/601/Ling-ao-Nuclear-Power-Plant-Unit-1 does not provide a listing of the current spent fuel inventory of the LingAo reactors, and additional information on the current spent fuel inventory at LingAo was not immediately available for this analysis.

The two LingAo reactors entered commercial operation in May-02 and Jan-03 respectively.

As of the end of 2013, the implied power generation in Unit 1 was 3,507 GWd, or 10,290 GWth-days, with unit 2 power generation 3,357 GWd, or 9,850 GWth-days.

Given the time that the reactors have been operating, the implied number of discharges for reactor 1 would be 7.79 through 1/1/2014, with 7.34 discharges for reactor 2, or a total of 15.13 discharges as of the end of 2013. This implies that the inventory of spent fuel in the two pools as of that time was 21,121.44 GWth-days, equivalent to 405.44 tHM discharged total, or 202.72 tHM for reactor 1 and 202.72 for reactor 2 (counting full discharges only).

From the data below, the spent fuel pool capacity of 1200 assemblies (presumably per reactor) appears to correspond to about 553.38 tHM per pool (one pool per reactor)

The description below suggests that typical operations leave room for the equivalent of about 3.50 fuel replacement cycles (for one reactor), suggesting that maximum effective working capacity would be 452.02 tHM per pool (at one pool per reactor).

Some references below (and elsewhere) list the design capacity of the LingAo spent fuel pools as 20 years with dense packing. years. This seems close to the estimated capacity above, based on an estimated 19.31 tHM/yr discharge per reactor.

We assume that the reactor has operated for 36 months from the beginning of 2014 as of the time of the radiological risk calculation.

We assume that the transport casks that would be used to move spent fuel from LingAo to Lanzhou or another storage site are of the NAC-STC type (see Liu Xuegang (2012), *China's Nuclear Energy Development and Spent Fuel Management Plans* , Nautilus Special Report available as http://nautilus.org/napsnet/napsnet-special-reports/chinas-nuclear-energy-development-and-spent-fuel-management-plans/

These casks hold 26 assemblies each, meaning that they hold 11.99 tHM each, and that to hold a refuelings' worth of cooled spent fuel from the spent fuel pool for 2 reactors will require 4.83 casks

This is somewhat less than the 104 assemblies per year (apparently) estimated in Zhou, 2011 (see below), but is on the same order of magnitude.

We consider three main scenarios for incidents involving the LingAo reactors and spent fuel pools. For the first scenario, which we call "Worst-case Reactor Incident" (or "S1"), one of the reactors is assumed to suffer a core breach and subsequent loss of coolant due to an extreme seismic event or attack. In this case, the spent fuel pool may or may not suffer an initial loss of coolant, either through being breached by the same event or by losing cooling capacity when utilities (power and/or water) are lost as a result of the incident, but because because cooling is assumed to be restored to the pool, the spent fuel in the pool is able to be cooled sufficiently that a zirconium cladding fire does NOT ensue.
We assume, in scenario 1, since the two LingAo units are physically separated, that the second reactor core remains intact, and standard or emergency cooling can be maintained, even if there is damage to the second reactor. This scenario therefore does not include common mode failures--such as the interruption of pumping and water utilities affecting both units, coupled with radiation or other conditions that prevent emergency cooling measures from being undertaken.
For the second scenario, which we call "Worst-case Spent Fuel Pool Incident" (or "S2"),we assume that as a result of a seismic event, catastrophic operational accident (such as dropping a transport cask into the pool), or terrorist attack, the pool suffers a coolant loss and cooling cannot be restored before cooling water mostly or completely evaporates. Further, because the spent fuel pool is dense-packed, fuel that have been most recently off-loaded from the reactor is assumed to reach temperatures high enough for cladding failure and ignition, resulting in a zirconim fire that ultimately engulfs all of the fuel in the pool.
For the third scenario, which we call "Worst Case Reactor and Spent Fuel Pool Incident" (or "S3"), we assume that one of the spent fuel pools and one of the reactors (probably for the same unit) are compromised to the extent that the reactor suffers a meltdown as in S1 and the spent fuel pool has a pool fire as in S2. This could come as a result of an accident or attack that breaches reactor containment and the spent fuel pool at the same time, or damages to a unit's reactor or pool causing common-mode failures in cooling utilities (electricity for pumps and/or water supplies), that cannot be rectified in time to prevent the failure of the unit's pool or reactor.

The "Participation Fraction" ("PART FRAC") of the material in the spent fuel pool is assumed to be a function of the density of racking in the pool. We assume that the racking continues to be high-density in all scenarios.
In S1 we assume that even if the incident focused on the reactor does cause a loss of coolant in the spent fuel pool, restored cooling happens rapidly enough that the cladding does not reach ignition temperature, and thus the Participation Fraction for the spent fuel pool in S1 is 0, and the release fraction is similarly 0
In S2 and S3, however, we assume that the full complement of fuel in the pool, which at the time of the incident for reactor 1 is 260.64 tHM, and for reactor 2 is 260.64 tHM, does participate in a pool fire
The Participation Fraction for the spent fuel pool in scenarios 2 and 3 for reactor 1 or 2 would therefore be 1.00
In this scenario involving cladding failure and significant Cs-137 emissions (S2), a release fraction of 0.3 is assumed.
Spent fuel in the second spent fuel pool is assumed to suffer no damage in the incident under any scenarios, and thus its participation and relaase fractions are both assumed to be 0

For one of the reactors, for S1 and S3, we assume that it experience a core melt, and thus its participation fraction is 1, though the participation fraction for the second reactor is assumed to be 0, and the release fraction is similarly 0.
Based on consideration of Table II.3-7 in the <u>Handbook</u>, as well as estimates of fraction of the Cs-137 inventory in the Fukushima reactor cores that were released to the atmosphere (see, for example, Stohl et al, 2012 (http://www.fukushimaishere.info/AtmosphereRprt_mar12.pdf) and Koo et al, 2014 (abstract at http://www.sciencedirect.com/science/article/pii/S0149197014000444), we assume a release fraction of 0.05 for one of the reactors for S1 and S3, which assume an incident that would breach containment and the reactor vessel, and severely damage the reactor and the fuel within.

For both of the reactors, for S2, we assume that the incident involving the spent fuel pool does not affect the reactors enough to cause a core melt (or emergency procedures are sufficient to prevent a core melt if the reactors is damaged, and thus the participation fraction for both reactors is by definition 0.
The release fraction ("REL FRAC") for S2 for the reactors is assumed to be 0, since the neither reactor is assumed to undergo a core melt.

In all three scenario, though dry casks or transport casks may be present at the time of the incident (especially if the incident occurs after about 2024), we assume that the casks will be sufficiently distant from the reactor and spent fuel pool and/or sufficiently robust that their participation and release fractions are all 0. An possible exceptional case might be if the incident (accident or attack) occurs the period when transport casks are being loaded, in which case, depending on where they are physically located near the spent fuel pool and how much fuel is in them at the time of the incident, there could be additional complications.
The spent fuel placed in transport casks, however, will have been cooled for many years (perhaps even 20), and is thus likely to be passively cooled if coolant is lost. The spent fuel in a not-yet-closed transport cask might be vulnerable to terrorist attack with an incendiary device that would ignite the cladding in the spent fuel in the cask, but this eventuality is not explicitly considered in our scenarios.

We assume an average wind speed of 3.4 meters/second, based very roughly on considerations of recent annual windspeed values for the spring and fall (when prevailing winds are mostly East to West from http://www.windfinder.com/windstatistics/ for Shanwei, which is East along the coast from Daya Bay, and Hong Kong, which is West and South from Daya Bay. An older document entitled "Environmental Radiation Monitoring in Hong Kong, Technical Report No. 3, Surface Meteorological Conditions in Daya Bay, 1984-1988, available as http://www.hko.gov.hk/publica/rm/rm003.pdf, dated July, 1991, by B.Y. Lee, M.C. Wong and W.Y. Chan of the Royal Observatory, Hong Kong, suggests that average wind speeds in Daya Bay are more likely to be similar to those in Shanwei than in Hong Kong.
This wind speed is equivalent to 12.07 km/hour

Given the approximate nature of this modeling effort, we use a deposition velocity ("DEP VEL") of 1 cm/second, or 0.01 which is a typical value used with the wedge model.
Alternatively, we could have chosen a deposition velocity by applying the figure below from Figure II.4-2 in the <u>Handbook</u>, along with the table at right from http://yosemite.epa.gov/oaqps/eogtrain.nsf/b81bacb527b016d785256e4a004c0393/c9862a32b0eb4f9885256b6d0064ce2b/$FILE/Lesson%206.pdf, which defines the Pasquill-Gifford categrories of atmospheric stability (A-G in the Figure II.4-2. For the Daya Bay site, data in the 1991 document above indicates that atmospheric stability is (or was as of the late 1980s) largely in category D, which assumes that insolation is not, on average, strong.
Reading a DV off the graph below for an average wind speed of 3.3528 meters/second and category D, we get a DV of about 0.78 cm/second, which is close to the typical value adopted as above.

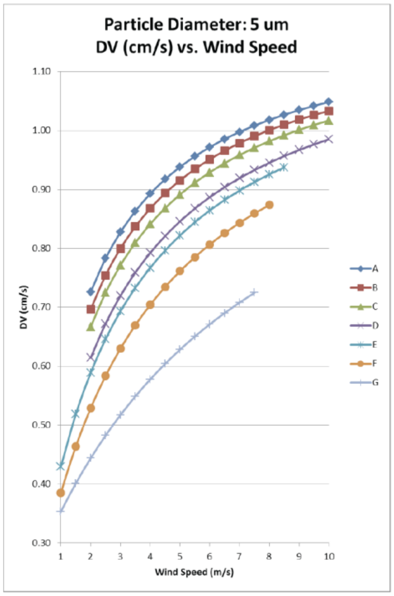


Table 6-1. Key to stability categories

Surface wind	Insolation			Night	
Speed (at 10 m) (m/s)		Moderate	Slight	≥ 4/8 low cloud cover*	≤ 3/8 cloud cover
< 2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
> 6	C	D	D	D	D

* Thinly overcast

Note: Neutral Class D should be assumed for overcast conditions during day or night.

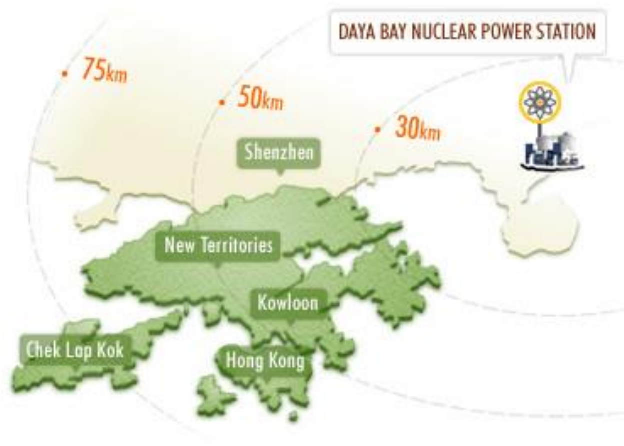
Notes:
(a) This figure is from: Rishel and Napier, 2012.
(b) The letters A through G refer to Pasquill-Gifford (Pasquill) categories of atmospheric stability.

For the variable Mixing Height ("MIX HT"), we use the default value from Table II.4-1 in the Handbook, 1000 meters, or 1 km
We also use the handbook defalut value for the wedge angle ("WEDGE ANG"), 0.25 radians, as well as for the
Shield Factor ("SHLD FAC"), set equal to 0.33
We make a first calculation with an exposure time of 1 year

Following from http://ecolo.org/documents/documents_in_english/china-LingAo-success-story.pdf (page 20):

The Ling Ao units are equipped with high density storage racks capable of storing more than 1200 fuel elements in two regions: region 1 for new fuel and region 2 for spent fuel. The arrangement of the racks and the low pitch between the storage cells is optimized. A powerful neutron absorber is used for rack fabrication. The storage capacity permits storage of spent fuel elements for 20 years of plant operation, plus one normal reload of new fuel and one complete core should forced unloading be necessary. The fuel storage rack design is also compatible with 18-month cycle fuel management and fuel enrichment up to 4.5%.

Following from https://www.hknuclear.com/dayabay/location/pages/locationsiteselection.aspx



Following from https://www.hknuclear.com/dayabay/waste/pages/spent.aspx

"The nuclear fuel that has been expended in the reactor during the fission process is known as spent fuel. Spent fuel assemblies are removed from the reactor during refuelling and held underwater in a fuel storage pool in the fuel building. Daya Bay produces about 50 tonnes of spent nuclear fuel each year and the station has the capacity to store for at least 10 years' worth of spent nuclear fuel."

Following from https://www.hknuclear.com/dayabay/plant/pages/plantandequipment.aspx

"Daya Bay comprises two identical 984 MW (gross) pressurised water reactor type electricity generating units adopting French reactor design and manufacture."

Following from https://www.hknuclear.com/dayabay/plant/features/pages/basicfeatures.aspx

Each generating unit at Daya Bay consists of a "nuclear island" (left picture (1)) where the steam is produced and a "conventional island" (left picture (2)) where the steam is used to produce electricity. These two generating units are supported by various other station facilities (left picture (3)).

Following from https://www.hknuclear.com/dayabay/plant/nuclearisland/reactor/pages/nuclear.aspx

"The reactor contains nuclear fuel which undergoes a fission process - the splitting of atoms -- to produce heat. At Daya Bay, uranium 235 with an enrichment of 4.45% is used as nuclear fuel. It is loaded as sintered fuel pellets of uranium oxide inside fuel rods to make up a fuel "assembly". Each square prismatic assembly is about half a tonne in weight and its 17 X 17 grid contains 264 fuel rods, 24 guide tubes for control rods and a tube for instrumentation. An assembly is about 4.4 metres tall and just over 20 centimetres wide." "Each reactor uses 157 fuel assemblies grouped into a core of about 3.7 metres high and 3 metres in diameter, producing just under 3,000 MW of heat. Although each fuel assembly has a set of 24 guide tubes for the control rods that help control the reaction process, not all of the 157 sets of guide tubes are used. At Daya Bay, 61 sets of control rods are enough to maintain the safe operation of the reactor and the unused guide tubes are plugged." "A fuel assembly stays inside the reactor for between three and four-and-a-half years. A change of fuel, known as refuelling, takes place roughly every 18 months and each time about 40% of the fuel assemblies are replaced.
Refuelling can be done in slightly over a week, but the opportunity is usually taken to conduct maintenance of the power station. This period typically takes 30 days, although more time may be taken if additional inspection and maintenance are considered necessary."

Please see the Daya Bay inputs and assumptions section of this Annex, above, for additional information used in analysis of both the Daya Bay and Ling'Ao reactors.

ANNEX 1C: Selected Additional Results: Daya Bay Analysis

APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

Scenario 1 Compiled Results and Graphics: CASE STUDY: "Worst-case Reactor Incident" at One of the Daya Bay, Guangdong Province, China 984 MWe PWRs

David von Hippel, Date Last Revised: 2/3/2015

Ground Contamination (kBq/sq. m.) for release occuring

Downwind Distance (km)	Ground Contamination (kBq/sq. m.)	1 year after refueling	3 years after refueling	5 years after refueling	10 years after refueling	20 years after refueling
5	31,382	25,229	31,382	19,075	25,229	19,075
10	15,459	12,428	15,459	9,397	12,428	9,397
20	7,502	6,031	7,502	4,560	6,031	4,560
30	4,855	3,903	4,855	2,951	3,903	2,951
40	3,534	2,841	3,534	2,148	2,841	2,148
50	2,744	2,206	2,744	1,668	2,206	1,668
60	2,220	1,784	2,220	1,349	1,784	1,349
75	1,698	1,365	1,698	1,032	1,365	1,032
100	1,182	950	1,182	718	950	718
125	878	706	878	533	706	533
150	679	546	679	413	546	413
175	540	434	540	328	434	328
200	439	353	439	267	353	267

Downwind Distance (km)	External Dose Rate (mSv/yr)	1 year after refueling	3 years after refueling	5 years after refueling	10 years after refueling	20 years after refueling
5	189.52	152.36	189.52	115.20	152.36	115.20
10	93.36	75.05	93.36	56.75	75.05	56.75
20	45.31	36.42	45.31	27.54	36.42	27.54
30	29.32	23.57	29.32	17.82	23.57	17.82
40	21.34	17.16	21.34	12.97	17.16	12.97
50	16.57	13.32	16.57	10.07	13.32	10.07
60	13.40	10.78	13.40	8.15	10.78	8.15
75	10.25	8.24	10.25	6.23	8.24	6.23
100	7.14	5.74	7.14	4.34	5.74	4.34
125	5.30	4.26	5.30	3.22	4.26	3.22
150	4.10	3.30	4.10	2.49	3.30	2.49
175	3.26	2.62	3.26	1.98	2.62	1.98
200	2.65	2.13	2.65	1.61	2.13	1.61

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Calculation of Collective Dose

Currently set to calculate for release 3 years after refuel

	Diameter (km)		Population Density	First Year Collective Radiation Dose
Location	Inner	Outer	persons/km^2	person-Sv/yr
Ling'Ao Community	5.5	7.5	10,308	4,862
Starling Inlet	28	32	1,333	1,173
Shenzhen	40	64	7,500	37,072
Zhongshan	104	120	3,600	9,918
Hong Kong	44	52	32,720	54,547

	Cumulative Collective Radiation Dose	Exposed Population	Percent Premature Deaths	Implied Number of Premature Deaths	Value of Premature Deaths
Location	person-Sv	People	%		$ million US
Ling'Ao Community	49,122	33,500	7.478	2,505	$ 25,052
Starling Inlet	11,848	40,000	1.511	604	$ 6,043
Shenzhen	374,555	2,340,000	0.816	19,102	$ 191,023
Zhongshan	100,206	1,612,800	0.317	5,111	$ 51,105
Hong Kong	551,118	3,141,120	0.895	28,107	$ 281,070
TOTAL of first four locations (not total of exposed area)	535,731	4,026,300	0.679	27,322	273,223

	Exposed Population	Implied Number of Premature Deaths	Value of Premature Deaths, $ million (US)	
Location	People		Lower Estimate	Higher Estimate
Ling'Ao Community	33,500	2,505	$ 2,666	$ 32,320
Starling Inlet	40,000	604	$ 643	$ 7,795
Shenzhen	2,340,000	19,102	$ 20,325	$ 246,439
Zhongshan	1,612,800	5,111	$ 5,438	$ 65,931
Hong Kong	3,141,120	28,107	$ 29,906	$ 362,609
TOTAL of first four locations (not total of exposed area)	4,026,300	27,322	$ 29,071	$ 352,485

APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

Scenario 2 Compiled Results and Graphics: CASE STUDY: "Worst-case Spent Fuel Pool Incident" at the Daya Bay, Guangdong Province, China PWR Power Plant

David von Hippel, Date Last Revised: 2/13/2015

	Ground Contamination (kBq/sq. m.) for release occuring					
Downwind Distance (km)	Ground Contamination (kBq/sq. m.)	1 year after refueling	3 years after refueling	5 years after refueling	10 years after refueling	20 years after refueling
5	88,720	86,750	88,720	87,673	86,590	87,446
10	43,703	42,733	43,703	43,188	42,654	43,076
20	21,209	20,739	21,209	20,959	20,700	20,905
30	13,724	13,419	13,724	13,562	13,395	13,527
40	9,991	9,769	9,991	9,873	9,751	9,847
50	7,758	7,585	7,758	7,666	7,571	7,646
60	6,275	6,135	6,275	6,201	6,124	6,185
75	4,800	4,694	4,800	4,744	4,685	4,731
100	3,341	3,267	3,341	3,302	3,261	3,293
125	2,481	2,426	2,481	2,452	2,422	2,445
150	1,919	1,876	1,919	1,896	1,873	1,891
175	1,527	1,493	1,527	1,509	1,490	1,505
200	1,240	1,212	1,240	1,225	1,210	1,222

Downwind Distance (km)	External Dose Rate (mSv/yr)	1 year after refueling	3 years after refueling	5 years after refueling	10 years after refueling	20 years after refueling
5	535.78	523.88	535.78	529.46	522.92	528.09
10	263.92	258.06	263.92	260.81	257.59	260.13
20	128.08	125.24	128.08	126.57	125.01	126.24
30	82.88	81.04	82.88	81.90	80.89	81.69
40	60.33	58.99	60.33	59.62	58.89	59.47
50	46.85	45.81	46.85	46.30	45.72	46.18
60	37.89	37.05	37.89	37.45	36.98	37.35
75	28.99	28.34	28.99	28.65	28.29	28.57
100	20.18	19.73	20.18	19.94	19.69	19.89
125	14.98	14.65	14.98	14.81	14.62	14.77
150	11.59	11.33	11.59	11.45	11.31	11.42
175	9.22	9.01	9.22	9.11	9.00	9.09
200	7.49	7.32	7.49	7.40	7.31	7.38

Following is for incident 3 years after refueling

	Accumulated Dose (mSv) Over Exposure Period (years)					
Downwind Distance (km)	1 year	3 years	5 years	10 years	15 years	50 years
5	395.41	851.48	1,210.61	2,001.63	2,681.66	5,413.23
10	194.78	419.44	596.35	986.00	1,320.98	2,666.55
20	94.53	203.56	289.41	478.51	641.08	1,294.10
30	61.17	131.72	187.27	309.63	414.83	837.38
40	44.53	95.88	136.33	225.40	301.98	609.58
50	34.57	74.45	105.86	175.02	234.48	473.33
60	27.97	60.22	85.62	141.57	189.66	382.85
75	21.39	46.07	65.50	108.30	145.09	292.88
100	14.89	32.07	45.60	75.39	101.00	203.88
125	11.06	23.81	33.86	55.98	74.99	151.38
150	8.55	18.42	26.19	43.30	58.00	117.09
175	6.80	14.65	20.83	34.44	46.15	93.15
200	5.53	11.90	16.92	27.97	37.48	75.65

Calculation of Collective Dose

Currently set to calculate for release 3 years after refueling

	Diameter (km)		Population Density	Initial Collective Radiation Dose
Location	Inner	Outer	persons/km2	person-Sv/yr
Ling'Ao Community	5.5	7.5	10,308	13,745
Starling Inlet	28	32	1,333	3,315
Shenzhen	40	64	7,500	104,804
Zhongshan	104	120	3,600	28,039
Hong Kong	44	52	32,720	154,209

	Cumulative Collective Radiation Dose	Exposed Population	Percent Premature Deaths	Implied Number of Premature Deaths	Value of Premature Deaths
Location	person-Sv	People	%		$ million US
Ling'Ao Community	138,872	33,500	21.142	7,082	$ 70,825
Starling Inlet	33,495	40,000	4.271	1,708	$ 17,083
Shenzhen	1,058,891	2,340,000	2.308	54,003	$ 540,035
Zhongshan	283,290	1,612,800	0.896	14,448	$ 144,478
Hong Kong	1,558,049	3,141,120	2.530	79,460	$ 794,605
TOTAL of first four locations (not total of exposed area)	1,514,549	4,026,300	1.918	77,242	772,420

	Exposed Population	Implied Number of Premature Deaths	Value of Premature Deaths, $ million (US)	
Location	People		Lower Estimate	Higher Estimate
Ling'Ao Community	33,500	7,082	$ 7,536	$ 91,371
Starling Inlet	40,000	1,708	$ 1,818	$ 22,038
Shenzhen	2,340,000	54,003	$ 57,460	$ 696,699
Zhongshan	1,612,800	14,448	$ 15,372	$ 186,391
Hong Kong	3,141,120	79,460	$ 84,546	$ 1,025,120
TOTAL of first four locations (not total of exposed area)	4,026,300	77,242	$ 82,185	$ 996,499

APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

Summary of Cs-137 Emissions Results from all Scenarios

David von Hippel, Date Last Revised: 2/3/15

	Atmospheric Emissions of Cs-137 (PBq) for an Incident Occuring				
Scenario	1 year after refueling	3 years after refueling	5 years after refueling	10 years after refueling	20 years after refueling
S1: Worst-case Reactor Incident	10.7	13.3	8.1	10.7	8.1
S2: Worst-case Spent Fuel Pool Incident	36.9	37.7	37.3	36.8	37.2

ANNEX 1D : Selected Additional Results: Ling'Ao Analysis

APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

Scenario 1 Compiled Results and Graphics: CASE STUDY: "Worst-case Reactor Incident" at One of the LingAo, Guangdong Province, China 990 MWe PWRs

David von Hippel, Date Last Revised:6/4/2015

Ground Contamination (kBq/sq. m.) for release occuring

Downwind Distance (km)	Ground Contamination (kBq/sq. m.)	1 year after Jan 2014	3 years after Jan 2014	5 years after Jan 2014	10 years after Jan 2014	20 years after Jan 2014
5	32,646	26,245	32,646	19,844	26,245	19,844
10	16,082	12,928	16,082	9,775	12,928	9,775
20	7,805	6,274	7,805	4,744	6,274	4,744
30	5,050	4,060	5,050	3,070	4,060	3,070
40	3,676	2,955	3,676	2,235	2,955	2,235
50	2,855	2,295	2,855	1,735	2,295	1,735
60	2,309	1,856	2,309	1,403	1,856	1,403
75	1,766	1,420	1,766	1,074	1,420	1,074
100	1,230	988	1,230	747	988	747
125	913	734	913	555	734	555
150	706	568	706	429	568	429
175	562	452	562	341	452	341
200	456	367	456	277	367	277

Downwind Distance (km)	External Dose Rate (mSv/yr)	1 year after Jan 2014	3 years after Jan 2014	5 years after Jan 2014	10 years after Jan 2014	20 years after Jan 2014
5	197.15	158.49	197.15	119.84	158.49	119.84
10	97.12	78.07	97.12	59.03	78.07	59.03
20	47.13	37.89	47.13	28.65	37.89	28.65
30	30.50	24.52	30.50	18.54	24.52	18.54
40	22.20	17.85	22.20	13.49	17.85	13.49
50	17.24	13.86	17.24	10.48	13.86	10.48
60	13.94	11.21	13.94	8.48	11.21	8.48
75	10.67	8.58	10.67	6.48	8.58	6.48
100	7.43	5.97	7.43	4.51	5.97	4.51
125	5.51	4.43	5.51	3.35	4.43	3.35
150	4.26	3.43	4.26	2.59	3.43	2.59
175	3.39	2.73	3.39	2.06	2.73	2.06
200	2.76	2.21	2.76	1.67	2.21	1.67

Following is for incident 3 years after January 2014.

	Accumulated Dose (mSv) Over Exposure Period (years)					
Downwind Distance (km)	1 year	3 years	5 years	10 years	15 years	50 years
5	145.50	313.32	445.47	736.54	986.78	1,991.92
10	71.67	154.34	219.44	362.82	486.09	981.22
20	34.78	74.90	106.50	176.08	235.90	476.19
30	22.51	48.47	68.91	113.94	152.65	308.13
40	16.38	35.28	50.16	82.94	111.12	224.31
50	12.72	27.40	38.95	64.40	86.28	174.17
60	10.29	22.16	31.51	52.09	69.79	140.88
75	7.87	16.95	24.10	39.85	53.39	107.77
100	5.48	11.80	16.78	27.74	37.17	75.02
125	4.07	8.76	12.46	20.60	27.60	55.70
150	3.15	6.78	9.64	15.93	21.34	43.09
175	2.50	5.39	7.67	12.67	16.98	34.28
200	2.03	4.38	6.23	10.29	13.79	27.84

Calculation of Collective Dose

Currently set to calculate for release 3 years after refueling

Location	Diameter (km) Inner	Outer	Population Density persons/km^2	Initial Collective Radiation Dose person-Sv/yr
Ling'Ao Community	5.5	7.5	10,308	5,058
Starling Inlet	28	32	1,333	1,220
Shenzhen	40	64	7,500	38,565
Zhongshan	104	120	3,600	10,318
Hong Kong	44	52	32,720	56,745

Location	Cumulative Collective Radiation Dose person-Sv	Exposed Population People	Percent Premature Deaths %	Implied Number of Premature Deaths	Value of Premature Deaths $ million US
Ling'Ao Community	51,101	33,500	7.780	2,606	$ 26,062
Starling Inlet	12,325	40,000	1.571	629	$ 6,286
Shenzhen	389,643	2,340,000	0.849	19,872	$ 198,718
Zhongshan	104,243	1,612,800	0.330	5,316	$ 53,164
Hong Kong	573,320	3,141,120	0.931	29,239	$ 292,393
TOTAL of first four locations (not total of exposed area)	557,313	4,026,300	0.706	28,423	284,230

Location	Exposed Population People	Implied Number of Premature Deaths	Value of Premature Deaths, $ million (US) Lower Estimate	Higher Estimate
Ling'Ao Community	33,500	2,606	$ 2,773	$ 33,622
Starling Inlet	40,000	629	$ 669	$ 8,109
Shenzhen	2,340,000	19,872	$ 21,144	$ 256,366
Zhongshan	1,612,800	5,316	$ 5,657	$ 68,587
Hong Kong	3,141,120	29,239	$ 31,111	$ 377,216
TOTAL of first four locations (not total of exposed area)	4,026,300	28,423	$ 30,242	$ 366,685

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APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

Scenario 2 Compiled Results and Graphics: CASE STUDY: "Worst-case Spent Fuel Pool Incident" at the LingAo, Guangdong Province, China PWR Power Plant

David von Hippel, Date Last Revised: 6/4/2015

Ground Contamination (kBq/sq. m.) for release occuring

Downwind Distance (km)	Ground Contamination (kBq/sq. m.)	1 year after Jan 2014	3 years after Jan 2014	5 years after Jan 2014	10 years after Jan 2014	20 years after Jan 2014
5	883,552	807,876	883,552	1,069,302	1,281,561	1,379,684
10	435,237	397,959	435,237	526,737	631,295	679,631
20	211,224	193,132	211,224	255,629	306,372	329,830
30	136,678	124,971	136,678	165,412	198,246	213,425
40	99,496	90,974	99,496	120,413	144,316	155,365
50	77,258	70,641	77,258	93,500	112,060	120,640
60	62,490	57,137	62,490	75,627	90,639	97,579
75	47,804	43,710	47,804	57,854	69,339	74,648
100	33,277	30,427	33,277	40,273	48,267	51,963
125	24,709	22,593	24,709	29,904	35,839	38,583
150	19,111	17,474	19,111	23,129	27,720	29,843
175	15,204	13,902	15,204	18,400	22,053	23,741
200	12,348	11,290	12,348	14,944	17,910	19,281

Downwind Distance (km)	External Dose Rate (mSv/yr)	1 year after Jan 2014	3 years after Jan 2014	5 years after Jan 2014	10 years after Jan 2014	20 years after Jan 2014
5	5,335.77	4,878.77	5,335.77	6,457.51	7,739.35	8,331.91
10	2,628.39	2,403.27	2,628.39	3,180.96	3,812.39	4,104.29
20	1,275.58	1,166.33	1,275.58	1,543.75	1,850.18	1,991.84
30	825.40	754.70	825.40	998.92	1,197.21	1,288.87
40	600.86	549.39	600.86	727.18	871.52	938.25
50	466.56	426.60	466.56	564.65	676.73	728.54
60	377.38	345.05	377.38	456.71	547.37	589.28
75	288.69	263.97	288.69	349.38	418.74	450.80
100	200.96	183.75	200.96	243.21	291.49	313.80
125	149.22	136.44	149.22	180.59	216.43	233.01
150	115.41	105.53	115.41	139.68	167.40	180.22
175	91.82	83.95	91.82	111.12	133.18	143.37
200	74.57	68.18	74.57	90.24	108.16	116.44

Following is for incident 3 years after January 2014.

	Accumulated Dose (mSv) Over Exposure Period (years)					
Downwind Distance (km)	1 year	3 years	5 years	10 years	15 years	50 years
5	3,937.82	8,479.87	12,056.43	19,934.07	26,706.46	53,909.96
10	1,939.76	4,177.18	5,938.98	9,819.50	13,155.57	26,555.99
20	941.38	2,027.21	2,882.23	4,765.48	6,384.50	12,887.81
30	609.15	1,311.76	1,865.02	3,083.63	4,131.26	8,339.40
40	443.43	954.91	1,357.66	2,244.76	3,007.39	6,070.76
50	344.32	741.48	1,054.22	1,743.04	2,335.22	4,713.89
60	278.50	599.74	852.70	1,409.85	1,888.83	3,812.81
75	213.06	458.80	652.31	1,078.53	1,444.95	2,916.79
100	148.31	319.38	454.08	750.78	1,005.85	2,030.41
125	110.12	237.14	337.16	557.47	746.86	1,507.62
150	85.18	183.42	260.78	431.17	577.66	1,166.08
175	67.76	145.92	207.47	343.02	459.56	927.68
200	55.03	118.51	168.49	278.58	373.22	753.39

Calculation of Collective Dose

Currently set to calculate for release 3 years after refueling

Location	Diameter (km) Inner	Diameter (km) Outer	Population Density persons/km^2	Initial Collective Radiation Dose person-Sv/yr
Ling'Ao Community	5.5	7.5	10,308	136,885
Starling Inlet	28	32	1,333	33,016
Shenzhen	40	64	7,500	1,043,740
Zhongshan	104	120	3,600	279,236
Hong Kong	44	52	32,720	1,535,756

Location	Cumulative Collective Radiation Dose person-Sv	Exposed Population People	Percent Premature Deaths %	Implied Number of Premature Deaths	Value of Premature Deaths $ million US
Ling'Ao Community	1,383,019	33,500	100.000	33,500	$ 335,000
Starling Inlet	333,578	40,000	42.531	17,012	$ 170,125
Shenzhen	10,545,429	2,340,000	22.984	537,817	$ 5,378,169
Zhongshan	2,821,263	1,612,800	8.921	143,884	$ 1,438,844
Hong Kong	15,516,505	3,141,120	25.193	791,342	$ 7,913,418
TOTAL of first four locations (not total of exposed area)	15,083,290	4,026,300	18.186	732,214	7,322,138

Location	Exposed Population People	Implied Number of Premature Deaths	Value of Premature Deaths, $ million (US) Lower Estimate	Higher Estimate
Ling'Ao Community	33,500	33,500	$ 35,644	$ 432,184
Starling Inlet	40,000	17,012	$ 18,101	$ 219,478
Shenzhen	2,340,000	537,817	$ 572,237	$ 6,938,376
Zhongshan	1,612,800	143,884	$ 153,093	$ 1,856,253
Hong Kong	3,141,120	791,342	$ 841,988	$ 10,209,100
TOTAL of first four locations (not total of exposed area)	4,026,300	732,214	$ 779,075	$ 9,446,290

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APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

Scenario 3 Compiled Results and Graphics: CASE STUDY: "Worst Case Reactor and Spent Fuel Pool Incident" at the LingAo, Guangdong Province, China PWR Power Plant

David von Hippel, Date Last Revised: 6/4/2015

Downwind Distance (km)	Ground Contamination (kBq/sq. m.)	Ground Contamination (kBq/sq. m.) for release occuring: 1 year after Jan 2014	3 years after Jan 2014	5 years after Jan 2014	10 years after Jan 2014	20 years after Jan 2014
5	916,199	834,122	916,199	1,089,146	1,307,806	1,399,528
10	451,318	410,887	451,318	536,512	644,224	689,406
20	219,028	199,407	219,028	260,373	312,646	334,574
30	141,728	129,031	141,728	168,481	202,306	216,495
40	103,172	93,930	103,172	122,648	147,271	157,600
50	80,112	72,936	80,112	95,235	114,355	122,375
60	64,799	58,994	64,799	77,030	92,495	98,982
75	49,571	45,130	49,571	58,928	70,759	75,721
100	34,507	31,416	34,507	41,020	49,256	52,710
125	25,622	23,327	25,622	30,458	36,573	39,138
150	19,817	18,042	19,817	23,558	28,288	30,272
175	15,766	14,353	15,766	18,742	22,505	24,083
200	12,804	11,657	12,804	15,221	18,277	19,558

Downwind Distance (km)	External Dose Rate (mSv/yr)	1 year after Jan 2014	3 years after Jan 2014	5 years after Jan 2014	10 years after Jan 2014	20 years after Jan 2014
5	5,532.92	5,037.26	5,532.92	6,577.35	7,897.84	8,451.75
10	2,725.51	2,481.35	2,725.51	3,240.00	3,890.47	4,163.32
20	1,322.71	1,204.22	1,322.71	1,572.39	1,888.07	2,020.49
30	855.89	779.22	855.89	1,017.46	1,221.73	1,307.41
40	623.06	567.24	623.06	740.67	889.37	951.74
50	483.80	440.46	483.80	575.12	690.59	739.02
60	391.32	356.26	391.32	465.19	558.58	597.75
75	299.36	272.54	299.36	355.87	427.31	457.28
100	208.39	189.72	208.39	247.72	297.46	318.32
125	154.73	140.87	154.73	183.94	220.87	236.36
150	119.68	108.96	119.68	142.27	170.83	182.81
175	95.21	86.68	95.21	113.18	135.91	145.44
200	77.32	70.40	77.32	91.92	110.37	118.11

Following is for incident 3 years after January 2014.

	Accumulated Dose (mSv) Over Exposure Period (years)					
Downwind Distance (km)	1 year	3 years	5 years	10 years	15 years	50 years
5	4,083.31	8,793.20	12,501.90	20,670.61	27,693.24	55,901.88
10	2,011.44	4,331.52	6,158.42	10,182.32	13,641.66	27,537.20
20	976.16	2,102.12	2,988.73	4,941.55	6,620.40	13,364.01
30	631.65	1,360.23	1,933.94	3,197.56	4,283.90	8,647.53
40	459.82	990.19	1,407.83	2,327.70	3,118.51	6,295.07
50	357.05	768.88	1,093.17	1,807.44	2,421.50	4,888.07
60	288.79	621.90	884.20	1,461.94	1,958.62	3,953.69
75	220.93	475.75	676.41	1,118.38	1,498.34	3,024.56
100	153.79	331.18	470.86	778.52	1,043.01	2,105.43
125	114.19	245.91	349.62	578.06	774.45	1,563.32
150	88.32	190.20	270.42	447.11	599.01	1,209.16
175	70.27	151.31	215.13	355.70	476.54	961.95
200	57.06	122.89	174.71	288.87	387.01	781.23

Calculation of Collective Dose

Currently set to calculate for release 3 years after refueling

Location	Diameter (km) Inner	Outer	Population Density persons/km^2	Initial Collective Radiation Dose person-Sv/yr
Ling'Ao Community	5.5	7.5	10,308	141,943
Starling Inlet	28	32	1,333	34,236
Shenzhen	40	64	7,500	1,082,306
Zhongshan	104	120	3,600	289,554
Hong Kong	44	52	32,720	1,592,500

Location	Cumulative Collective Radiation Dose person-Sv	Exposed Population People	Percent Excess Deaths %	Implied Number of Excess Deaths	Value of Excess Deaths $ million US
Ling'Ao Community	1,434,120	33,500	100.000	33,500	$ 335,000
Starling Inlet	345,903	40,000	44.103	17,641	$ 176,411
Shenzhen	10,935,073	2,340,000	23.833	557,689	$ 5,576,887
Zhongshan	2,925,506	1,612,800	9.251	149,201	$ 1,492,008
Hong Kong	16,089,825	3,141,120	26.124	820,581	$ 8,205,811
TOTAL of first four locations (not total of exposed area)	15,640,603	4,026,300	18.827	758,031	7,580,306

Location	Exposed Population People	Implied Number of Excess Deaths	Value of Excess Deaths, $ million (US) Lower Estimate	Higher Estimate
Ling'Ao Community	33,500	33,500	$ 35,644	$ 432,184
Starling Inlet	40,000	17,641	$ 18,770	$ 227,587
Shenzhen	2,340,000	557,689	$ 593,381	$ 7,194,742
Zhongshan	1,612,800	149,201	$ 158,750	$ 1,924,840
Hong Kong	3,141,120	820,581	$ 873,098	$ 10,586,316
TOTAL of first four locations (not total of exposed area)	4,026,300	758,031	$ 806,545	$ 9,779,353

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ANNEX 2: Selected Inputs, Assumptions, and Additional Results of Radiological Risk Estimates for Hamaoka Nuclear Power Plants (Japan)

ANNEX 2A: Selected Inputs and Assumptions: Hamaoka Analysis

APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

CASE STUDY: Japan's Hamaoka Reactor Complex

David von Hippel, Date Last Revised: 5/28/2015

	Unit 3	Unit 4	Unit 5		
Nominal thermal capacity of reactor	3293	3293	3926	MWth	http://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=362 and similar
Electricity generation capacity of reactor (gross)	1100	1137	1380	MWe	as above
Electricity generation capacity of reactor (net)	1056	1092	1325	MWe	as above
Level of enrichment in U235	3.00%	3.00%	3.40%		http://nuclear-power-plants.findthedata.com/l/468/Hamaoka-Nuclear-Power-Plant-Unit-5 and similar
Burn-up rate:	33	33	39.5	GWd/tHM	as above
Mass of Uranium in reactor core	139.81	139.81	159.58	te heavy metal (HM)	
which implies	42.46	42.46	40.65	kg/MWth	
Number of fuel assemblies per core	764	764	872		
Implied tHM per assembly	0.183	0.183	0.183		

Lifetime performance through 2014 from IAEA website above

	Electricity Supplied (TWh)	Energy Availability Factor	Operation Factor	Energy Unavailability Factor	Load Factor	
Hamaoka Unit 3	**171.1**	**66.70%**	**67.20%**	**33.30%**	**66.30%**	No generation reported since 2010
Hamaoka Unit 4	**130.35**	**66.20%**	**66.80%**	**33.80%**	**66.20%**	Online through part of 2011, offline since
Hamaoka Unit 5	**38.95**	**29.90%**	**30.40%**	**70.10%**	**30.60%**	Offline in most of 2009 and in 2010, online for part of 2011, offline since

Following from http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China--Nuclear-Fuel-Cycle/:
"A standard 18-month fuel cycle is the normal routine for Daya Bay, Ling Ao, and early M310 to CPR-1000 reactors. This has average burn-up of 43 GWd/t, with maximum of 50 GWd/t."

	Unit 3	Unit 4	Unit 5	
We therefore assume a burn-up of:	43			
We assume that	20.0%	20.0%	33.3%	of fuel is replaced every
	12	12	24	months (see below)
We further assume future capacity factors of	70%	70%	70%	for future reactor operations.
These assumptions imply that fuel removed has been in the reactor for about	60.00	60.00	72.07	months.
GW-th-days of burnup in fuel removed from core	841	841	2,006	
Implied burn-up per tHM	30	30	38	Note that fraction of fuel replaced is adjusted to roughly meet burn-up targets above with reported fuel replacement cycle and estimated capacity factor.
Total GW-th-days of burnup in core at refuel	2,524	2,524	4,016	These formulae will need to be adjusted if fraction of fuel replacement is adjusted

The website http://hamaoka.chuden.jp/english/about/management.html

lists the end FY 2013 spent fuel pool inventory at Hamaoka Unit 3 as	2,060	assemblies, or	376.98	tHM,
lists the end FY 2013 spent fuel pool inventory at Hamaoka Unit 4 as	1,977	assemblies, or	361.79	tHM, and
lists the end FY 2013 spent fuel pool inventory at Hamaoka Unit 5 as	2,538	assemblies, or	464.45	tHM.

	Unit 3	Unit 4	Unit 5	
Implied annual average discharge per reactor:	27.96	27.96	26.57	tHM/yr
or, by an alternative calculation	25.50	25.50	25.39	tHM/yr (assuming design burn-up)

From the data in "Hamaoka_Parameters_2" of this workbook, the spent fuel assemblies appears to correspond to

	Unit 3	Unit 4	Unit 5	
	3,134	3,120	3,696	assemblies seem to correspond to
about	573.52	570.96	676.37	tHM
The comparison of this result with the inventories reported above suggests that current pool capacity leaves room for about	7.03	7.48	3.99	

fuel replacement cycles (for each reactor), which implies
about as much free space is left in these pools as typically would be the case for reactor operations (a full core plus one refueling) for Unit 5, and a little more than that for units 3 and 4.

We assume that the reactors have operated for 36 months from restart in 2016 as of the time of this radiological risk calculation.

We assume that no transport casks are on site at the Hamaoka complex, as fuel is not being transported off-site (but this assumption should be confirmed)

The article "Chubu Electric applies with NRA to build dry storage facility at Hamaoka nuclear plant", available at http://www.fukushima-is-still-news.com/2015/01/dry-storage-for-hamaoka.html, suggests that the utility owners of Hamaoka have applied to build a dry-cask storage facility with a capacity of 400 tonnes of spent fuel (assumed to be tHM) that would start operating as of fiscal 2018.
An older reference (https://www.inmm.org/AM/Template.cfm?Section=Spent_Fuel_Seminar_2012&Template=/CM/ContentDisplay.cfm&ContentID=3603) suggests an earlier start date (2016) and a larger size (700 tU) for this facility.
Either size facility will be full in less than 10 years if all three Hamaoka units operate as above and the spent fuel pools are operated at a relatively steady state of fuel placement and removal, even if the pools remain dense packed (and even more if they are not), so we assume that the facilities will be able to expand to accommodate additional casks as needed.

The presentation http://www-ns.iaea.org/downloads/rw/conferences/spentfuel2010/sessions/session-eight-b/session-8b-japan.pdf suggests that dry casks used currently at the Fukushima and Tokai facilities have an average capacity of about 10 tHM per cask.
The website http://www.holtecinternational.com/?s=Hi-Storm+100U suggests that a common cask used in the US holds 89 BWR assemblies, or about 16.29 tHM per cask. We use 10 tHM per cask as working assumption, which implies an average of 55 assemblies per cask. This assumption appear consistent with practice at Fukushima, as described in "The Future Of Fukushima Daiichi Spent Fuel", dated December 17, 2012, and available as http://www.fukuleaks.org/web/?p=8638.
We further assume that fuel has cooled for an average of 15 years in pools before being placed in casks.

We consider two main scenarios for incidents involving the Hamaoka reactors and spent fuel pools. For the first scenario, which we call "Worst-case Reactor Incident" (or "S1"), one of the reactors (unit #3 or 4) is assumed to suffer a core breach and subsequent loss of coolant due to an extreme seismic event or attack. In this case, the spent fuel pool or pools may or may not suffer a loss of coolant, either through being breached by the same event or by losing cooling capacity when utilities (power and/or water) are lost as a result of the incident, but because cooling is assumed to be restored to the pool(s), the spent fuel in the pool(s) is able to be cooled sufficiently that a zirconium cladding fire does NOT ensue.
We assume, in scenario 1, that even though the Hamaoka units #3 and 4 are not physically separated, though the second reactor core also suffers damage, and emergency cooling can be maintained for the second reactor due to the installation of post-Fukushima redundant safety measures, even if there is damage to the second reactor.
This scenario therefore does not include common mode failures--such as the interruption of pumping and water utilities affecting both units, coupled with radiation or other conditions that prevent emergency cooling measures from being undertaken.
For the second scenario, which we call "Worst-case Spent Fuel Pool Incident" (or "S2"),we assume that as a result of a seismic event, catastrophic operational accident (such as dropping a transport cask into the pool), or terrorist attack, the pool in Unit #3 suffers a coolant loss and cooling cannot be restored before cooling water mostly or completely evaporates. Further, those regions of the stored spent fuel that have been most recently (within the past few months) have been off-loaded from the two reactors are assumed to reach temperatures high enough for cladding failure and ignition, resulting in a zirconim fire that engulfs an amount of spent fuel equal to the most recent off-loading.
For the third scenario, which we call "Worst Case Reactor and Spent Fuel Pool Incident" (or "S3"), we assume that one of the spent fuel pools and one of the reactors (probably for the same unit) are compromised to the extent that the reactor suffers a meltdown as in S1 and the spent fuel pool has a pool fire as in S2. This could come as a result of an accident or attack that breaches reactor containment and the spent fuel pool at the same time, or damages to a unit's reactor or pool causing common-mode failures in cooling utilities (electricity for pumps and/or water supplies), that cannot be rectified in time to prevent the failure of the unit's pool or reactor.

The "Participation Fraction" ("PART FRAC") of the material in the spent fuel pool is assumed to be a function of the density of racking in the pool. We assume that the racking continues to be high-density in all scenarios.
In S1 we assume that even if the incident focused on the reactor does cause a loss of coolant in the spent fuel pool, restored or emergency cooling happens rapidly enough that the cladding does not reach ignition temperature, and thus the Participation Fraction for the spent fuel pool in S1 is 0, and the release fraction is similarly 0
In S2 and S3, however, we assume that the full complement of fuel in the pool, which at the time of the incident for reactor #3 is 376.98 tHM, and for reactor #4 is 361.79 tHM, does participate in a pool fire
The Participation Fraction for the spent fuel pool in scenarios 2 and 3 for reactor #3 or #4 would therefore b 1.00
In these scenarios involving cladding failure and significant Cs-137 emissions (S2 and S3), a release fraction of 0.3 is assumed.
Spent fuel in the other spent fuel pools is assumed to suffer no damage in the incident under any scenarios, and thus its participation and relaase fractions are both assumed to be 0

For one of the reactors, for S1, we assume that it experience a core melt, and thus its participation fraction is 1, though the participation fraction for the second reactor is assumed to be 0, and the release fraction is similarly 0.
Based on consideration of Table II.3-7 in the Handbook, as well as estimates of fraction of the Cs-137 inventory in the Fukushima reactor cores that were released to the atmosphere (see, for example, Stohl et al, 2012 (http://www.fukushimaishere.info/AtmosphereRprt_mar12.pdf) and Koo et al, 2014 (abstract at http://www.sciencedirect.com/science/article/pii/S0149197014000444), we assume a release fraction of 0.05 for one of the reactors for S1 and S3, which assumes an incident that would breach containment and the reactor vessel, and severely damage the reactor and the fuel within.

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For the both of the reactors, for S2, we assume that the incident involving one of the spent fuel pools does not affect the reactors enough to cause a core melt (or emergency procedures are sufficient to prevent a core melt if the reactors is damaged, and thus the participation fraction for both reactors is by definition 0.
The release fraction ("REL FRAC") for S2 for the reactors is assumed to be 0, since the neither reactor is assumed to undergo a core melt.

In either scenario, though dry casks or transport casks are present at the time of the incident (and dry casks, at least, may well be), we assume that the casks will be sufficiently distant from the reactor and spent fuel pool and/or sufficiently robust that their participation and release fractions are all 0. An possible exceptional case might be if the incident (accident or attack) occurs the period when transport casks are being loaded, in which case, depending on where they are physically located near the spent fuel pool and how much fuel is in them at the time of the incident, there could be additional complications. The spent fuel placed in transport casks, however, has been cooled for several years, and is thus likely to be passively cooled if coolant is lost. The spent fuel in a not-yet-closed transport cask might be vulnerable to terrorist attack with an incendiary device that would ignite the cladding in the spent fuel in the cask, but this eventuality is not explicitly considered in our scenarios.

We assume an average wind speed of 10 miles per hour, or 4.5 meters/second, based very roughly on considerations of recent annual windspeed values for the summer (when prevailing winds are mostly Southwest (or SSW) to Northeast (or ENE) from http://www.windfinder.com/windstatistics/omaezaki?fspot=honshu_omaezaki
at Omaezaki, which is along the coast and within a few miles of the Hamaoka Plant, and Tokyo and nearby cities, are North and East of Hamaoka.
Given the approximate nature of this modeling effort, we use a deposition velocity ("DEP VEL") of 1 cm/second, or 0.01
which is a typical value used with the wedge model.
Alternatively, we could have chosen a deposition velocity by applying the figure below from Figure II.4-2 in the Handbook, along with the table at right from http://yosemite.epa.gov/oaqps/eogtrain.nsf/b81bacb527b016d785256e4a004c0393/c9862a32b0eb4f9885256b6d0064ce2b/$FILE/Lesson%206.pdf, which defines the Pasquill-Gifford categories of atmospheric stability (A-G in the Figure below). For the Hamaoka site, assuming moderate to slight insolation, atmospheric stability is likely to be approximated by category B or C, which assumes that insolation is not, on average, strong.
Reading a DV off the graph below for an average wind speed of 4.4704 meters/second and category B or C, we get a DV of about 0.9 cm/second, which is close to the typical value adopted as above.

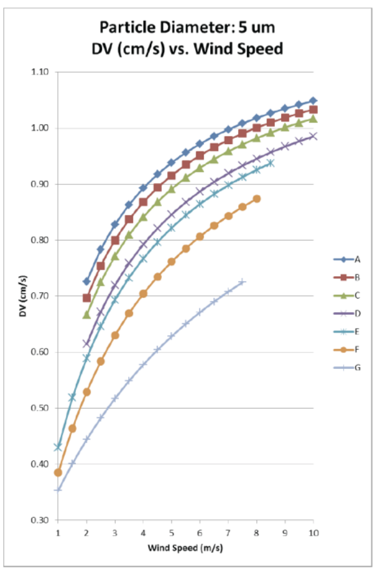


Table 6-1. Key to stability categories

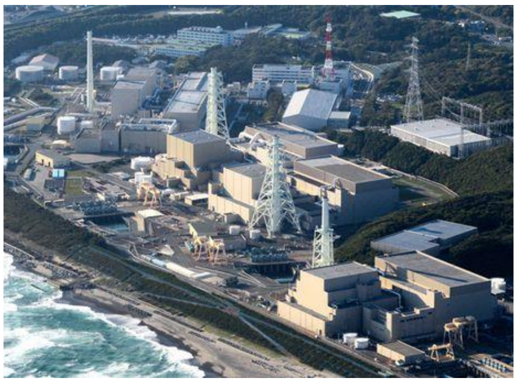
Surface wind	Insolation			Night	
Speed (at 10 m) (m/s)		Moderate	Slight	≥ 4/8 low cloud cover*	≤ 3/8 cloud cover
< 2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
> 6	C	D	D	D	D

* Thinly overcast
Note: Neutral Class D should be assumed for overcast conditions during day or night.

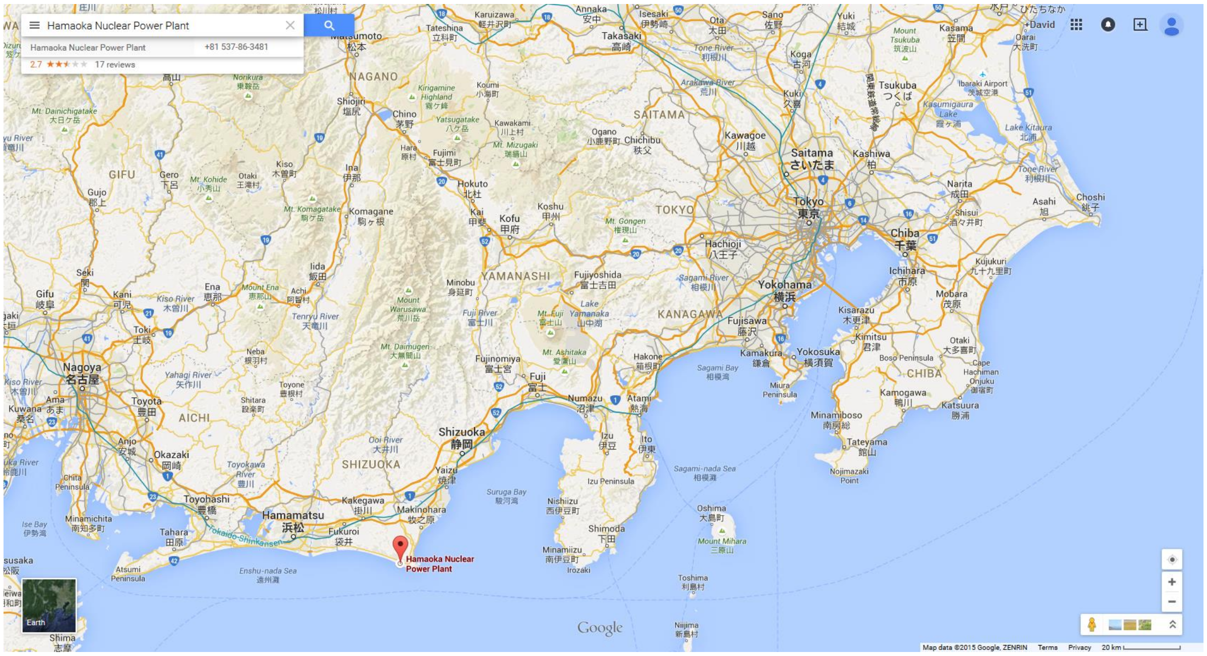
Notes:
(a) This figure is from: Rishel and Napier, 2012.
(b) The letters A through G refer to Pasquill-Gifford (Pasquill) categories of atmospheric stability.

For the variable Mixing Height ("MIX HT"), we use the default value from Table II.4-1 in the Handbook, 1000 meters, or 1 km
We also use the handbook defalut value for the wedge angle ("WEDGE ANG"), 0.25 radians, as well as for the
Shield Factor ("SHLD FAC"), set equal to 0.33
We make a first calculation with an exposure time of 1 year

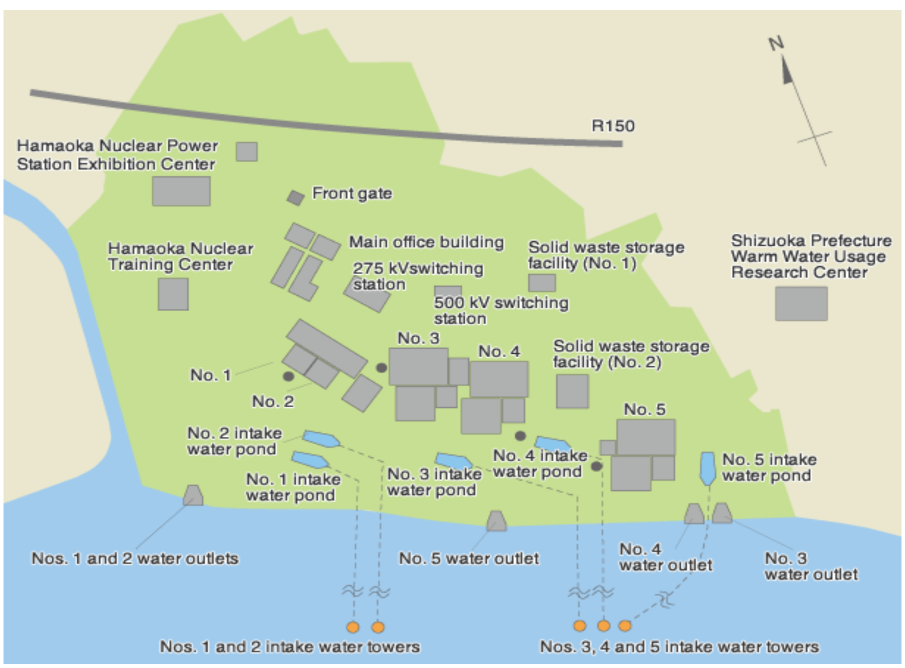
Following from http://ajw.asahi.com/article/0311disaster/fukushima/AJ201105071833



Folowing from https://www.google.com/maps/place/Hamaoka+Nuclear+Power+Plant/@35.3765925,138.9260849,9z/data=!4m2!3m1!1s0x0:0xb63fba287ddb6f69



Following from http://hamaoka.chuden.jp/english/about/layout.html



Statistics/Characteristics of Hamaoka Reactors

	Hamaoka Unit 3	Hamaoka Unit 4	Hamaoka Unit 5	
Reactor Type	BWR	BWR	BWR	http://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=362 and similar
Reactor Model	BWR-5	BWR-5	ABWR	As above

Power				
NSSS thermal power	3293	3293	3926	As above
Gross electrical power	1100	1137	1380	As above
Net electrical power	1056	1092	1325	As above

Reactor core and fuel				
Active core height/ length				
Active core diameter				
Fuel inventory t Heavy Metal	139.81	139.81	159.58	http://nuclear-power-plants.findthedata.com/l/468/Hamaoka-Nuclear-Power-Plant-Unit-3 gives fuel inventory of Unit 3 as 134 tHM
Number of assemblies	764	764	872	http://www.hitachi-hgne.co.jp/en/download/abwr.pdf
Fuel mass per assembly (kg)	183.00	183.00	183.00	Based on value from G. Thompson *Handbook* accompanying this workbook, table I.2.4, and similar to other sources, including http://www.nucleartourist.com/basics/hlwaste.htm.
Fuel	UO_2	UO_2	UO_3	
Fuel enrichment, initial core	2.20%	2.20%	2.60%	http://nuclear-power-plants.findthedata.com/l/468/Hamaoka-Nuclear-Power-Plant-Unit-5 and similar
Fuel enrichment, reload	3.00%	3.00%	3.40%	http://nuclear-power-plants.findthedata.com/l/468/Hamaoka-Nuclear-Power-Plant-Unit-5 and similar
Number of fuel rods per assembly/bundle	63	63	63	From http://www.nucleartourist.com/basics/hlwaste.htm
Fuel rod configuration	8 x 8 square	8 x 8 square	8 x 8 square	
Fuel cycle length	12 months	12 months	24 months	http://nuclear-power-plants.findthedata.com/l/468/Hamaoka-Nuclear-Power-Plant-Unit-5 and similar

Valuation of Excess Deaths

Values below are from p. 27 of W. Kip Viscusi and Josepth E. Aldy (2003), "The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World", The Journal of Risk and Uncertainty, 27:1; 5–76, 2003, one version of which is available as http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0483-09.pdf/$file/EE-0483-09.pdf.

	Value in 2000 dollars (million)	Value in 2012 dollars (million)
Japan	$ 9.70	$ 12.90
ROK	$ 0.80	$ 1.06
US		$ 10.00

Inflator, 2000 to 2012 dollars, from http://www.bls.gov/data/inflation_calculator.htm	1.33

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APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

CASE STUDY: Japan's Hamaoka Reactor Complex

David von Hippel, Date Last Revised: 5/28/2015

Additional Information on Hamaoka Reactors and Spent Fuel Storage

Following from http://hamaoka.chuden.jp/english/about/management.html

Nuclear fuel can be used to generate nuclear power for three to five years. After it is used up (it is now referred to as spent fuel), it is stored and controlled in spent fuel pools at the power station. The Hamaoka Nuclear Power Station has 6,625 spent fuel assemblies in storage as of October 2011.

(Units: assemblies)

Values as of end of fiscal year	No. 1	No. 2	No. 3	No. 4	No. 5	total
End of FY2002	356	968	2,038	1,275	-	4,637
End of FY2003	356	934	2,158	1,275	-	4,723
End of FY2004	356	934	1,914	1,435	0	4,639
End of FY2005	356	934	1,874	1,283	0	4,447
End of FY2006	234	934	2,042	1,463	0	4,673
End of FY2007	14	714	2,036	1,831	264	4,859
End of FY2008	138	1,164	1,820	1,831	858	5,811
End of FY2009	59	1,164	2,004	2,011	1,005	6,243
End of FY2010	1	1,164	2,176	2,065	1,219	6,625
End of FY2011	1	1,164	2,060	1,977	1,373	6,575
End of FY2012	0	988	2,060	1,977	1,550	6,575
End of FY2013	0	0	2,060	1,977	2,538	6,575
Storage capacity	740	1,820	3,134	3,120	3,696	12,510

Following from http://hamaoka.chuden.jp/english/about/facilities.html

Overview of major facilities

		Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Name	**Reactor type**	*Boiling water reactor (BWR)*		Boiling water reactor (BWR)		Advanced boiling water reactor (ABWR)
Power output		*540 MW*	*840 MW*	1,100 MW	1,137 MW	1,380 MW
Start of construction		*Mar-75*	*Mar-78*	Nov-86	Feb-93	Mar-03
Commencement of operation		*Mar-80*	*Nov-82*	Aug-91	Sep-97	Jan-09
Current status		*Decommissioning under way(operation*		Undergoing regular facility Undergoing measures to		

(Note) Operation was suspended at the request of the Prime Minister (Unit 4 on May 13, 2011 and Unit 5 on May 14, 2011)

Following from http://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=JP

Reactors

Name	Type	Status	Location	Reference Unit Power [MW]	Gross Electrical Capacity [MW]	First Grid Connection
HAMAOKA-1	BWR	Permanent Shutdown	OMAEZAKI-SHI	515	540	8/14/1978
HAMAOKA-2	BWR	Permanent Shutdown	OMAEZAKI-SHI	806	840	5/5/1982
HAMAOKA-3	BWR	Operational	OMAEZAKI-SHI	1056	1100	1/21/1991
HAMAOKA-4	BWR	Operational	OMAEZAKI-SHI	1092	1137	1/28/1997
HAMAOKA-5	BWR	Operational	OMAEZAKI-SHI	1325	1380	5/1/2008

The website http://nuclear-power-plants.findthedata.com/l/468/Hamaoka-Nuclear-Power-Plant-Unit-5 and similar list Hamaoka units 3 through 5 as having burnup, fuel cycles, and enrichment as follows:

	GWd/tHM	% enrichment	Fuel cycle (Months)	Core inventory (tHM)	Spent Fuel Pool Inventory
Unit 3	33	3%	12	134	193
Unit 4	33	3%	12		
Unit 5	39.5	3.40%	24		

Following from http://www-pub.iaea.org/MTCD/publications/PDF/CNPP2010_CD/pages/AnnexII/tables/table2.htm

Country	Reactor		Type	Model	Capacity [MW]			Operator	NSSS Supplier	Construction Start	Grid Connection	Commercial Operation
	Code	Name			Thermal	Gross	Net					
	JP -36	HAMAOKA-3	BWR	BWR-5	3293	1100	1056	CHUBU	TOSHIBA	1983-4	1987-1	1987-8
	JP -49	HAMAOKA-4	BWR	BWR-5	3293	1137	1092	CHUBU	TOSHIBA	1989-10	1993-1	1993-9
	JP -60	HAMAOKA-5	BWR	ABWR	3926	1267	1212	CHUBU	TOSHIBA	2000-7	2004-4	2005-1

Reactor		EAF % 2000 to 2009	UCF % 2000 to 2009	Non-electrical Applics
Code	Name			
JP -36	HAMAOKA-3	71.3	71.5	-
JP -49	HAMAOKA-4	75.6	76.7	-
JP -60	HAMAOKA-5	54.7	62.3	-

Proposal to build dry storage for fuel at Hamaoka-4

http://www.fukushima-is-still-news.com/2015/01/dry-storage-for-hamaoka.html

Following from http://fissilematerials.org/library/rr12.pdf

Utility	Plant	Type	Net Capacity GWe	Annual Discharge Uranium T	Spent Fuel Stored Uranium T	Available Capacity Uranium T	Years Until Full	Years of Discharge in pool
Chubu	Hamaoka :	BWR	3.47	55	1,140	1,740	11	15

APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

CASE STUDY: Japan's Hamaoka Reactor Complex
David von Hippel, Date Last Revised: 5/28/15

Data and Assumptions on Weather and Population for Plume Modeling

Following from http://www.citypopulation.de/Japan-Shizuoka.html

Prefecture

The population development of Shizuoka Prefecture according to census results and latest estimates.

Name	Abbr.	Status	Native	Capital	Area A-L (km²)	Population Census (Cf) 10/1/1985	Population Census (Cf) 10/1/1990	Population Census (Cf) 10/1/1995	Population Census (Cf) 10/1/2000
Japan	**JPN**		**日本国**	**Tōkyō**	**372,910**	**121,048,923**	**123,611,167**	**125,570,246**	**126,925,843**
Shizuoka	22	Pref	静岡県	Shizuoka	7,780	3,574,692	3,670,840	3,737,689	3,767,393

(1985) - (2010) Statistics Bureau Japan (web).
(2014) 都道府県市区町村 (http://uub.jp/).

Major Cities

	Name	Population Estimate (E) 10/1/2014
1	Hamamatsu	791,191
2	Shizuoka	706,553
3	Fuji	250,410
4	Numazu	193,978
5	Iwata	164,755
6	Fujieda	143,578
7	Yaizu	139,606
8	Fujinomiya	131,325
9	Kakegawa	114,229
10	Mishima	110,653

The Nautilus Institute
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Cities & Towns

The population of all cities and municipalities of Shizuoka Prefecture with more than 20,000 inhabitants according to census results and latest estimates.

Name	Status	Native	Population Census (Cf) 10/1/1995	Population Census (Cf) 10/1/2000	Population Census (Cf) 10/1/2005	Population Census (Cf) 10/1/2010	Population Estimate (E) 10/1/2014
Atami	City	熱海市	45,610	42,936	41,202	39,611	37,664
Fuji	City	富士市	246,985	251,559	253,297	254,027	250,410
Fujieda	City	藤枝市	138,388	141,643	141,944	142,151	143,578
Fujinomiya	City	富士宮市	129,999	130,372	131,476	132,001	131,325
Fukuroi	City	袋井市	74,826	78,732	82,991	84,846	85,187
Gotemba	City	御殿場市	81,803	82,533	85,976	89,030	88,151
Hamamatsu	City	浜松市	766,832	786,306	804,032	800,866	791,191
Itō	City	伊東市	72,287	71,720	72,441	71,437	69,136
Iwata	City	磐田市	162,667	166,002	170,899	168,625	164,755
Izu (Shuzenju)	City	伊豆市	39,426	38,581	36,627	34,202	31,817
Izunokuni (Nirayama)	City	伊豆の国市	50,328	50,062	50,011	49,269	48,748
Kakegawa	City	掛川市	109,978	114,328	117,857	116,363	114,229
Kannami	Town	函南町	37,375	38,611	38,803	38,571	38,264
Kikukawa	City	菊川市	46,334	47,036	47,502	47,041	46,145
Kosai	City	湖西市	60,714	60,827	60,994	60,107	58,856
Makinohara (Sagara - Haibara)	City	牧之原市	52,067	51,672	50,645	49,019	45,989
Mishima	City	三島市	107,890	110,519	112,241	111,838	110,653
Mori	Town	森町	21,321	20,689	20,273	19,435	18,588
Nagaizumi	Town	長泉町	34,208	36,169	38,716	40,763	42,092
Numazu	City	沼津市	216,470	211,559	208,005	202,304	193,978
Omaezaki (Hamaoka)	City	御前崎市	35,316	36,059	35,272	34,700	32,835
Oyama	Town	小山町	22,780	22,235	21,478	20,629	19,447
Shimada	City	島田市	103,490	102,585	102,108	100,276	98,149
Shimizu	Town	清水町	29,518	30,870	31,961	32,302	32,193
Shimoda	City	下田市	29,103	27,798	26,557	25,013	23,390
Shizuoka	City	静岡市	738,674	729,980	723,323	716,197	706,553
Susono	City	裾野市	49,729	52,682	53,062	54,546	53,362
Yaizu	City	焼津市	139,083	141,452	143,101	143,249	139,606
Yoshida	Town	吉田町	26,475	27,492	28,648	29,815	29,159

(1995) - (2010) Statistics Bureau Japan (web).

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Prefecture

The population development of Kanagawa Prefecture according to census results and latest estimates.

Name	Abbr.	Status	Native	Capital	Area A-L (km²)	Population Census (Cf) 10/1/1985	Population Census (Cf) 10/1/1990	Population Census (Cf) 10/1/1995	Population Census (Cf) 10/1/2000	Population Census (Cf) 10/1/2005	Population Census (Cf) 10/1/2010	Population Estimate (E) 10/1/2014
Japan	**JPN**		**日本国**	**Tōkyō**	**372,910**	**121,048,923**	**123,611,167**	**125,570,246**	**126,925,843**	**127,767,994**	**128,057,352**	**127,105,466**
Kanagawa	14	Pref	神奈川県	Yokohama	2,416	7,431,974	7,980,391	8,245,903	8,489,974	8,791,587	9,048,331	9,098,984

(1985) - (2010) Statistics Bureau Japan (web).
(2014) 都道府県市区町村 (http://uub.jp/).

Major Cities

	Name	Population Estimate (E) 10/1/2014
1	Yokohama	3,710,008
2	Kawasaki	1,461,043
3	Sagamihara	722,931
4	Fujisawa	419,916
5	Yokosuka	407,240
6	Hiratsuka	257,200
7	Chigasaki	237,826
8	Yamato	232,621
9	Atsugi	225,166
10	Odawara	195,125

Cities & Towns

The population of all cities and municipalities of Kanagawa Prefecture with more than 20,000 inhabitants according to census results and latest estimates.

Name	Status	Native	Population Census (Cf) 10/1/1995	Population Census (Cf) 10/1/2000	Population Census (Cf) 10/1/2005	Population Census (Cf) 10/1/2010	Population Estimate (E) 10/1/2014
Aikawa	Town	愛川町	43,088	42,760	42,045	42,089	40,350
Atsugi	City	厚木市	208,627	217,369	222,403	224,420	225,166
Ayase	City	綾瀬市	80,680	81,019	81,767	83,167	83,990
Chigasaki	City	茅ヶ崎市	212,874	220,809	228,420	235,081	237,826
Ebina	City	海老名市	113,430	117,519	123,764	127,707	129,259
Fujisawa	City	藤沢市	368,651	379,185	396,014	409,657	419,916
Hadano	City	秦野市	164,722	168,142	168,317	170,145	168,842
Hayama	Town	葉山町	29,883	30,413	31,531	32,766	32,478
Hiratsuka	City	平塚市	253,822	254,633	258,958	260,780	257,200
Isehara	City	伊勢原市	98,123	99,544	100,579	101,039	100,998
Kamakura	City	鎌倉市	170,329	167,583	171,158	174,314	173,530
Kawasaki	City	川崎市	1,202,820	1,249,905	1,327,011	1,425,512	1,461,043
Minamiashigara	City	南足柄市	43,596	44,156	44,134	44,020	43,363
Miura	City	三浦市	54,152	52,253	49,861	48,352	45,748
Ninomiya	Town	二宮町	30,576	30,802	30,247	29,522	28,767
Odawara	City	小田原市	200,103	200,173	198,741	198,327	195,125
Ōiso	Town	大磯町	32,285	32,259	32,590	33,032	32,439
Sagamihara	City	相模原市	646,516	681,150	701,620	717,544	722,931
Samukawa	Town	寒川町	47,438	46,369	47,457	47,672	47,508
Yamato	City	大和市	203,933	212,761	221,220	228,186	232,621
Yokohama	City	横浜市	3,307,136	3,426,651	3,579,628	3,688,773	3,710,008
Yokosuka	City	横須賀市	432,193	428,645	426,178	418,325	407,240
Yugawara	Town	湯河原町	28,389	27,721	27,430	26,848	25,749
Zama	City	座間市	118,159	125,694	128,174	129,436	129,026
Zushi	City	逗子市	56,578	57,281	58,033	58,302	57,729

(1995) - (2010) Statistics Bureau Japan (web).
(2014) 都道府県市区町村 (http://uub.jp/).

Prefecture

The population development of Tokyo Metropolitan Prefecture according to census results and latest estimates.

Name	Abbr.	Status	Native	Capital	Area A-L (km²)	Population Census (Cf) 10/1/1985	Population Census (Cf) 10/1/1990	Population Census (Cf) 10/1/1995	Population Census (Cf) 10/1/2000	Population Census (Cf) 10/1/2005	Population Census (Cf) 10/1/2010	Population Estimate (E) 10/1/2014
Japan	**JPN**		**日本国**	**Tōkyō**	**372,910**	**121,048,923**	**123,611,167**	**125,570,246**	**126,925,843**	**127,767,994**	**128,057,352**	**127,105,466**
Tōkyō	13	MPref	東京都	Tōkyō	2,188	11,829,363	11,855,563	11,773,602	12,064,101	12,576,611	13,159,388	13,378,584

(1985) - (2010) Statistics Bureau Japan (web).
(2014) 都道府県市区町村 (http://uub.jp/).

Major Cities

	Name	Population Estimate (E) 10/1/2014
1	Tōkyō	9,143,041
2	Hachiōji	579,740
3	Machida	428,766
4	Fuchū	259,082
5	Chōfu	226,435
6	Nishitōkyō	199,232
7	Kodaira	189,692
8	Mitaka	188,023
9	Hino	182,998
10	Tachikawa	180,247

Cities & Towns

The population of all cities and municipalities of Tokyo Metropolitan Prefecture with more than 20,000 inhabitants according to census results and latest estimates.

Tokyo Metropolitan Prefecture administers the city districts ("special wards") of Tokyo directly. Therefore, Tokyo City was abolished in 1943. Tokyo refers in city tables to the entirety of special wards, which corresponds to former Tokyo City.

Name	Status	Native	Population Census (Cf) 10/1/1995	Population Census (Cf) 10/1/2000	Population Census (Cf) 10/1/2005	Population Census (Cf) 10/1/2010	Population Estimate (E) 10/1/2014
Akiruno (Akigawa)	City	あきる野市	75,355	78,351	79,587	80,868	80,825
Akishima	City	昭島市	107,292	106,532	110,143	112,297	111,247
Chōfu	City	調布市	198,574	204,759	216,119	223,593	226,435
Fuchū	City	府中市	216,211	226,769	245,623	255,506	259,082
Fussa	City	福生市	61,497	61,427	61,074	59,796	58,257
Hachiōji	City	八王子市	503,363	536,046	560,012	580,053	579,740
Hamura	City	羽村市	55,095	56,013	56,514	57,032	55,885
Higashikurume	City	東久留米市	111,097	113,302	115,330	116,546	116,214
Higashimurayama	City	東村山市	135,112	142,290	144,929	153,557	151,872
Higashiyamato	City	東大和市	76,355	77,212	79,353	83,068	85,228
Hino	City	日野市	166,537	167,942	176,538	180,052	182,998
Inagi	City	稲城市	62,806	69,235	76,492	84,835	86,724
Kiyose	City	清瀬市	67,386	68,037	73,529	74,104	74,369
Kodaira	City	小平市	172,946	178,623	183,796	187,035	189,692
Koganei	City	小金井市	109,279	111,825	114,112	118,852	120,773
Kokubunji	City	国分寺市	105,786	111,404	117,604	120,650	122,276
Komae	City	狛江市	74,656	75,711	78,319	78,751	80,508
Kunitachi	City	国立市	66,719	72,187	72,667	75,510	75,407
Machida	City	町田市	360,522	377,494	405,544	426,987	428,766
Mitaka	City	三鷹市	165,721	171,612	177,016	186,083	188,023
Mizuho	Town	瑞穂町	32,714	32,892	33,691	33,497	33,037
Musashimurayama	City	武蔵村山市	67,015	66,052	66,553	70,053	70,524
Musashino	City	武蔵野市	135,051	135,746	137,525	138,734	142,548
Nishitōkyō (Hoya - Tanashi)	City	西東京市	175,073	180,885	189,735	196,511	199,232
Ōme	City	青梅市	137,234	141,394	142,354	139,339	136,657
Tachikawa	City	立川市	157,884	164,709	172,566	179,668	180,247
Tama	City	多摩市	148,113	145,862	145,877	147,648	147,649
Tōkyō [Tokyo]		東京都区部	7,967,614	8,134,688	8,489,653	8,945,695	9,143,041

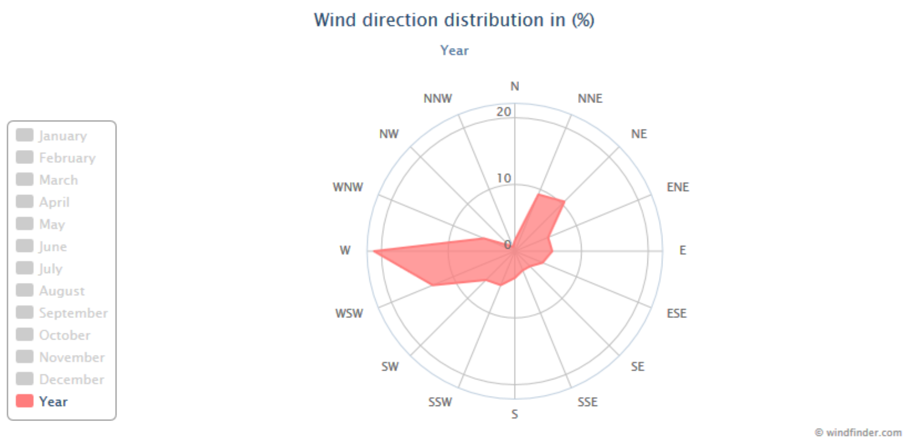
(1995) - (2010) Statistics Bureau Japan (web).
(2014) 都道府県市区町村 (http://uub.jp/).

Wind statistics for Omaezaki from http://www.windfinder.com/windstatistics/omaezaki?fspot=honshu_omaezaki
This station is about 00 km W of the Hamaoka Power Station

Wind statistics | Report | Forecast | Tides | Maps

Statistics based on observations taken between 05/2006 - 04/2015 daily from 7am to 7pm local time. You can order the raw wind and weather data in Excel format from our historical weather data request page.

Month of year	Jan 01	Feb 02	Mar 03	Apr 04	May 05	Jun 06	Jul 07	Aug 08	Sep 09	Oct 10	Nov 11	Dec 12	Year 1-12
Dominant Wind dir.													
Wind probability >= 4 Beaufort (%)	63	51	54	40	33	21	28	19	23	26	42	59	**38**
Average Wind speed (mph)	15	14	14	13	12	9	10	9	10	10	13	15	**12**
Average air temp. (°F)	46	48	53	60	68	73	78	82	77	69	60	50	**62**



We assume a wind direction that points the wedge angle in the direction of Tokyo, which based on the wind rose above is not uncommon (if not the most common) wind direction in the summer months.

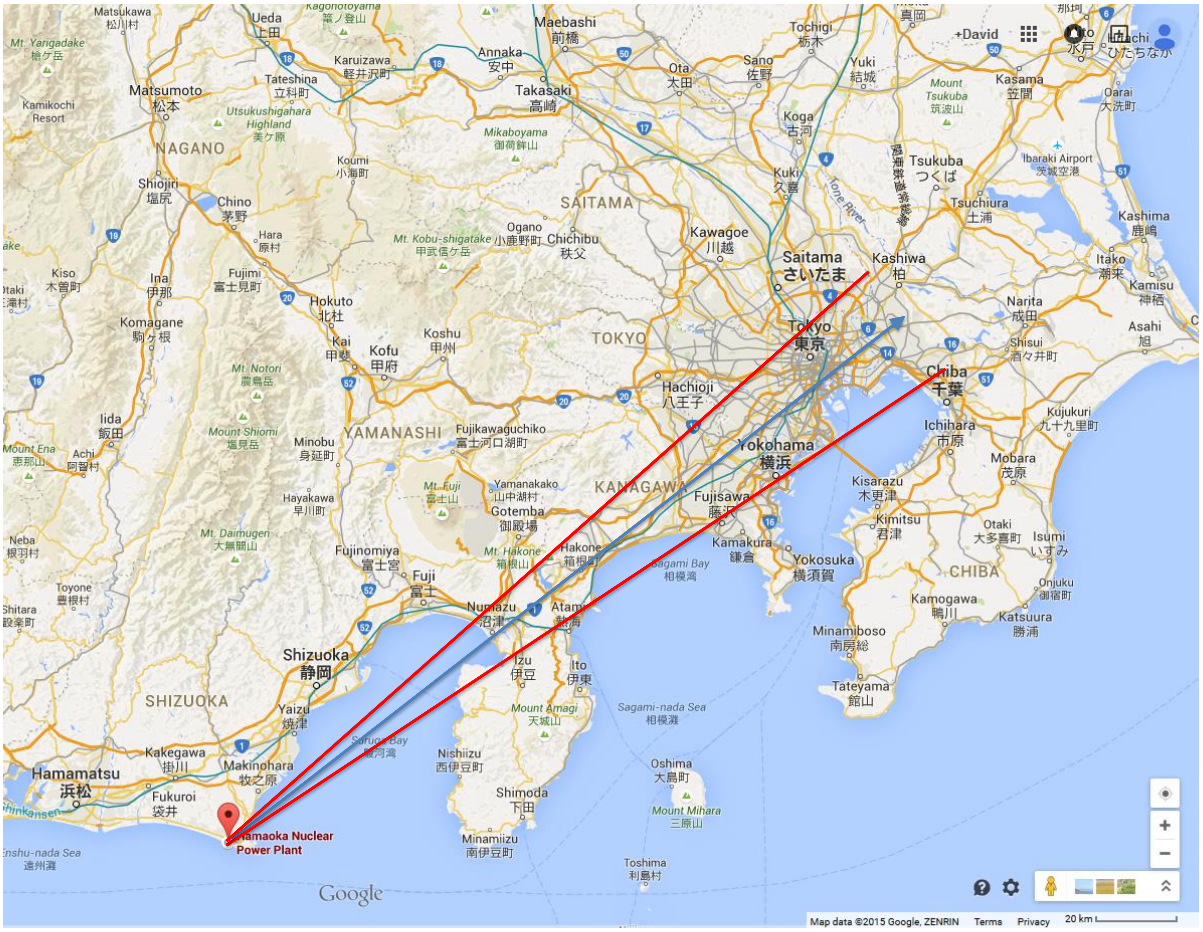
Conversions:

One mile per hour equals 0.44704 meters per second.
One radian equals 57.30 degrees, therefore a wedge angle of 0.25 radians equals 14.32 degrees.
For every 10 units of distance from the source, the width of the arc is approximately 1.26 units

Assuming the wind direction in the maps below, the cities in the path of the wedge would be:

Numazu, at a distance of	80	km (near edge) and	90	km far edge, and an estimated 2014 population of	193,978
Atami, at a distance of	100	km (near edge) and	105	km far edge, and an estimated 2014 population of	37,664
Fujisawa, at a distance of	150	km (near edge) and	160	km far edge, and an estimated 2014 population of	419,916
Yokohama, at a distance of	160	km (near edge) and	180	km far edge, and an estimated 2014 population of	3,710,008
		Population density	8500	per square km (Wikipedia, for incorporated area)	
Tokyo, at a distance of	180	km (near edge) and	210	km far edge, and an estimated 2014 population of	9,143,041

Prefecture of Tokyo population density (2012) estimated as 6,038 per square km (Tokyo Metropolitan Government, http://www.metro.tokyo.jp/ENGLISH/ABOUT/HISTORY/history03.htm)


Hamaoka Nuclear
Power Plant
Tokyo
東京
Chiba
千葉
Saitama
さいたま
Kashiwa
Yokohama
横浜
Shizuoka
静岡
Hamamatsu
浜松
SHIZUOKA
YAMANASHI
KANAGAWA
TOKYO
SAITAMA
NAGANO
CHIBA
Matsumoto
Kofu
Hachioji
Fujisawa
Yokosuka
Kamakura
Kisarazu
Kimitsu
Ichihara
Mobara
Narita
Tsukuba
Tsuchiura
Kashima
Maebashi
Takasaki
Kawagoe
Chichibu
Gotemba
Fujinomiya
Fuji
Numazu
Atami
Hakone
Izu
Ito
Shimoda
Minamiizu
Nishiizu
Oshima
Toshima
Tateyama
Minamiboso
Kamogawa
Katsuura
Yaizu
Makinohara
Kakegawa
Fukuroi
Suruga Bay
Sagami Bay
Sagami-nada Sea
Google
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20 km

ANNEX 2B: Selected Additional Results: Hamaoka Analysis

APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

Scenario 1 Compiled Results and Graphics: CASE STUDY: "Worst-case Reactor Incident" at One of the Hamaoka, Japan, BWRs (1100 MWe)

David von Hippel, Date Last Revised:5/28/2015

Ground Contamination (kBq/sq. m.) for release occuring

Downwind Distance (km)	Ground Contamination (kBq/sq. m.)	1 year after restart	3 years after restart	5 years after restart	10 years after restart	20 years after restart
5	26,130	26,130	26,130	26,130	26,130	26,130
10	12,920	12,920	12,920	12,920	12,920	12,920
20	6,317	6,317	6,317	6,317	6,317	6,317
30	4,118	4,118	4,118	4,118	4,118	4,118
40	3,020	3,020	3,020	3,020	3,020	3,020
50	2,363	2,363	2,363	2,363	2,363	2,363
60	1,925	1,925	1,925	1,925	1,925	1,925
75	1,490	1,490	1,490	1,490	1,490	1,490
100	1,056	1,056	1,056	1,056	1,056	1,056
125	799	799	799	799	799	799
150	630	630	630	630	630	630
175	510	510	510	510	510	510
200	422	422	422	422	422	422

Downwind Distance (km)	External Dose Rate (mSv/yr)	1 year after restart	3 years after restart	5 years after restart	10 years after restart	20 years after restart
5	157.80	157.80	157.80	157.80	157.80	157.80
10	78.02	78.02	78.02	78.02	78.02	78.02
20	38.15	38.15	38.15	38.15	38.15	38.15
30	24.87	24.87	24.87	24.87	24.87	24.87
40	18.24	18.24	18.24	18.24	18.24	18.24
50	14.27	14.27	14.27	14.27	14.27	14.27
60	11.63	11.63	11.63	11.63	11.63	11.63
75	9.00	9.00	9.00	9.00	9.00	9.00
100	6.38	6.38	6.38	6.38	6.38	6.38
125	4.83	4.83	4.83	4.83	4.83	4.83
150	3.80	3.80	3.80	3.80	3.80	3.80
175	3.08	3.08	3.08	3.08	3.08	3.08
200	2.55	2.55	2.55	2.55	2.55	2.55

Following is for incident 3 years after refueling

	Accumulated Dose (mSv) Over Exposure Period (years)					
Downwind Distance (km)	1 year	3 years	5 years	10 years	15 years	50 years
5	116.46	250.79	356.56	589.54	789.82	1,594.35
10	57.58	124.00	176.30	291.49	390.52	788.31
20	28.15	60.63	86.20	142.52	190.94	385.43
30	18.35	39.52	56.19	92.91	124.48	251.27
40	13.46	28.99	41.21	68.14	91.29	184.29
50	10.53	22.68	32.24	53.31	71.42	144.17
60	8.58	18.48	26.27	43.44	58.20	117.48
75	6.64	14.30	20.33	33.61	45.02	90.88
100	4.71	10.14	14.41	23.83	31.93	64.46
125	3.56	7.67	10.90	18.03	24.16	48.76
150	2.81	6.04	8.59	14.21	19.03	38.42
175	2.27	4.90	6.96	11.52	15.43	31.14
200	1.88	4.05	5.76	9.53	12.77	25.77

Calculation of Collective Dose

Currently set to calculate for release 3 years after refueling

Location	Diameter (km) Inner	Outer	Population Density persons/km^2	Initial Collective Radiation Dose person-Sv/yr
Numazu	80	90	913	1,506
Atami	100	105	294	233
Fujisawa	150	160	1,084	1,528
Yokohama	160	180	5,667	15,457
Tokyo	180	210	6,038	23,363

Location	Cumulative Collective Radiation Dose person-Sv	Exposed Population People	Percent Excess Deaths %	Implied Number of Excess Deaths	Value of Excess Deaths $ million US
Numazu	15,212	193,978	0.400	776	$ 7,758
Atami	2,355	37,664	0.319	120	$ 1,201
Fujisawa	15,441	419,916	0.188	787	$ 7,875
Yokohama	156,168	4,816,667	0.165	7,965	$ 79,645
Tokyo	236,051	8,830,575	0.136	12,039	$ 120,386
TOTAL of all locations (not total of exposed area)	425,226	14,298,800	0.152	21,687	216,865

Location	Exposed Population People	Implied Number of Excess Deaths	Value of Excess Deaths, $ million (US) Lower Estimate	Higher Estimate
Numazu	193,978	776	$ 825	$ 10,009
Atami	37,664	120	$ 128	$ 1,550
Fujisawa	419,916	787	$ 838	$ 10,159
Yokohama	4,816,667	7,965	$ 8,474	$ 102,751
Tokyo	8,830,575	12,039	$ 12,809	$ 155,310
TOTAL of all locations (not total of exposed area)	14,298,800	21,687	$ 23,074	$ 279,778

APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

Scenario 2 Compiled Results and Graphics: CASE STUDY: "Worst-case Spent Fuel Pool Incident" at the One of the Hamaoka, Japan, BWRs (1100 MWe)

David von Hippel, Date Last Revised:5/28/2015

		Ground Contamination (kBq/sq. m.) for release occuring				
Downwind Distance (km)	Ground Contamination (kBq/sq. m.)	1 year after restart	3 years after restart	5 years after restart	10 years after restart	20 years after restart
5	515,932	508,489	515,932	523,037	539,430	567,045
10	255,097	251,417	255,097	258,610	266,715	280,369
20	124,727	122,928	124,727	126,445	130,408	137,083
30	81,312	80,139	81,312	82,432	85,015	89,367
40	59,635	58,775	59,635	60,456	62,351	65,543
50	46,653	45,980	46,653	47,295	48,777	51,274
60	38,017	37,469	38,017	38,541	39,749	41,783
75	29,410	28,986	29,410	29,815	30,750	32,324
100	20,858	20,557	20,858	21,145	21,808	22,924
125	15,779	15,551	15,779	15,996	16,497	17,342
150	12,434	12,254	12,434	12,605	13,000	13,666
175	10,078	9,933	10,078	10,217	10,537	11,076
200	8,339	8,218	8,339	8,453	8,718	9,165

Downwind Distance (km)	External Dose Rate (mSv/yr)	1 year after restart	3 years after restart	5 years after restart	10 years after restart	20 years after restart
5	3,115.71	3,070.77	3,115.71	3,158.62	3,257.62	3,424.38
10	1,540.53	1,518.31	1,540.53	1,561.75	1,610.69	1,693.15
20	753.23	742.36	753.23	763.60	787.53	827.85
30	491.04	483.96	491.04	497.81	513.41	539.69
40	360.13	354.94	360.13	365.09	376.54	395.81
50	281.73	277.67	281.73	285.61	294.57	309.65
60	229.59	226.27	229.59	232.75	240.04	252.33
75	177.61	175.05	177.61	180.05	185.70	195.20
100	125.96	124.14	125.96	127.70	131.70	138.44
125	95.29	93.91	95.29	96.60	99.63	104.73
150	75.09	74.00	75.09	76.12	78.51	82.53
175	60.86	59.98	60.86	61.70	63.63	66.89
200	50.36	49.63	50.36	51.05	52.65	55.35

Following is for incident 3 years after refueling

	Accumulated Dose (mSv) Over Exposure Period (years)					
Downwind Distance (km)	1 year	3 years	5 years	10 years	15 years	50 years
5	2,299.40	4,951.64	7,040.10	11,640.08	15,594.67	31,480
10	1,136.91	2,448.28	3,480.90	5,755.31	7,710.61	15,565
20	555.88	1,197.06	1,701.95	2,814.00	3,770.02	7,610
30	362.39	780.39	1,109.53	1,834.50	2,457.75	4,961
40	265.78	572.34	813.74	1,345.44	1,802.54	3,639
50	207.92	447.75	636.59	1,052.54	1,410.13	2,847
60	169.43	364.87	518.76	857.71	1,149.11	2,320
75	131.07	282.26	401.31	663.53	888.96	1,794
100	92.96	200.18	284.61	470.58	630.46	1,273
125	70.32	151.44	215.31	355.99	476.93	963
150	55.42	119.33	169.66	280.52	375.83	759
175	44.92	96.72	137.52	227.37	304.62	615
200	37.16	80.03	113.78	188.13	252.04	509

Calculation of Collective Dose

Currently set to calculate for release 3 years after refueling

Location	Diameter (km) Inner	Diameter (km) Outer	Population Density persons/km^2	Initial Collective Radiation Dose person-Sv/yr
Numazu	80	90	913	29,727
Atami	100	105	294	4,603
Fujisawa	150	160	1,084	30,175
Yokohama	160	180	5,667	305,186
Tokyo	180	210	6,038	461,296

Location	Cumulative Collective Radiation Dose person-Sv	Exposed Population People	Percent Excess Deaths %	Implied Number of Excess Deaths	Value of Excess Deaths $ million US
Numazu	300,346	193,978	7.897	15,318	$ 153,177
Atami	46,503	37,664	6.297	2,372	$ 23,717
Fujisawa	304,870	419,916	3.703	15,548	$ 155,484
Yokohama	3,083,451	4,816,667	3.265	157,256	$ 1,572,560
Tokyo	4,660,707	8,830,575	2.692	237,696	$ 2,376,961
TOTAL of all locations (not total of exposed area)	8,395,879	14,298,800	2.995	428,190	4,281,898

Location	Exposed Population People	Implied Number of Excess Deaths	Value of Excess Deaths, $ million (US) Lower Estimate	Higher Estimate
Numazu	193,978	15,318	$ 16,298	$ 197,613
Atami	37,664	2,372	$ 2,523	$ 30,597
Fujisawa	419,916	15,548	$ 16,543	$ 200,590
Yokohama	4,816,667	157,256	$ 167,320	$ 2,028,760
Tokyo	8,830,575	237,696	$ 252,909	$ 3,066,517
TOTAL of all locations (not total of exposed area)	14,298,800	428,190	$ 455,594	$ 5,524,077

Scenario 3 Compiled Results and Graphics: CASE STUDY: "Worst-case Reactor and Spent Fuel Pool Incident" at One of the Hamaoka, Japan, BWRs (1100 MWe)

David von Hippel, Date Last Revised:5/28/2015

		Ground Contamination (kBq/sq. m.) for release occuring				
Downwind Distance (km)	Ground Contamination (kBq/sq. m.)	1 year after restart	3 years after restart	5 years after restart	10 years after restart	20 years after restart
5	542,062	534,620	542,062	549,168	565,560	593,175
10	268,016	264,337	268,016	271,530	279,635	293,289
20	131,044	129,245	131,044	132,762	136,725	143,400
30	85,430	84,257	85,430	86,550	89,133	93,486
40	62,655	61,795	62,655	63,477	65,371	68,563
50	49,015	48,342	49,015	49,658	51,140	53,637
60	39,943	39,394	39,943	40,466	41,674	43,709
75	30,900	30,475	30,900	31,305	32,239	33,813
100	21,914	21,613	21,914	22,202	22,864	23,981
125	16,578	16,350	16,578	16,795	17,297	18,141
150	13,064	12,884	13,064	13,235	13,630	14,295
175	10,588	10,443	10,588	10,727	11,047	11,587
200	8,761	8,641	8,761	8,876	9,141	9,587

Downwind Distance (km)	External Dose Rate (mSv/yr)	1 year after restart	3 years after restart	5 years after restart	10 years after restart	20 years after restart
5	3,273.51	3,228.57	3,273.51	3,316.42	3,415.42	3,582.18
10	1,618.55	1,596.33	1,618.55	1,639.77	1,688.72	1,771.17
20	791.37	780.51	791.37	801.75	825.68	866.00
30	515.91	508.83	515.91	522.67	538.28	564.56
40	378.37	373.18	378.37	383.33	394.78	414.05
50	296.00	291.94	296.00	299.88	308.84	323.91
60	241.21	237.90	241.21	244.38	251.67	263.96
75	186.60	184.04	186.60	189.05	194.69	204.20
100	132.34	130.52	132.34	134.08	138.08	144.82
125	100.11	98.74	100.11	101.43	104.45	109.55
150	78.89	77.81	78.89	79.93	82.31	86.33
175	63.94	63.07	63.94	64.78	66.71	69.97
200	52.91	52.18	52.91	53.60	55.20	57.90

Following is for incident 3 years after refueling

	Accumulated Dose (mSv) Over Exposure Period (years)					
Downwind Distance (km)	1 year	3 years	5 years	10 years	15 years	50 years
5	2,415.86	5,202.43	7,396.66	12,229.61	16,384.50	33,074
10	1,194.50	2,572.28	3,657.19	6,046.79	8,101.13	16,353
20	584.04	1,257.69	1,788.15	2,956.52	3,960.96	7,996
30	380.74	819.91	1,165.73	1,927.41	2,582.23	5,213
40	279.24	601.33	854.96	1,413.58	1,893.83	3,823
50	218.45	470.42	668.83	1,105.85	1,481.55	2,991
60	178.02	383.35	545.03	901.16	1,207.31	2,437
75	137.71	296.56	421.64	697.14	933.98	1,885
100	97.67	210.32	299.03	494.41	662.39	1,337
125	73.88	159.11	226.21	374.02	501.09	1,012
150	58.22	125.38	178.26	294.73	394.86	797
175	47.19	101.62	144.48	238.89	320.05	646
200	39.05	84.08	119.55	197.66	264.81	535

Calculation of Collective Dose

Currently set to calculate for release 3 years after refuelir

Location	Diameter (km) Inner	Outer	Population Density persons/km^2	Initial Collective Radiation Dose person-Sv/yr
Numazu	80	90	913	31,233
Atami	100	105	294	4,836
Fujisawa	150	160	1,084	31,703
Yokohama	160	180	5,667	320,643
Tokyo	180	210	6,038	484,660

Location	Cumulative Collective Radiation Dose person-Sv	Exposed Population People	Percent Excess Deaths %	Implied Number of Excess Deaths	Value of Excess Deaths $ million US
Numazu	315,558	193,978	8.297	16,093	$ 160,935
Atami	48,859	37,664	6.616	2,492	$ 24,918
Fujisawa	320,311	419,916	3.890	16,336	$ 163,359
Yokohama	3,239,619	4,816,667	3.430	165,221	$ 1,652,206
Tokyo	4,896,758	8,830,575	2.828	249,735	$ 2,497,347
TOTAL of all locations (not total of exposed area)	8,821,105	14,298,800	3.146	449,876	4,498,763

Location	Exposed Population People	Implied Number of Excess Deaths	Value of Excess Deaths, $ million (US) Lower Estimate	Higher Estimate
Numazu	193,978	16,093	$ 17,123	$ 207,622
Atami	37,664	2,492	$ 2,651	$ 32,147
Fujisawa	419,916	16,336	$ 17,381	$ 210,749
Yokohama	4,816,667	165,221	$ 175,795	$ 2,131,510
Tokyo	8,830,575	249,735	$ 265,718	$ 3,221,827
TOTAL of all locations (not total of exposed area)	14,298,800	449,876	$ 478,668	$ 5,803,855

The Nautilus Institute
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ANNEX 3: Selected Inputs, Assumptions, and Additional Results of Radiological Risk Estimates for Experimental LWR under Construction at Yongbyon (DPRK)

ANNEX 3A: Selected Inputs and Assumptions: DPRK LWR Analysis

APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

CASE STUDY: DPRK 100 MWth Reactor Currently Under Construction at Yongbyon
David von Hippel, Date Last Revised: 2/14/14

Nominal thermal capacity of reactor	100	MWth
Electricity generation capacity of reactor	25	MWe
Level of enrichment in U235	3.50%	
Mass of Uranium in reactor core	4	te heavy metal (HM)
which implies	40	kg/MWth
Height of containment structure	40	meters
Diameter of containment structure	22	meters

Estimates above from "Redefining denuclearization in North Korea" by Siegfried S. Hecker, 20 December 2010, Bulletin of the Atomic Scientists, availalble as http://thebulletin.org/web-edition/features/redefining-denuclearization-north-korea-0.

From Handbook to Support Assessment of SNF Radiological Risk, by G. Thompson (2013), Table 1.4-2

for a PWR of rated power	3,411	MWth
The total mass of U in the reactor core is	137	te HM, or
	40.16	kg/MWth
Design burnup	32	GW-days/te U
Assuming a fresh fuel assay of	3.20%	U235

We assume that the DPRK would have difficulty reaching this level of burnup, particularly
in the early phases of use of the reactor, due to lack of familiarity with fuel fabrication methods.

we therefore assume that the averge fuel burnup is	20.00%	less, on average
than the design burnup above over the life of the reactor.		
implied by the fuel replacement schedule before, so we use the latter to estimate radiation load,		
the DPRK LWR would be:	28.00	GW-days/te U
At a capacity factor of	80%	(assumption)
The DPRK LWR's core would have reached its burnup in	1,400.00	days, or
	3.84	years
This is less than the	4.5	years
implied by the fuel replacement schedule before, so we assume that the		
actual average burnup at discharge is	28.00	GW-days/te U
which implies an average actual thermal output of the reactor when operating at full power of		
	24.89	GW-days/yr
or	0.09	GWth
or	85.24	MWth

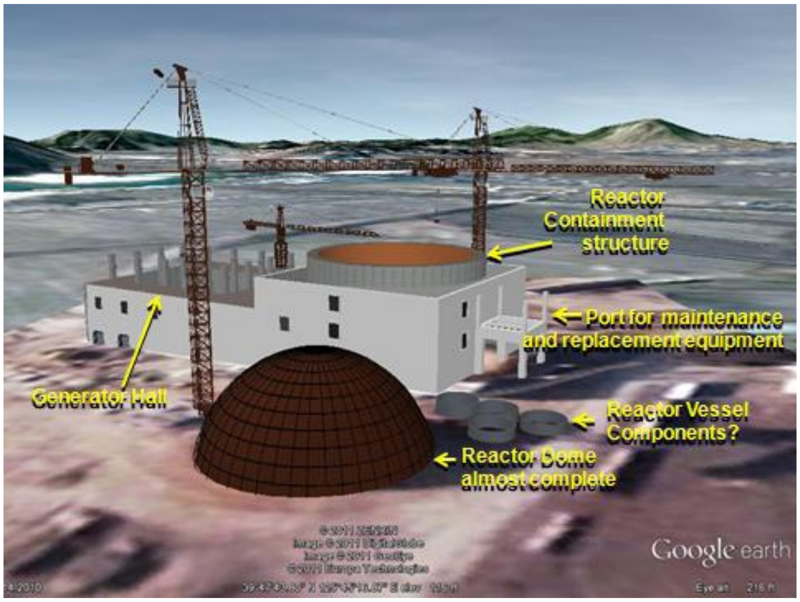
We assume that the DPRK LWR will be a PWR based on a report from S. Hecker that he was told by DPRK engineers that it would be a PWR design. We do not know whether the LWR would use stainless steel cladding or zircaloy cladding for fuel pins. Stainless steel might be used if the DPRK had difficulty with zircaloy metallurgy, but there is some evidence that the DPRK has . previously produced (or perhaps obtained through trade) magnesium alloys including some zirconium for use in the (nomina) 5 MWe gas-graphite nuclear reactor used for plutomium production. Stainless steel is thought to be a more likely material for the DPRK to use for cladding at present.

Following from http://38north.org/2011/11/elwr111411/

"Consistent with its much smaller size than the KEDO reactors, the new ELWR measures only 20 meters in width compared to the KEDO containments that are 40 meters across. The actual ELWR site shows a similar layout in construction site philosophy (figure 6).

From http://www.nytimes.com/2012/08/22/world/asia/progress-on-new-nuclear-reactor-in-north-korea.html
Allison Puccioni, a satellite image analyst at IHS Jane's Defence Weekly, said Tuesday that North Korea had completed a major step in the construction by placing a 69-foot dome on the reactor building. She based her conclusion on images taken by the GeoEye-1 satellite on Aug. 6.

http://iis-db.stanford.edu/pubs/23658/HeckerPBNCfinal.pdf
Includes following image:



Following from http://www.dailynk.com/english/read.php?cataId=nk00100&num=10090

IAEA "Troubled" by LWR Progress

By Kim Da Seul, intern [2012-11-30 19:36] Yukiya Amano, the current director general of the International Atomic Energy Agency (IAEA) revealed on the 29th that the IAEA believes North Korea has made good progress on its new light water nuclear reactor at Yongbyon.

Amano, speaking at a regular meeting of the IAEA, said, "The Democratic People's Republic of Korea- DPRK has continued construction of the light water reactor and largely completed work on the exterior of the main buildings."

However, he said that the IAEA is unsure of the timeframe for the operation of the new reactor, explaining, "The Agency remains unable to determine the reactor's design features or the likely date for it commissioning. Similarly, while the Agency continues to monitor the reported uranium enrichment facility, using satellite imagery, its configuration and operational status

Based on the above and other references reviewed, there seems to be no clear consensus as yet as to many of the design parameters of the DPRK's LWR. There have been indications of construction associated with using river water for cooling that suggests that the assumption above of a simpler cooling strategy (associated witha BWR) might be correct. There does not seem to be an obvious mention of spent fuel pool design in the literature to date.

We assume that the reactor has operated for 20 years as of the time of this radiological risk calculation, and replaced approximately 33.3% of its core every 1.5 years, consistent with the design of BWRs and PWRs in general. At the end of 20 years, the amount of spent fuel in the spent fuel storage pool, which we assume to be located, as in other PWR designs, in a building adjacent to the reactor containment building, would be 16.44 tonnes

We further assume that the ratio of spent fuel storage capacity at the DPRK LWR will be similar, in terms of the ratio of core size to pool storage capacity, as at LWRs in other places, and therefore the ratio of core size to spent fuel pool capacity is about 5 to one (see, for example, http://www.ips-dc.org/reports/spent_nuclear_fuel_pools_in_the_us_reducing_the_deadly_risks_of_storage).
This places the spent fue pool capacity at the DPRK reactor at 20 tonnes HM

Assume that fuel burn-up at the DPRK plant is consistent with the refueling schedule above
(By way of comparison, the Big Rock Point plant achieved about 30 GW-days/THM at times during its lifetime.)
At that level, the average burn-up in the DPRK plant would be 28.00 GW-days/teHM
We assume that design burn-up, and burn-up achieved in the years before the date of the risk calculation
is about the same as the figure provided above, or 28.00 GW-days/teHM
Average age (after discharge) of spent fuel in the spent fuel pool 9.25 years

We consider three main scenarios for incidents involving the reactor and spent fuel pool. For the first scenario, which we call "Worst-case Accident" (or "S1"), the reactor itself is assumed to be highly unlikely to suffer a meltdown due to its small size. The spent fuel pool is assumed to suffer loss of coolant.
For the second scenario, which we call "Worst-case Attack" (or "S2"),we assume that as a result of sabotage of reactor controls/components and/or an explosion that breaches the containment dome and reactor vessel, sufficient damage is caused that the cladding in the fuel in the reactor fails. In this scenario, the spent fuel pool cooling system also fails (it is also targeted by the attackers).
For the final scenario, which we call "Worst-case Attack/Zircaloy cladding" (or "S3"),again, as a result of sabotage of reactor controls/components and/or an explosion that breaches the containment dome and reactor vessel, sufficient damage is caused that the cladding in the fuel in the reactor fails. In addition, in this scenario, the spent fuel pool cooling system also fails (it is also targeted by the attackers) but, different from SC2, in this case the use of Zircaloy cladding is assumed, meaning that coolant. loss results in a cladding fire if the pool is dense-packed..

The "Participation Fraction" ("PART FRAC") of the material in the spent fuel pool is assumed to be a function of the density of racking in the pool. We assume that the racking is low-density until the pool fills to a level at which its would be at capacity if one core and one refueling was added to the pool, and at that point the pool is converted to high-density racking. The threshold amount of spent fuel in the pool that would trigger moving to high-density racking is therefore 14.67 teHM
The Participation Fraction for the spent fuel pool after 20 years of operation would therefore be 1
For the reactor, for S1, we that it does not experience a core melt, and thus its participation fraction is 0
For the reactor, for S2 and S3, we assume that it experiences a core melt and containment failure, or is involved in a fire started by a failure of the spent fuel pool when the latter is operated in a high-density mode (though that may be less likely if the DPRK uses stainless cladding for its fuel rods), so the Participation Fraction for the reactor is by definition 1

The release fraction ("REL FRAC") for S1 for the reactor is assumed to be 0, since the reactor is small enough that it can be cool itself by passive means in the event of most conceivable accidents.
Based on consideration of Table II.3-7 in the <u>Handbook</u>, we assume a release fraction of 0.3 for the reactor for S2 and S3, which assume an attack that would breach containment and the reactor vessel, and severely damage the reactor and the fuel within.
For the inventory of Cs-137 in the spent fuel pools in the event of an accident or attack if stainless steel cladding is used we assume that a release fraction of 0.03 would apply to the approximately 4.30 PBq of Cs-137 that has been most recently discharged from the reactor, as the other spent fuel in the pool could not get hot enough, even if cooling were lost, to result in cladding failure and significant Cs-137 emissions. In the scenario where Zircaloy cladding is assumed to be used (S3), a release fraction of 0.3 is assumed.

If dry casks or transport casks are present (though we assume, for the time period considered above, that they are not), we assume that they will be sufficiently distant from the reactor and spent fuel pool that their participation and release fractions are all 0

We assume an average wind speed of 7 meters/second, based very roughly on estimated values for the area around Yongbyon from
http://www.3tier.com/static/ttcms/us/images/support/maps/3tier_5km_global_wind_speed.pdf.
This wind speed is equivalent to 25.2 km/hour

Given the approximate nature of this modeling effort, we use a deposition velocity ("DEP VEL") of 1 cm/second, or 0.01 meters/second.
which is a typical value used with the wedge model.
Alternatively, we could have chosen a deposition velocity by applying the figure below from Figure II.4-2 in the <u>Handbook</u>, along with the table at right from http://yosemite.epa.gov/oaqps/eogtrain.nsf/b81bacb527b016d785256e4a004c0393/c9862a32b0eb4f9885256b6d0064ce2b/$FILE/Lesson%206.pdf, which defines the Pasquill-Gifford categrories of atmospheric stability (A-G in the Figure II.4-2. For the Yongbyon site, our choice of categories of atmospheric stability is largely constrained by our choice of an average windspeed, so we choose category D, which assumes that insolation is not, on average, strong.
Reading a DV off the graph below for an average wind speed of 7 meters/second and category D, we get a DV of about 0.92 cm/second, which is very close to the typical value adopted as above.

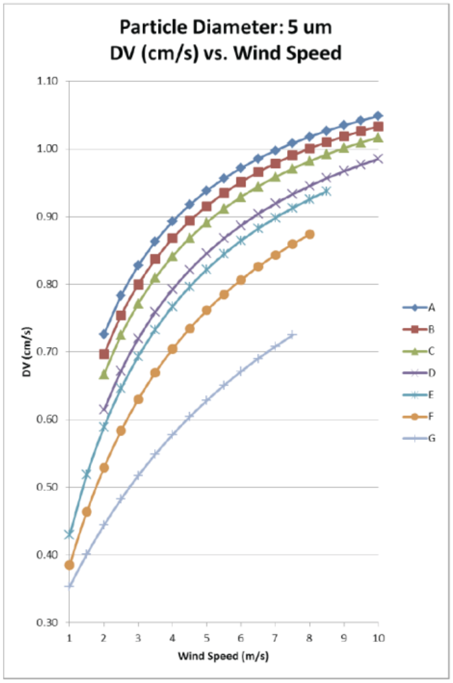


Table 6-1. Key to stability categories

Surface wind	Insolation			Night	
Speed (at 10 m) (m/s)		Moderate	Slight	≥ 4/8 low cloud cover*	≤ 3/8 cloud cover
< 2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
> 6	C	D	D	D	D

* Thinly overcast

Note: Neutral Class D should be assumed for overcast conditions during day or night.

Notes:
(a) This figure is from: Rishel and Napier, 2012.
(b) The letters A through G refer to Pasquill-Gifford (Pasquill) categories of atmospheric stability.

For the variable Mixing Height ("MIX HT"), we use the default value from Table II.4-1 in the Handbook, 1000 meters, or 1 km
We also use the handbook defalut value for the wedge angle ("WEDGE ANG"), 0.25 radians, as well as for the
Shield Factor ("SHLD FAC"), set equal to 0.33
We make a first calculation with an exposure time of 1 year

Step 5: Characterization of Downwind Assets

We assume that an accident at the Yongbyon reactor happens in the Winter, when prevaling winds in North Korea in general are from the north and north-west (http://www.fao.org/forestry/country/18310/en/prk/). We were not able to immediately find wind direction data more specific to the Yongbyon area.
The city of Yongbyon itself is about 1-2 km East and 500 m or so North of the reactor site, and the city of Dong-An is essentially adjacent to the site on the North.
We couldn't immediately find population data for either town, but both look from satellite photos to have several thousand residents. The Plutonium separation complex and other elements of the Yongbyon research area are located 1-2 km due South of the reactor site.
Downwind from Yongbyon in the Winter are the following cities:

	Population (as of 2008)	From Wikipedia, http://en.wikipedia.org/wiki/List_of_cities_in_North_Korea, based on DPRK Census
Kaechon, 15 km South/Southeast	320,000	
Anju, 30 km South/Southwest, an imporant coal-mining region	240,000	
Sunchon, 50 km south, 10 km east	297,000	
Sukchon, 60 km south, 10 km west (rough estimate)	100,000	(county, population 178,000, city population is rough estimate)
Pyongsong, 80 km south	284,000	
Pyongyang, 130 km south	3,255,000	
Kaesong, 250 km south, 70 km east	308,000	
Seoul (ROK), 310 km south, 100 km east (metro area)	16,000,000	metro area--rough estimate
Seoul (ROK), 310 km south, 100 km east	10,582,000	Seoul City (from Wikipedia, https://en.wikipedia.org/wiki/Seoul, original source http://english.seoul.go.kr/gtk/about/fact.php)

In addition, several major rivers (draining into the Korea West sea) and lakes/reservoirs lie south of the reactor complex, including
Chongchon River, 10-15 km South
A tributary of the Taedong river (which flows through Pyongyang), about 30 km South

The Pukchang power plant is located about 35 km southeast of the reactor site.

Valuation of Excess Deaths

Values below are from p. 27 of W. Kip Viscusi and Josepth E. Aldy (2003), "The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World", The Journal of Risk and Uncertainty, 27:1; 5–76, 2003, one version of which is available as http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0483-09.pdf/$file/EE-0483-09.pdf.

	Value in 2000 dollars (million)	Value in 2012 dollars (million)
Japan	$ 9.70	$ 12.90
ROK	$ 0.80	$ 1.06
US		$ 10.00

Inflator, 2000 to 2012 dollars, from http://www.bls.gov/data/inflation_calculator.htm	1.33

Implied coal use in a plant similar in size to the Yongbyon LWR

Capacity	25	MWe	
Average capacity factor	80%		
Implied generation	175.2	GWh	
Efficiency	30%		
Implied fuel requirements	2,102,400	GJ/yr	
Coal cost/value	$3.50	per GJ	Rough estimate based on 2012 price of DPRK coal sold to China
Annual fuel cost of replacement generation	7,358,400.00		

ANNEX 3B: Selected Additional Results: DPRK LWR Analysis

APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

Scenario 1 Compiled Results and Graphics: CASE STUDY: DPRK 100 MWth Reactor Currently Under Construction at Yongbyon

David von Hippel, Date Last Revised: 2/20/14

		Ground Contamination (kBq/sq. m.) for release occuring				
Downwind Distance (km)	Ground Contamination (kBq/sq. m.)	1 year after start-up	3 years after start-up	5 years after start-up	15 years after start-up	20 years after start-up
5	147	-	-	-	-	147
10	73	-	-	-	-	73
20	36	-	-	-	-	36
50	14	-	-	-	-	14
75	9	-	-	-	-	9
100	6	-	-	-	-	6
125	5	-	-	-	-	5
150	4	-	-	-	-	4
175	3	-	-	-	-	3
200	3	-	-	-	-	3
250	2	-	-	-	-	2
300	2	-	-	-	-	2
350	1	-	-	-	-	1

Downwind Distance (km)	External Dose Rate (mSv/yr)	1 year after start-up	3 years after start-up	5 years after start-up	15 years after start-up	20 years after start-up
5	0.88	-	-	-	-	0.88
10	0.44	-	-	-	-	0.44
20	0.22	-	-	-	-	0.22
50	0.08	-	-	-	-	0.08
75	0.05	-	-	-	-	0.05
100	0.04	-	-	-	-	0.04
125	0.03	-	-	-	-	0.03
150	0.02	-	-	-	-	0.02
175	0.02	-	-	-	-	0.02
200	0.02	-	-	-	-	0.02
250	0.01	-	-	-	-	0.01
300	0.01	-	-	-	-	0.01
350	0.01	-	-	-	-	0.01

Following is for accident after 20 years of operation

Downwind Distance (km)	Accumulated Dose (mSv) Over Exposure Period (years): 1 year	3 years	5 years	10 years	15 years	50 years
5	0.65	1.41	2.00	3.31	4.43	8.94
10	0.32	0.70	0.99	1.64	2.20	4.44
20	0.16	0.34	0.49	0.81	1.08	2.19
50	0.06	0.13	0.19	0.31	0.42	0.84
75	0.04	0.08	0.12	0.20	0.27	0.54
100	0.03	0.06	0.09	0.14	0.19	0.39
125	0.02	0.05	0.07	0.11	0.15	0.30
150	0.02	0.04	0.05	0.09	0.12	0.24
175	0.01	0.03	0.04	0.07	0.10	0.20
200	0.01	0.03	0.04	0.06	0.08	0.17
250	0.01	0.02	0.03	0.05	0.06	0.13
300	0.01	0.02	0.02	0.04	0.05	0.10
350	0.01	0.01	0.02	0.03	0.04	0.08

Calculation of Collective Dose

Currently set to calculate for release 20 years after start-up

	Diameter (km)		Population Density	Initial Collective Radiation Dose
Location	Inner	Outer	persons/km^2	person-Sv/yr
Yongbyon	0	2	2,000	4
Kaechon	13	17	20,000	87
Pyongyang	120	140	5,008	93
Seoul	315	335	4,185	59

	Cumulative Collective Radiation Dose	Exposed Population	Percent Excess Deaths	Implied Number of Excess Deaths	Value of Excess Deaths
Location	person-Sv	People	%		$ million US
Yongbyon	45	1,000	0.229	2	$ 23
Kaechon	881	300,000	0.015	45	$ 449
Pyongyang	936	3,255,000	0.001	48	$ 477
Seoul	592	6,800,000	0.000	30	$ 302
TOTAL of Above (not total of exposed area)	2,455	10,356,000	0.001	125	1,252

	Exposed Population	Implied Number of Excess Deaths	Value of Excess Deaths, $ million (US)	
			Lower Estimate	Higher Estimate
Location	People			
Yongbyon	1,000	2	$ 2	$ 23
Kaechon	300,000	45	$ 48	$ 449
Pyongyang	3,255,000	48	$ 51	$ 477
Seoul	6,800,000	30	$ 32	$ 302
TOTAL of Above (not total of exposed area)	10,356,000	125	$ 133	$ 1,252

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APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

Scenario 2 Compiled Results and Graphics: CASE STUDY: DPRK 100 MWth Reactor Currently Under Construction at Yongbyon

David von Hippel, Date Last Revised: 2/20/14

Downwind Distance (km)	Ground Contamination (kBq/sq. m.)	Ground Contamination (kBq/sq. m.) for release occuring: 1 year after start-up	3 years after start-up	5 years after start-up	15 years after start-up	20 years after start-up
5	2,129	991	2,478	1,983	2,974	2,129
10	1,057	492	1,230	984	1,476	1,057
20	521	243	606	485	728	521
50	200	93	232	186	279	200
75	128	60	149	120	179	128
100	93	43	108	87	130	93
125	72	33	84	67	100	72
150	58	27	67	54	81	58
175	48	22	56	44	67	48
200	40	19	47	38	56	40
250	30	14	35	28	42	30
300	23	11	27	22	33	23
350	19	9	22	17	26	19

Downwind Distance (km)	External Dose Rate (mSv/yr)	1 year after start-up	3 years after start-up	5 years after start-up	15 years after start-up	20 years after start-up
5	12.86	5.99	14.97	11.97	17.96	12.86
10	6.38	2.97	7.43	5.94	8.92	6.38
20	3.15	1.46	3.66	2.93	4.39	3.15
50	1.21	0.56	1.40	1.12	1.68	1.21
75	0.78	0.36	0.90	0.72	1.08	0.78
100	0.56	0.26	0.65	0.52	0.78	0.56
125	0.43	0.20	0.50	0.40	0.61	0.43
150	0.35	0.16	0.41	0.32	0.49	0.35
175	0.29	0.13	0.34	0.27	0.40	0.29
200	0.24	0.11	0.28	0.23	0.34	0.24
250	0.18	0.08	0.21	0.17	0.25	0.18
300	0.14	0.07	0.16	0.13	0.20	0.14
350	0.11	0.05	0.13	0.10	0.16	0.11

Following is for accident after 20 years of operation

	Accumulated Dose (mSv) Over Exposure Period (years)					
Downwind Distance (km)	1 year	3 years	5 years	10 years	15 years	50 years
5	9.49	20.43	29.05	48.04	64.35	129.91
10	4.71	10.14	14.42	23.85	31.95	64.49
20	2.32	5.00	7.11	11.75	15.75	31.79
50	0.89	1.92	2.72	4.50	6.03	12.18
75	0.57	1.23	1.75	2.90	3.88	7.84
100	0.41	0.89	1.27	2.10	2.81	5.67
125	0.32	0.69	0.98	1.62	2.17	4.38
150	0.26	0.55	0.79	1.30	1.74	3.52
175	0.21	0.46	0.65	1.08	1.44	2.91
200	0.18	0.39	0.55	0.91	1.22	2.46
250	0.13	0.29	0.41	0.68	0.91	1.83
300	0.10	0.22	0.32	0.53	0.70	1.42
350	0.08	0.18	0.25	0.42	0.56	1.13

Calculation of Collective Dose

Currently set to calculate for release 20 years after start-up

	Diameter (km)		Population Density	Initial Collective Radiation Dose
Location	Inner	Outer	persons/km^2	person-Sv/yr
Yongbyon	0	2	2,000	4
Kaechon	13	17	20,000	87
Pyongyang	120	140	5,008	93
Seoul	315	335	4,185	59

	Cumulative Collective Radiation Dose	Exposed Population	Percent Excess Deaths	Implied Number of Excess Deaths	Value of Excess Deaths
Location	person-Sv	People	%		$ million US
Yongbyon	324	1,000	1.650	17	$ 165
Kaechon	6,344	300,000	0.108	324	$ 3,236
Pyongyang	6,739	3,255,000	0.011	344	$ 3,437
Seoul	4,262	6,800,000	0.003	217	$ 2,174
TOTAL of Above (not total of exposed area)	17,670	10,356,000	0.009	901	9,012

	Exposed Population	Implied Number of Excess Deaths	Value of Excess Deaths, $ million (US)	
Location	People		Lower Estimate	Higher Estimate
Yongbyon	1,000	17	$ 18	$ 165
Kaechon	300,000	324	$ 344	$ 3,236
Pyongyang	3,255,000	344	$ 366	$ 3,437
Seoul	6,800,000	217	$ 231	$ 2,174
TOTAL of Above (not total of exposed area)	10,356,000	901	$ 959	$ 9,012

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APPLICATION OF "WORKBOOK TO CALCULATE ASPECTS OF SNF RADIOLOGICAL RISK"

Scenario 3 Compiled Results and Graphics: CASE STUDY: DPRK 100 MWth Reactor Currently Under Construction at Yongbyon

David von Hippel, Date Last Revised: 2/20/14

Ground Contamination (kBq/sq. m.) for release occuring

Downwind Distance (km)	Ground Contamination (kBq/sq. m.)	1 year after start-up	3 years after start-up	5 years after start-up	15 years after start-up	20 years after start-up
5	16,681	991	2,478	1,983	2,974	16,681
10	8,281	492	1,230	984	1,476	8,281
20	4,082	243	606	485	728	4,082
50	1,564	93	232	186	279	1,564
75	1,006	60	149	120	179	1,006
100	728	43	108	87	130	728
125	562	33	84	67	100	562
150	452	27	67	54	81	452
175	374	22	56	44	67	374
200	316	19	47	38	56	316
250	235	14	35	28	42	235
300	182	11	27	22	33	182
350	146	9	22	17	26	146

Downwind Distance (km)	External Dose Rate (mSv/yr)	1 year after start-up	3 years after start-up	5 years after start-up	15 years after start-up	20 years after start-up
5	100.74	5.99	14.97	11.97	17.96	100.74
10	50.01	2.97	7.43	5.94	8.92	50.01
20	24.65	1.46	3.66	2.93	4.39	24.65
50	9.45	0.56	1.40	1.12	1.68	9.45
75	6.08	0.36	0.90	0.72	1.08	6.08
100	4.40	0.26	0.65	0.52	0.78	4.40
125	3.39	0.20	0.50	0.40	0.61	3.39
150	2.73	0.16	0.41	0.32	0.49	2.73
175	2.26	0.13	0.34	0.27	0.40	2.26
200	1.91	0.11	0.28	0.23	0.34	1.91
250	1.42	0.08	0.21	0.17	0.25	1.42
300	1.10	0.07	0.16	0.13	0.20	1.10
350	0.88	0.05	0.13	0.10	0.16	0.88

Following is for accident after 15 years of operation

	Accumulated Dose (mSv) Over Exposure Period (years)					
Downwind Distance (km)	1 year	3 years	5 years	10 years	15 years	50 years
5	13.25	28.54	40.58	67.09	89.89	181.45
10	6.58	14.17	20.15	33.31	44.62	90.08
20	3.24	6.98	9.93	16.42	22.00	44.40
50	1.24	2.68	3.81	6.29	8.43	17.02
75	0.80	1.72	2.45	4.05	5.42	10.95
100	0.58	1.25	1.77	2.93	3.92	7.92
125	0.45	0.96	1.37	2.26	3.03	6.11
150	0.36	0.77	1.10	1.82	2.44	4.92
175	0.30	0.64	0.91	1.50	2.01	4.07
200	0.25	0.54	0.77	1.27	1.70	3.43
250	0.19	0.40	0.57	0.95	1.27	2.56
300	0.14	0.31	0.44	0.73	0.98	1.98
350	0.12	0.25	0.35	0.59	0.78	1.58

Following is for accident after 20 years of operation

	Accumulated Dose (mSv) Over Exposure Period (years)					
Downwind Distance (km)	1 year	3 years	5 years	10 years	15 years	50 years
5	74.34	160.10	227.62	376.35	504.21	1,017.81
10	36.91	79.48	113.00	186.84	250.31	505.28
20	18.19	39.18	55.70	92.09	123.38	249.06
50	6.97	15.01	21.34	35.29	47.28	95.44
75	4.48	9.66	13.73	22.70	30.42	61.40
100	3.25	6.99	9.94	16.43	22.01	44.43
125	2.51	5.40	7.67	12.68	16.99	34.30
150	2.01	4.34	6.17	10.20	13.66	27.58
175	1.67	3.59	5.10	8.43	11.30	22.81
200	1.41	3.03	4.31	7.12	9.54	19.26
250	1.05	2.26	3.21	5.30	7.11	14.34
300	0.81	1.75	2.49	4.12	5.51	11.13
350	0.65	1.40	1.99	3.28	4.40	8.88

Location	Diameter (km) Inner	Outer	Population Density persons/km^2	Initial Collective Radiation Dose person-Sv/yr
Yongbyon	0	2	2,000	500
Kaechon	13	17	20,000	9,900
Pyongyang	120	140	5,008	10,500
Seoul	315	335	4,185	6,700

Location	Cumulative Collective Radiation Dose person-Sv	Exposed Population People	Percent Excess Deaths %	Implied Number of Excess Deaths	Value of Excess Deaths $ million US
Yongbyon	1,900	1,000	9.700	100	$ 970
Kaechon	37,100	300,000	0.630	1,900	$ 18,900
Pyongyang	39,400	3,255,000	0.060	2,000	$ 20,100
Seoul	24,900	6,800,000	0.019	1,300	$ 12,700
TOTAL of Above (not total of exposed area)	103,300	10,356,000	0.051	5,232	52,670

	Exposed Population	Implied Number of Excess Deaths	Value of Excess Deaths, $ million (US)	
Location	People		Lower Estimate	Higher Estimate
Yongbyon	1,000	100	$ 110	$ 1,000
Kaechon	300,000	1,900	$ 2,000	$ 19,000
Pyongyang	3,255,000	2,000	$ 2,100	$ 20,000
Seoul	6,800,000	1,300	$ 1,400	$ 13,000
TOTAL of Above (not total of exposed area)	10,356,000	5,300	$ 5,610	$ 53,000

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ANNEX 4: Selected Inputs, Assumptions, and Additional Results of Regional (East Asia) Nuclear Fuel Cycle Analysis

ANNEX 4A: Selected Inputs and Assumptions

FUTURE REGIONAL NUCLEAR FUEL CYCLE COOPERATION IN EAST ASIA:
ENERGY SECURITY COSTS AND BENEFITS

Calculations for East Asia Science and Security (EASS) and Related Follow-on (2012-2016) Projects, funded by MacArthur Foundation

Common Factors for Calculations

Prepared by:	David Von Hippel
Last Modified:	8/14/2015

Common Factors

Conversions:

Pounds per kg:	2.2	
Units U per unit U_3O_8	0.847993	
Becquerels (Bq) per Curie (Ci)	3.70E+10	(disintegrations per second)
Atomic Weight of Natural Uranium	238.0289	grams/mol
Units U per unit UF6	0.676012	
Assumed USD inflation rate post-2015:	2%	/yr

Inflation Factors (to 2009 US dollars)

1990	1.64
1991	1.58
1992	1.53
1993	1.48
1994	1.45
1995	1.41
1996	1.37
1997	1.34
1998	1.32
1999	1.29
2000	1.26
2001	1.22
2002	1.20
2003	1.17
2004	1.14
2005	1.11
2006	1.07
2007	1.04
2008	1.00
2009	1.00
2010	0.98
2011	0.95
2012	0.93
2013	0.92
2014	0.90
2015	0.90
2016	0.88
2017	0.87
2018	0.85
2019	0.83
2020	0.82

Through 2015, from U.S. Bureau of Labor Statistics Inflation Calculator, http://www.bls.gov/data/inflation_calculator.htm; 2016-on based on assumed inflation rate.

Discount Rate	5%	;yr (real basis)

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FUTURE REGIONAL NUCLEAR FUEL CYCLE COOPERATION IN EAST ASIA: ENERGY SECURITY COSTS AND BENEFITS

Calculations for East Asia Science and Security (EASS) and Related Follow-on (2012-2016) Projects, funded by MacArthur Foundation

Estimates of Uranium Prices

Prepared by:	David Von Hippel
Last Modified:	8/26/2015

Historical Uranium Spot Prices

Conversions:

Pounds per kg:	2.2
Units U per unit U_3O_8	0.847993

Historical prices below from Cameco "URANIUM PRICES, Uranium Spot Price History, though July, 2015,
available as http://www.cameco.com/invest/markets/uranium-price.
except 2011 - 2012 from "Uranium Miner", available as http://www.uraniumminer.net/market_price.htm. Values from these two data sets appear reasonably consistent.
As of 2015, Cameco's "long term prices" were $10-$12 per lb higher than spot prices.
Prices shaded green are "UxC Uranium U3O8 Futures Quotes", available from http://www.cmegroup.com/trading/metals/other/uranium.html.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Unweighted Average	
													$/lb$U_3O_8$	$/kg U
2020	$47.40	$47.40	$52.45	$50.30	$46.45	$48.40	$47.05						$48.49	$ 125.81
2019	$45.20	$45.20	$45.20	$45.75	$45.75	$45.75	$46.30	$46.30	$46.30	$46.85	$46.85	$46.85	$46.03	$ 119.41
2018	$42.65	$42.65	$42.65	$43.40	$43.40	$43.40	$44.10	$44.10	$44.10	$44.65	$44.65	$44.65	$43.70	$ 113.37
2017	$39.15	$39.65	$39.65	$40.05	$40.45	$40.85	$41.05	$41.20	$41.40	$41.65	$41.90	$42.15	$40.76	$ 105.75
2016	$36.80	$37.05	$37.10	$37.20	$37.25	$37.45	$38.00	$38.20	$38.45	$38.75	$38.75	$39.15	$37.85	$ 98.19
2015	$37.00	$38.63	$38.36	$37.13	$35.00	$36.38	$35.50	$36.40	$36.40	$36.40	$36.45	$36.50	$36.68	$ 95.16
2014	$35.45	$35.38	$34.00	$30.43	$28.25	$28.23	$28.50	$31.50	$35.40	$36.38	$39.50	$35.50	$33.21	$ 86.16
2013	$43.88	$42.00	$42.25	$40.50	$40.45	$39.60	$34.75	$34.50	$35.00	$34.50	$36.08	$34.50	$38.17	$ 99.02
2012	$52.00	$52.00	$51.00	$51.75	$52.00	$51.00	$49.25	$48.50	$46.50	$42.50	$42.00	$43.50	$48.50	$ 125.83
2011	$72.00	$69.25	$62.50	$55.50	$57.50	$54.25	$51.75	$49.00	$52.50	$52.00	$51.75	$51.75	$56.65	$ 146.96
2010	$42.38	$41.13	$41.88	$41.75	$40.75	$41.75	$45.63	$45.25	$46.63	$52.00	$60.63	$62.25	$46.84	$ 121.51
2009	$47.50	$44.50	$42.00	$44.50	$49.00	$51.50	$47.00	$46.00	$42.88	$48.00	$45.38	$44.50	$46.06	$ 119.50
2008	$78.00	$73.00	$71.00	$65.00	$60.00	$59.00	$64.50	$64.50	$53.00	$45.00	$55.00	$52.50	$61.71	$ 160.09
2007	$75.00	$85.00	$95.00	$113.00	$125	$136.00	$120.00	$90.00	$85.00	$85.00	$93.00	$90.00	$99.33	$ 257.71
2006	$37.50	$38.63	$40.75	$41.50	$43.00	$45.75	$47.38	$50.25	$54.88	$60.13	$63.50	$72.00	$49.61	$ 128.70
2005	$21.10	$21.75	$22.55	$25.00	$29.00	$29.00	$29.50	$30.10	$31.63	$33.25	$34.75	$36.38	$28.67	$ 74.37
2004	$15.55	$16.63	$17.63	$17.68	$17.80	$18.50	$18.50	$19.63	$20.00	$20.23	$20.50	$20.60	$18.60	$ 48.27
2003	$10.15	$10.15	$10.10	$10.88	$10.95	$10.90	$11.05	$11.30	$12.23	$12.73	$13.75	$14.45	$11.55	$ 29.97
2002	$9.70	$9.93	$9.83	$9.90	$9.90	$9.90	$9.85	$9.85	$9.75	$9.90	$9.88	$10.20	$9.88	$ 25.64
2001	$7.23	$7.95	$8.20	$8.85	$8.85	$8.83	$8.93	$9.10	$9.40	9.48	$9.50	$9.55	$8.82	$ 22.89
2000	$9.45	$9.38	$9.20	$8.85	$8.43	$8.13	$8.08	$7.75	$7.43	$7.20	$7.13	$7.10	$8.18	$ 21.22
1999	$10.50	$10.50	$10.85	$10.85	$10.63	$10.35	$10.25	$10.05	$9.83	$9.73	$9.68	$9.60	$10.24	$ 26.55
1998	$11.90	$10.88	$10.73	$10.78	$10.83	$10.83	$10.50	$10.23	$9.83	$9.20	$8.75	$8.75	$10.27	$ 26.64
1997	$14.25	$13.70	$13.00	$12.18	$11.45	$10.60	$10.50	$10.25	$10.93	$12.63	$12.75	$12.10	$12.03	$ 31.21
1996	$12.95	$15.33	$15.83	$16.13	$16.50	$16.55	$16.50	$16.35	$15.90	$15.45	$14.95	$14.70	$15.60	$ 40.46
1995	$9.68	$10.38	$11.08	$11.55	$11.78	$11.83	$11.88	$11.80	$11.75	$11.75	$11.83	$12.23	$11.46	$ 29.74
1994	$9.50	$9.48	$9.48	$9.35	$9.25	$9.25	$9.33	$9.15	9.08	$9.08	9.48	9.6	$9.34	$ 24.22
1993	$9.75	$10.05	$10.10	$10.20	$10.08	$10.15	$9.90	$10.05	$10.25	$10.23	$9.95	$9.88	$10.05	$ 26.07
1992	$7.95	$8.00	$7.88	$7.83	$7.73	$7.83	$7.83	$8.08	$8.68	$10.38	$10.40	$9.98	$8.55	$ 22.18
1991	$9.15	$9.45	$9.35	$9.05	$9.23	$9.08	$8.65	$8.88	$8.33	$7.38	$7.40	$8.75	$8.73	$ 22.64
1990	$8.88	$8.75	$8.80	$8.85	$9.30	$11.30	$11.73	$11.48	$10.30	$8.43	$9.65	9.75	$9.77	$ 25.34
1989	$11.55	$11.23	$10.73	$10.15	$9.80	$9.73	$9.73	$9.65	$9.60	$9.40	9.25	$9.00	$9.99	$ 25.90
1988	$16.40	$16.20	$15.95	$15.88	$15.45	$15.18	$14.65	$14.13	$13.80	$13.18	$12.85	$11.88	$14.63	$ 37.95

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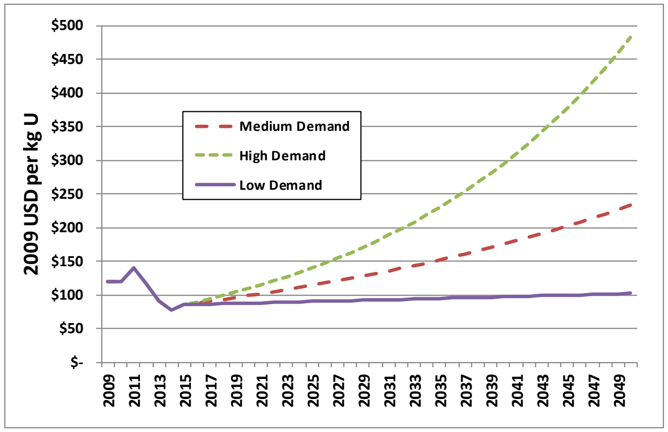
Projections of Uranium Costs

No recent long-term projections of Uranium costs were immediately available. An older (2001) IAEA report (Analysis of Uranium Supply to 2050, (May 2001, STI/PUB/1104), suggests that in a medium nuclear fuels demand scenario, uranium resources with production costs of $130 would become economic in 2034 (assuming known resource development only), and in a high demand scenario, those resources would become economic in 2026. Converting this cost to 2009 dollars yields $ 163.80 per kg U (inflation from 2000 to 2009 from http://data.bls.gov/cgi-bin/cpicalc.pl). Starting with actual 2015 Uranium spot prices, these estimates suggest an annual average growth rate in Uranium prices of 2.90% under a medium demand scenario, and 5.06% under a high demand scenario. These very rough estimates, extrapolated to 2050, yield the following Uranium price trends. Note that in the high demand case, by 2050 Uranium prices approach recent estimates of the costs of extracting Uranium from seawater. For the low price trajectory case below, we assume a modest 0.50% annual real increase in Uranium costs, which is the same escalation rate used by a team of MIT researchers in preparing "Update of the MIT 2003 Future of Nuclear Power Study", dated 2009, and available as http://web.mit.edu/nuclearpower/pdf/nuclearpower-update2009.pdf. For 2016-2020, the medium demand case assumptions yield values fairly close to the UxC Uranium Futures Quotes for that period as of August 2015.

Year	Medium Demand	High Demand	Low Demand
2009	$ 119.50	$ 119.50	$ 119.50
2010	$ 119.08	$ 119.08	$ 119.08
2011	$ 139.61	$ 139.61	$ 139.61
2012	$ 117.02	$ 117.02	$ 117.02
2013	$ 91.10	$ 91.10	$ 91.10
2014	$ 77.54	$ 77.54	$ 77.54
2015	$ 85.64	$ 85.64	$ 85.64
2016	$ 88.13	$ 89.98	$ 86.07
2017	$ 90.68	$ 94.53	$ 86.50
2018	$ 93.31	$ 99.32	$ 86.93
2019	$ 96.02	$ 104.34	$ 87.37
2020	$ 98.80	$ 109.62	$ 87.81
2021	$ 101.67	$ 115.17	$ 88.24
2022	$ 104.61	$ 121.00	$ 88.69
2023	$ 107.65	$ 127.12	$ 89.13
2024	$ 110.77	$ 133.56	$ 89.57
2025	$ 113.98	$ 140.32	$ 90.02
2026	$ 117.29	$ 147.42	$ 90.47
2027	$ 120.69	$ 154.88	$ 90.93
2028	$ 124.19	$ 162.72	$ 91.38
2029	$ 127.79	$ 170.96	$ 91.84
2030	$ 131.49	$ 179.61	$ 92.30
2031	$ 135.31	$ 188.70	$ 92.76
2032	$ 139.23	$ 198.25	$ 93.22
2033	$ 143.27	$ 208.28	$ 93.69
2034	$ 147.42	$ 218.82	$ 94.16
2035	$ 151.69	$ 229.90	$ 94.63
2036	$ 156.09	$ 241.53	$ 95.10
2037	$ 160.62	$ 253.76	$ 95.58
2038	$ 165.28	$ 266.60	$ 96.05
2039	$ 170.07	$ 280.09	$ 96.53
2040	$ 175.00	$ 294.27	$ 97.02
2041	$ 180.08	$ 309.16	$ 97.50
2042	$ 185.30	$ 324.81	$ 97.99
2043	$ 190.67	$ 341.25	$ 98.48
2044	$ 196.20	$ 358.52	$ 98.97
2045	$ 201.89	$ 376.67	$ 99.47
2046	$ 207.74	$ 395.73	$ 99.96
2047	$ 213.77	$ 415.76	$ 100.46
2048	$ 219.96	$ 436.80	$ 100.97
2049	$ 226.34	$ 458.91	$ 101.47
2050	$ 232.91	$ 482.14	$ 101.98

Year	Historical Uranium Price (2009 $/kg U)*
2000	$ 26.73
2001	$ 27.92
2002	$ 30.77
2003	$ 35.07
2004	$ 55.02
2005	$ 82.55
2006	$ 137.70
2007	$ 268.01
2008	$ 160.09
2009	$ 119.50
2010	$ 119.08
2011	$ 139.61
2012	$ 117.02
2013	$ 91.10
2014	$ 77.54
2015	$ 85.64
2016	$ 86.63
2017	$ 91.48
2018	$ 96.15
2019	$ 99.28
2020	$ 102.55

*Values for 2016-2020 and from August 2015 based on UxC Uranium Futures Quotes (see above).



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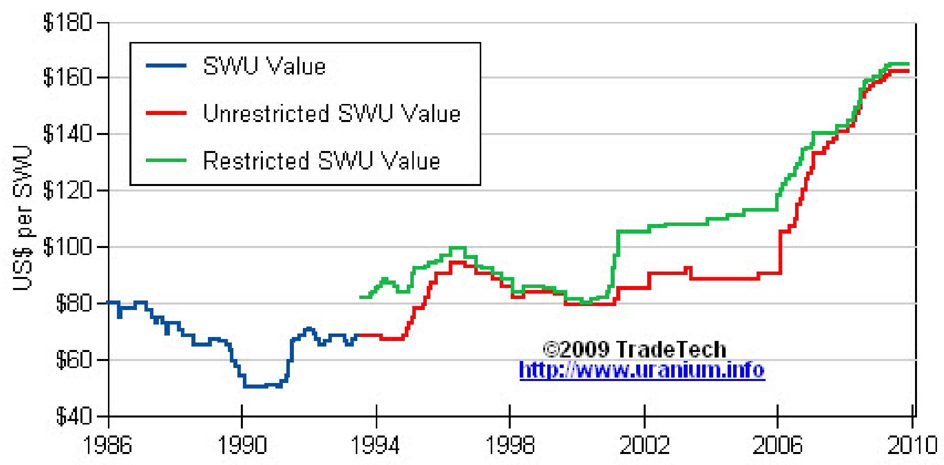
Projections of Uranium Enrichment Costs

No recent long-term projections of Uranium enrichment costs were immediately available. We use the historical data below with three assumed growth rates to produce three candidate cost trajectories.

The following data are from "TradeTech and its Web site, http://www.uranium.info", accessed as of 2009 via http://www.uranium.info/index.cfm?go=c.page&id=34

For the years 2000-2009, average SWU values (arithmetic averages of restricted and unrestricted mid-year values) were estimated from the table and graph below. These data imply an average real escalation in SWU value from 2000-2009 of 5.27% percent annually. Given that this time period spans an era when enriched uranium from nuclear weapons programs was used for power reactors in large quantities, this growth rate is probably not suitable for use as a future long-term growth rate, even in a high case. If more recent years are included in the calculation (see UCx graph, below), a much more modest average real escalation rate of 1.40% percent annually is implied.

We use an average real escalation rate of 1.00% annually as a reference case (medium demand) assumption, with 2.50% annually for a high demand case, and 0.00% annual growth used as a low-case projection of enrichment value.



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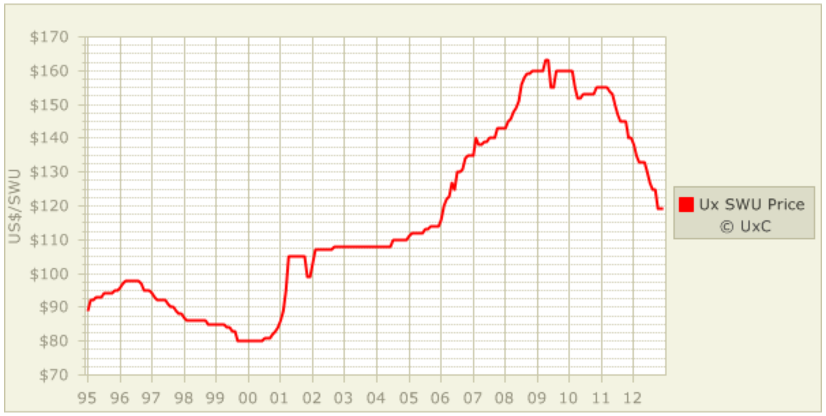
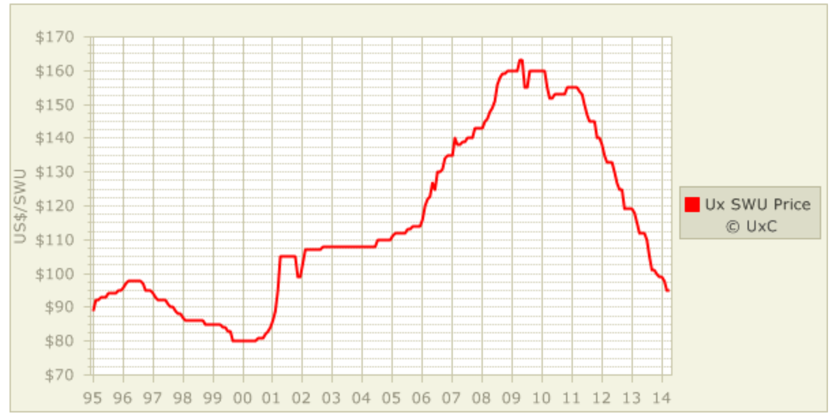
Following are from UCx, "Spot Ux SWU Pricet Chart", available as http://www.uxc.com/review/uxc_pricechart.aspx?chart=spot-swu-full, and dated 1-9-2013 and 5-26-14, respectively.





Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Prices from 1986-2001, and 2007-present are available to clients only.												
2002												
Unrestricted	85	85	90	90	90	90	90	90	90	90	90	90
Restricted	105	105	107	107	107	107	107	107	108	108	108	108
2003												
Unrestricted	90	90	90	92	92	88	88	88	88	88	88	88
Restricted	108	108	108	108	108	108	108	108	108	108	108	110
2004												
Unrestricted	88	88	88	88	88	88	88	88	88	88	88	88
Restricted	110	110	110	110	110	110	111	111	111	111	111	111
2005												
Unrestricted	88	88	88	88	88	90	90	90	90	90	90	90
Restricted	113	113	113	113	113	113	113	113	113	113	113	113
2006												
Unrestricted	90	105	105	105	107	107	110	115	117	120	124	126
Restricted	118	120	122	124	125	125	128	129	131	134	135	135
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**

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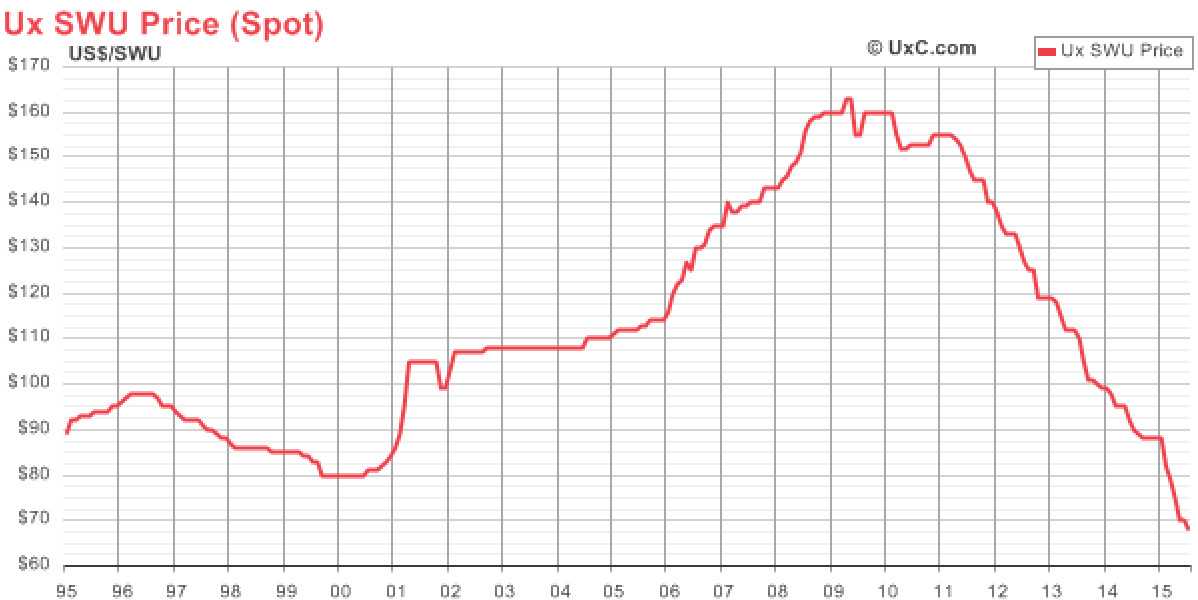
For graph below Source: The Ux Consulting Company, LLC, http://www.uxc.com/, accessed 8-14-15.



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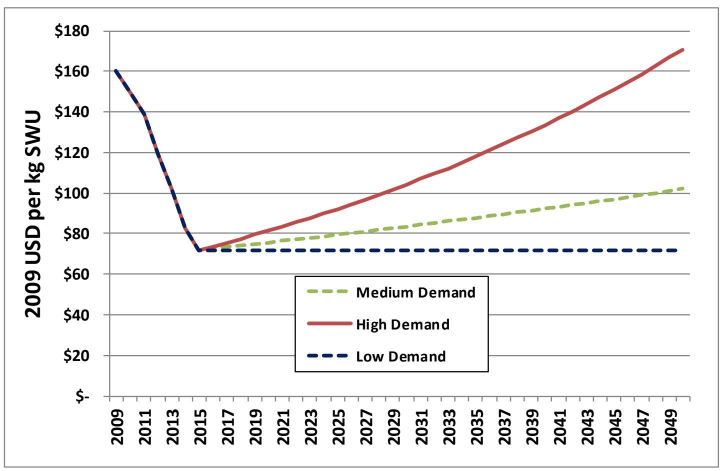
Year	Medium Demand	High Demand	Low Demand
2009	$ 160.00	$ 160.00	$ 160.00
2010	$ 148.96	$ 148.96	$ 148.96
2011	$ 138.70	$ 138.70	$ 138.70
2012	$ 119.04	$ 119.04	$ 119.04
2013	$ 102.12	$ 102.12	$ 102.12
2014	$ 82.80	$ 82.80	$ 82.80
2015	$ 72.00	$ 72.00	$ 72.00
2016	$ 72.72	$ 73.80	$ 72.00
2017	$ 73.45	$ 75.65	$ 72.00
2018	$ 74.18	$ 77.54	$ 72.00
2019	$ 74.92	$ 79.47	$ 72.00
2020	$ 75.67	$ 81.46	$ 72.00
2021	$ 76.43	$ 83.50	$ 72.00
2022	$ 77.19	$ 85.59	$ 72.00
2023	$ 77.97	$ 87.73	$ 72.00
2024	$ 78.75	$ 89.92	$ 72.00
2025	$ 79.53	$ 92.17	$ 72.00
2026	$ 80.33	$ 94.47	$ 72.00
2027	$ 81.13	$ 96.83	$ 72.00
2028	$ 81.94	$ 99.25	$ 72.00
2029	$ 82.76	$ 101.73	$ 72.00
2030	$ 83.59	$ 104.28	$ 72.00
2031	$ 84.43	$ 106.88	$ 72.00
2032	$ 85.27	$ 109.56	$ 72.00
2033	$ 86.12	$ 112.30	$ 72.00
2034	$ 86.98	$ 115.10	$ 72.00
2035	$ 87.85	$ 117.98	$ 72.00
2036	$ 88.73	$ 120.93	$ 72.00
2037	$ 89.62	$ 123.95	$ 72.00
2038	$ 90.52	$ 127.05	$ 72.00
2039	$ 91.42	$ 130.23	$ 72.00
2040	$ 92.34	$ 133.48	$ 72.00
2041	$ 93.26	$ 136.82	$ 72.00
2042	$ 94.19	$ 140.24	$ 72.00
2043	$ 95.13	$ 143.75	$ 72.00
2044	$ 96.08	$ 147.34	$ 72.00
2045	$ 97.05	$ 151.02	$ 72.00
2046	$ 98.02	$ 154.80	$ 72.00
2047	$ 99.00	$ 158.67	$ 72.00
2048	$ 99.99	$ 162.64	$ 72.00
2049	$ 100.99	$ 166.70	$ 72.00
2050	$ 102.00	$ 170.87	$ 72.00

Year	Historical Enrichment Value (2009 $/kg SWU)	
2000	100.80	
2001	97.60	
2002	118.20	
2003	125.19	
2004	113.43	
2005	112.67	
2006	127.33	
2007	135.20	
2008	140.00	
2009	160.00	
2010	148.96	Rough estimate of annual average from UCx graph above
2011	138.70	Rough estimate of annual average from UCx graph above
2012	119.04	Rough estimate of annual average from UCx graph above
2013	102.12	Rough estimate of annual average from UCx graph above
2014	82.80	Rough estimate of annual average from UCx graph above
2015	72.00	Rough estimate of annual average from UCx graph above



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FUTURE REGIONAL NUCLEAR FUEL CYCLE COOPERATION IN EAST ASIA: ENERGY SECURITY COSTS AND BENEFITS

Calculations for East Asia Science and Security (EASS) and Related Follow-on (2012-2016) Projects, funded by MacArthur Foundation

Estimates of Average Uranium Ore Concentrations

Prepared by:	David Von Hippel
Last Modified:	1/9/2013

WORLD URANIUM OUTPUT AND CALCULATION OF AVERAGE ORE GRADE

Following data from World Nuclear Association (2012), "World Uranium Mining", last updated August, 2012, and available as http://www.world-nuclear.org/info/inf23.html

Production from mines (tonnes U)

Country	2002	2003	2004	2005	2006	2007	**2008**	**2009**	**2010**	**2011**	Estimated Average Ore % U
Canada	11604	10457	11597	11628	9862	9476	9000	10173	9783	9145	14.500
Kazakhstan	2800	3300	3719	4357	5279	6637	8521	14020	17803	19451	0.072
Australia	6854	7572	8982	9516	7593	8611	8430	7982	5900	5983	0.121
Niger	3075	3143	3282	3093	3434	3153	3032	3243	4198	4351	0.167
Namibia	2333	2036	3038	3147	3067	2879	4366	4626	4496	3258	0.033
Russia (est)	2900	3150	3200	3431	3262	3413	3521	3564	3562	2993	0.142
Uzbekistan	1860	1598	2016	2300	2260	2320	2338	2657	2874	3000	0.140
USA	919	779	878	1039	1672	1654	1430	1453	1660	1537	0.149
Ukraine (est)	800	800	800	800	800	846	800	840	850	890	0.140
China (est)	730	750	750	750	750	712	769	1200	1350	1500	0.132
Malawi								104	670	846	
South Africa	824	758	755	674	534	539	655	104	670	846	0.035
Brazil	270	310	300	110	190	299	330	563	583	582	0.250
India (est)	230	230	230	230	177	270	271	290	400	400	0.020
Czech Repub.	465	452	412	408	359	306	263	345	148	265	0.308
Romania (est)	90	90	90	90	90	77	77	258	254	229	
Germany	221	104	77	94	65	41	0	75	77	77	
Pakistan (est)	38	45	45	45	45	45	45	0	0	52	
France	20	0	7	7	5	4	5	50	45	45	
Total of Above	36,033	35,574	40,178	41,719	39,444	41,282	43,853	51,547	55,323	55,450	
total world	**36 072**	**35 574**	**40 178**	**41 719**	**39 444**	**41 282**	**43 853**	**51 450**	**54 660**	**54 610**	
tonnes U_3O_8	42 529	41 944	47 382	49 199	46 516	48 683	51 716	60 675	64 461	64 402	
percentage of world demand				65%	63%	64%	68%	78%	78%	85%	
Estimated Global Weighted-average Ore grade (% as U) for countries where grade estimates available											2.49
Estimated Global Weighted-average Ore grade (% as U) for countries where grade estimates available, less Canada											0.10

ORE GRADE AND PRODUCTION/RESERVES/CAPACITY DATA BY COUNTRY

Production data in yellow highlights from same World Nuclear Association source as table above, and used as more up-to-date, when available.

Country	Mine Name	Ore %	Output (te Ore)	Output (te U)	Implied country weighted average Ore %	Notes
Argentina	Cachocira	0.3	340		0.3	Mine-specific data from Selected Countries extracted from Wikipedia, "List of uranium mines", available as http://en.wikipedia.org/wiki/List_of_uranium_mines. Production data in yellow highlights is for 2011 from same World Nuclear Association source as table above (except Canada, which is from World Nuclear Association (2013), "Uranium in Canada", last updated January 2013, and available as , used as more up-to-date than Wikipedia source, when available.
Australia	Olympic Dam	0.05		3353	0.121	
	Ranger	0.2		2240		
	Beverley	0.18		1064		
Brazil	Caetité	0.25		400	0.25	
Canada	MacArthur River	18.33		7686	14.500	
	McClean Lake	0.53		666		
	Rabbit Lake	0.76		1463		
China	[See below]	0.132		1500	0.132	
Czech Republic	Rozna	0.378		400	0.308	Ore % estimated from NEA 2007, page 171--see ***Source 2***.
	Straz	0.030		100		Output figures are nominal annual U production per year.
DPRK		0.200			0.200	Rough estimate; see ***Note 5***
India	All	0.0196		271	0.020	Ore % estimated from NEA 2007, page 211--see ***Source 2***.
Indonesia	Remaja-Hitam Ore Body	0.2	*7500*		0.228	See ***Note 1***; figures shown are reserves, not output
	Rirang-Tanah Merah Ore Body	0.65	*500*			See ***Note 1***; figures shown are reserves, not output
Kazakhstan	All	0.072		19451	0.072	Ore % estimated from NEA 2007 based on planned nominal capacities and ore % by "Centre", pages 242-243--see Source 2. Almost all Centres use or will use ISL.
Namibia	Rossing	0.03	*40000*	1822	0.033	Ore % estimated from NEA 2007, page 264--see ***Source 2***.
	Langer Heinrich	0.06	*4500*			Output figures are ore production per day.
Niger	Arlit (operating)	0.28	*1900*		0.167	Ore % estimated from NEA 2007, page 273--see ***Source 2***.
	Arlit (planned)	0.07	*3800*			Output figures are ore production per day.
	Akouta	0.4	*1800*			
Russia	PPGHO	0.18		3500	0.142	Ore % estimated from NEA 2007, page 297--see ***Source 2***.
	Dalur	0.04		800		Output figures are nominal annual U production per year.
	Khiagda	0.05		1000		
	Elkon	0.15		5000		
	Gornoe	0.2		600		
	Orlov	0.082		600		
South Africa	All	0.035		846	0.035	Ore % estimate--See ***Note 3***
Ukraine	All	0.1		890	0.100	Ore % estimated from NEA 2007, page 346--see ***Source 2***.
United States	Canon City	0.160		*210*	0.149	Ore % estimated from NEA 2007, page 346--see ***Source 2***.
	Sweetwater	0.035		350		Output figures are nominal annual U production per year.
	White Mesa	0.181		1200		ISL "Centres" not included (no ore % data available for those).
Uzbekistan		0.14		3000	0.140	Ore % estimate--See ***Note 4***
Vietnam	An Diem Deposit	0.034		500	0.099	Recoverable te U, page 375, NEA 2007, see ***Source 2***.
	Khe Hoa-Khe Cao deposit	0.104		6744		Ore % estimate--See ***Note 6***

MacArthur River Data from World Nuclear Association 2013

	Te U	Ore % U
Probable	77,780	23.81%
Proven	70,800	12.30%
Weighted Average		18.33%

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China's Operating Uranium Mines (from World Nuclear Association (2010), "China's Nuclear Fuel Cycle", updated March, 2010, and available as http://www.world-nuclear.org/info/inf63b_china_nuclearfuelcycle.html, except as noted).

Mine	Province	Type	Nominal capacity (tonnes U per year)	Started	Ore %	Source for Ore % data
Fuzhou	Jiangxi	Underground & open pit	300	1966	0.12%	Derived from ore output and tU output data from NEA (Nuclear Energy Agency) "Redbook" 2007, page 159 (***Source 2***).
Chongyi	Jiangxi	Underground & open pit	120	1979	0.09%	
Yining	Xinjiang	In-situ leach (ISL)	200	1993		
Lantian	Shaanxi	Underground	100	1993	0.14%	
Benxi	Liaoning	Underground	120	1996	0.20%	
Weighted average of mines with ore % available					0.13%	
Fraction of production from Underground Mines					76.2%	

Additional Notes and Sources

1. Indonesian mines are thought to be dormant. Figures in "Output" column are actually central estimates of range of reserves, and "Ore %" data are central values for range of Uranium "grades" (assumed to be %) provided. Source, Countries of Strategic Nuclear Concern: Indonesia, Carolyn Taylor, Yana Feldman, Charles Mahaffey, Brett Marvin, Jack Boureston, SIPRI, 2004, quoted in Natilus Institute "Muria peninsula nuclear power proposal: Uranium Mining", at http://www.globalcollab.org/Nautilus/australia/reframing/aust-ind-nuclear/ind-np/muria/uranium-mining.

2. NEA (Nuclear Energy Agency, 2008), Uranium 2007--Resources, Production, and Demand (also called "Red Book") available ("Read only version") as http://www.oecdbookshop.org/oecd/get-it.asp?REF=6608031E.PDF&TYPE=browse.

3. Ore concentration for South Africa is a very rough estimate based on data in Wise Uranium Project -- Mine Ownership, Africa, available as http://www.wise-uranium.org/uoafr.html#EASTRANDT.

4. No specific estimate for the average grade of Uranium ore in Uzbekistan was immediately available. J. W. S. van Leeuwen (2006), of Oxford Research Group, in Energy from Uranium, dated July 2006 (available as http://www.stormsmith.nl/publications/Energy%20from%20Uranium%20-%20July%202006.pdf), ascribes a value of 0.14 % for Uzbek ore based on an average value for sandstone ores globally.

5. P. Hayes (2004), in "North Korea's Uranium Exports: Much Ado About Something", Nautilus Institute Northeast Asia Peace and Security Network Special Report, dated May 25, 2004, and available as http://www.nautilus.org/archives/pub/ftp/napsnet/special_reports/Hayes-DPRKuranium.txt), describes DPRK uranium resources as "The deposits are uraniferous black shale occurrences (perhaps similar to that at Ok'chon in South Korea) occurring at a depth about 200 meters. The ore grades are about 0.2%". "North Korea's Nuclear Weapons Programme", by the International Institute for Strategic Studies, 2006, available as http://www.iiss.org/publications/strategic-dossiers/north-korean-dossier/north-koreas-weapons-programmes-a-net-asses/north-koreas-nuclear-weapons-programme, states ""It has been estimated that, at its peak in the early 1990s, North Korea was able to produce about 300 tonnes of yellow cake [U3O8] annually, equal to approximately 30,000 tonnes of uranium ore.". The latter would imply an ore grade of about 0.1% U. At present, we use the 0.2% value.

6. In Chapter 16, "Vietnam", the book Uranium Resources of the World cites a measurement for the Uranium content of "unweathered sandstone" in the Nong Son Basin where Vietnam's major Uranium resources lie of 0.104%. This value is just a measurement, not a basin-wide average but is the only figure immediately available to characterize this deposit, and is in the range of typical values for sandstone Uranium deposits. F.J. Dahlkamp (2009), Uranium Deposits of the Word: Asia, Springer-Verlag.

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FUTURE REGIONAL NUCLEAR FUEL CYCLE COOPERATION IN EAST ASIA:
ENERGY SECURITY COSTS AND BENEFITS

Calculations for East Asia Science and Security (EASS) and Related Follow-on (2012-2016) Projects, funded by MacArthur Foundation

Estimates of Uranium Mining and Milling Volumes: "National Enrichment, National Reprocessing" Scenario (Regional Scenario 1)

Using Nuclear Fuel Requirements Estimates from "Business-as-Usual" Capacity Expansion Case

Prepared by:	David Von Hippel
Last Modified:	10/19/2015

General Assumptions

All costs in approximately **2009 US Dollars** unless otherwise noted

Average tons ore mined per kg U metal extracted, imported Uranium	0.040	*See **Note 7**. Corresponds to a U content in ore of*	2.493%
Fraction of imported Uranium from conventional underground & open pit mines	62%	as of 2008 (*See **Note 1**).*	
Fraction of imported Uranium from conventional underground & open pit mines	62%	as of 2050	
Fraction of imported Uranium from in-situ leaching operations	28%	as of 2008 (*See **Note 1**).*	
Fraction of imported Uranium from in-situ leaching operations	28%	as of 2050	
Average % of imported U from conventional mines that is from underground mines	56%	(See ***Note 6***)	
Fossil fuel used in open pit mining per te ore	407	MJ	(See ***Note 2***)
Fossil fuel used in underground mining per te ore	58	MJ	(See ***Note 2***)
Electricity used in open pit mining per te ore	2.68	kWhe	(See ***Note 2***)
Electricity used in underground mining per te ore	70.6	kWhe	(See ***Note 2***)
Electricity used in in-isitu leaching (ISL) per kg Uranium	26	kWhe	(See ***Note 3***)
Fossil fuel used in in-isitu leaching (ISL) per kg Uranium	0	MJ	*Placeholder*
Fossil fuel used in milling Uranium per te ore	483	MJ	(See ***Note 2***)
Electricity used in milling Uranium per te ore	18.6	kWhe	(See ***Note 2***)
Water use in Uranium milling per tonne U produced	1,000	cubic m.	(See ***Note 4***)
2009 Average Uranium Price	$ 120	$/kg U (2009 USD)	
2050 Average Uranium Price	102	assuming Low	price trajectory (see "Uranium_Prices" worksheet in this workbook)
Radioactivity in tailings from Uranium Milling	1.30	GBq per tonne ore assuming concentration of	1% U in ore. (See ***Note 5***)

	Australia	China	DPRK	Indonesia	Japan	ROK	RFE	Taiwan	Vietnam	Notes and Sources
Target fraction of Uranium from in-country mines	100%	50%	50%	50%	0%	0%	100%	0%	50%	
Year in-country mining starts	2000	2000	2020	2025	2000	2000	2000	2000	2025	
Year in-country mining reaches target level	2000	2000	2030	2030	2000	2000	2000	2000	2030	
Average tons ore mined per kg U metal, domestic Uranium	0.825	0.759	0.500	0.438	0.994	0.500	0.705	0.994	1.008	(See ***Note 8***)
% of domestic U from conventional underground & open pit mines	91%	76%	100%	100%	100%	100%	82.8%	100%	100%	All Placeholders
% of domestic U from in-situ leaching mines	9.2%	24%	0%	0%	0%	0%	17%	0%	0%	except Australia, China,
Ave. % of domestic U from conventional mines that is from underground mines	0%	100%	100%	100%	100%	100%	100%	100%	100%	Russia (see ***Note 9***)

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NOTES AND SOURCES

1. World Nuclear Association (2009), "World Uranium Mining". Available as http://www.world-nuclear.org/info/inf23.html. As of 2008, 62% of uranium was mined in conventional underground and open pit mines, 28% was removed through in situ leaching (ISL), and 10% of Uranium was extracted as a by-product of other metals mining in the Olympic Dam mine in Australia.

2. WISE Uranium Project (2009), "Nuclear Fuel Energy Balance Calculator - HELP", available as http://www.wise-uranium.org/nfceh.html, notes:with regard to fossil fuel use in Uranium mining, "Values vary in wide ranges, depending on ore deposit and mining technique used. Typical values are per t ore for open pit mines, and 57.7 MJ per t ore for underground mines in the US." Regarding electricity use in Uranium mining, the same source states "Values vary in wide ranges, depending on ore deposit and mining technique used. Typical values are 2.68 kWhe per t ore for open pit mines, and 70.6 kWhe per t ore for underground mines in the US".

3. World Nuclear Association (2009), "In Situ Leach (ISL) Mining of Uranium", dated June, 2009, and available as http://www.world-nuclear.org/info/inf27.html, lists examples of electricity consumption during ISL Uranium mining as: "Unit power consumption is about 19 kWh/kgU (16 kWh/kg U3O8) in Australia and around 33 kWh/kgU in Kazakhstan." The average of these values is used here.

4. Down the Yellowcake Road (2008), "Uranium Milling Explained", available as http://downtheyellowcakeroad.org/html/Milling.html, lists a US Uranium mill proposed for reopening as potentially using 1.3 million gallons of water per day to process peak production of 1200 tons of ore per day. This converts to 4.50 cubic meters water per metric ton ore processed.
Water consumption for Uranium production in Namibia, which produces about 10 percent of the world's Uranium, is estimated at 10 Million cubic meters annually as of 2008, when production was 5104 tonnes of Uranium, or about 1,959 cubic meters per (metric) ton U, from J.S. Iita (2009), "URANIUM PRODUCTION PROSPECTS AND CHALLENGES –NAMIBIA", presented at IAEA, VIENNA, AUSTRIA-SEPTEMBER 2009. Available as http://www.iaea.org/OurWork/ST/NE/NEFW/documents/RawMaterials/GCRoundTable2009/NAMIBIA_URANIUM%20PRODUCTION%20PROSPECTS%20AND%20CHALLENGES%20.pdf.
A survey of water consumption in a number of mines around the world yielded a wide range of results from about 46 to 860 cubic meters of water per metric ton U_3O_8.
The same survey cites a much higher average of about 7,700 cubic meters per te U_3O_8 for an Australian mine that uses the in situ leaching production method.
Source: G. M Mudd and M. Diesendorf (2007), "Sustainability Aspects of Uranium Mining : Towards Accurate Accounting ?", 2nd International Conference on Sustainability Engineering & Science, Auckland, New Zealand - 20-23 February 2007, Available as http://civil.eng.monash.edu.au/about/staff/muddpersonal/2007-SustEngSci-Sust-v-Uranium-Mining.pdf.
Given this wide range of estimates, and the fact that it is difficult to determine whether all of these estimates consistently include all water requirements in U mining and milling, we adopt a placeholder value of 1000 cubic meters per metric ton Uranium produced pending receipt of more definitive studies.

5. Based on results from Wise Uranium Project, "Uranium Decay Calculator" (http://www.wise-uranium.org/rccu.html) assuming Uranium ore with U concentration of 1%, natural Uranium in equilibrium with its projeny in the mill tailing, and including all activities. The value shown is estimated activity for roughly the period 1 to 10,000 years after mining. Based on the results of the Calculator, tailings activity varies roughly linearly with Uranium content of ore in the typical range of U contents found in economically exploitable ores.

6. The World Nuclear Association web page "Uranium Mining" (http://www.world-nuclear.org/education/mining.htm, accessed 4/2010) lists Uranium sources by type of mine as "[a]bout half of the world's uranium now comes from underground mines, about 30% from open cut mines and over 20% from ISL" These figures are somewhat different from those provided by the same group in source 1, above. To try and reconcile these figures, however, we assume that 40% of the 72% of Uranium listed in source 1 as coming from underground mines, surface mines, or as a by-product from the Olympic Dam metals mine in Australia comes from (dedicated Uranium) underground mines, meanin 55.6% of total Uranuim not from ISL is from underground mining.

7. Current global average for Uranium ore grade as estimated in "Uranium_Production" worksheet in this workbook. Although most Uranium mines in the world have ore concentrations in range from 0.03 to 0.4 percent Uranium, the global average is brought up significantly by the exceedingly high quality (and quantity) Uranium mined at MacArthur River, Canada. Mining in the rest of the world uses ores averaging on the order of 0.1 percent Uranium.

8. Estimateds as prepared in "Uranium_Production" worksheet in this workbook. Values for Japan and Taiwan, which have very limited Uranium resources. (and will not mine Uranium under any of the scenarios considered) are set at the world average excluding Canada. The value for the ROK, which also has limited resources (but is apparently considering exploring some areas) is set at present at the estimate used for the DPRK.

9. Estimates of fractions of ore mined by type for China, Russia, and Australia are rough estimates based on production data for recent years (Russia, Australia) or production capacity data (China) from the document below, some of which is presented in the "Uranium_Production" worksheet in this workbook.
NEA (Nuclear Energy Agency, 2008), Uranium 2007--Resources, Production, and Demand (also called "Red Book")
available ("Read only version") as http://www.oecdbookshop.org/oecd/get-it.asp?REF=6608031E.PDF&TYPE=browse.

FUTURE REGIONAL NUCLEAR FUEL CYCLE COOPERATION IN EAST ASIA: ENERGY SECURITY COSTS AND BENEFITS

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Estimates of Uranium Transport, Conversion, and Enrichment Requirements: "National Enrichment, National Reprocessing" Scenario (Regional Scenario 1)

Using Nuclear Fuel Requirements Estimates from "Business-as-Usual" Capacity Expansion Case

Prepared by: David Von Hippel
Last Modified: 10/19/2015

General Assumptions

All costs in approximately **2009 US Dollars** unless otherwise noted

Fraction of imported enrichment services from gas diffusion plants as of 2007	30%	(See ***Note 1***).	
Target fraction of imported enrichment services from gaseous diffusion plants	0%		
Year that target fraction of imported enrichment services from gaseous diffusion plants reached	2030		
Average distance from mining area to enrichment facility for imported uranium or domestic uranium not enriched in-country (km)	10,000	Very rough estimate of average distance between major Uranium producers and enrichment facilities in Europe	
Average cost of uranium (yellowcake) transport, rail ($/tonne-km U_3O_8)	$ 0.0209	(See ***Note 6***).	
Average cost of uranium (yellowcake) transport, ocean freight ($/tonne-km U_3O_8)	$ 0.0127	Estimated from container freight average rates--see ***Note 7***	
Fossil fuel used in uranium conversion (to UF_6)	2.39	MJ/kg U	(See ***Note 3***)
Electricity used in uranium conversion (to UF_6)	1	kWhe/kg U	Placeholder only
Losses in uranium conversion (to UF_6)	0.5%	of incoming natural uranum feed (as in country workbooks)	
Electricity use in gaseous diffusion enrichment plants per (kg) SWU	2,400	kWhe	(See ***Note 2***)
Electricity use in centrifuge-based enrichment plants per (kg) SWU	50	kWhe	(See ***Note 2***)
Tails assay for enrichment plants (fraction as U_{235})	0.24%		(See ***Note 2***)
Fraction U_{235} in natural Uranium	0.71%		(See ***Note 2***)
Tonnes depleted Uranium produced (as U) per unit natural Uranium feed	88.98%	Assuming 4.51% enrichment	
Average cost of uranium conversion (to UF_6) per kg U	$ 14.01		(See ***Note 4***)
Solid waste from uranium conversion (to UF_6)	0.7	t/t U	(See ***Note 5***)
Liquid waste from uranium conversion (to UF_6)	6.5	m^3/t U	(See ***Note 5***)
2012 Average enrichment costs (per kg SWU)	$ 119	(2009 USD)	
2050 Average enrichment costs (per kg SWU)	102	assuming Medium	price trajectory (see "Uranium_Prices" worksheet in this workbook)

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	Australia	China	DPRK	Indonesia	Japan	ROK	RFE	Taiwan	Vietnam	
										All Rough Estimates--
Average distance from mining area to enrichment facility (km)	2500	1000	300	1000	8000	500	2000	500	500	For Japan, see ***Note 10***
Predominant transport mode for domestic Uranium production	Ship	Rail	Rail	Ship	Ship	Ship	Rail	Ship	Ship	Assumptions
Target fraction of Uranium needs enriched in-country	0%	100%	100%	0%	100%	100%	100%	0%	0%	Assumptions
Year in-country enrichment starts	2030	2000	2020	2025	2010	2020	2000	2025	2025	(See ***Note 8***)
Year in-country enrichment reaches target level	2030	2025	2030	2030	2015	2030	2000	2030	2030	(See ***Note 8***)
Average electricity use for in-country enrichment	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	kWhe/SWU
Average level of enrichment before 2008 (% U_{235})	4.34%	4.34%	4.34%	4.34%	4.34%	4.34%	4.34%	4.34%	4.34%	from country workbooks
Average level of enrichment after 2007 (% U_{235})	4.51%	4.51%	4.51%	4.51%	4.51%	4.51%	4.51%	4.51%	4.51%	from country workbooks
Implied Separative Work Units (SWU) for level of enrichment before 2008 (kg SWU/kg U in enriched product)	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	Calculated based on Equation from
Implied Separative Work Units (SWU) for level of enrichment after 2007 (kg SWU/kg U in enriched product)	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	7.05	MIT Study (see ***Note 1***)

NOTES AND SOURCES

1. "The Future of Nuclear Power," An Interdisciplinary MIT Study, Massachusetts Institute of Technology (2003), available as http://web.mit.edu/nuclearpower/pdf/nuclearpower-full.pdf. SWU equation referenced is shown on page 146.
   Note that it is assumed that all enrichment carried out in the countries in this study is assumed to be in centrifuge plants, though some of the enrichment services imported by the countries of the region are in gaseous diffusion plants.

2. Estimate of "tails assay" and U_{235} content of natural uranium from study referenced in Note 1, page 145 was 0..3%.
   An update to the MIT study, "Update of the MIT 2003 Future of Nuclear Power Study", dated 2009, and available as http://web.mit.edu/nuclearpower/pdf/nuclearpower-update2009.pdf, uses an "optimal tails assay" calculated based on current uranium prices of 0.24%, which we use here.
   Typical values for the fraction of U_{235} in enrichment tails from centrifuge enrichment plants range from 0.25% to 0.3%, suggests WISE Uranium Project (2009), "Nuclear Fuel Energy Balance Calculator - HELP", available as http://www.wise-uranium.org/nfceh.html.
   The WISE source also lists the electricity requirements for gaseous diffusion enrichment to be between 2300 and 2500 kWhe/kg SWU, and for centrifuge enrichment as "less than 50 kWhe/kg SWU", though the document ACP & World Enrichment Market Final, USEC, dated September 5, 2013 by Edward Kee and Jennifer Cascone Fauver of NERA Consulting, available as http://www.centrusenergy.com/sites/default/files/NERA_ACP_And_World_Enrichment_Market_0.pdf, suggests a range from 50 to 300 kWhe/kg SWU for centrifuge enrichment in general.

3. A direct estimate of the fuel used in UF6 production from Uranium Oxide was not immediately available, but the World Nuclear Association document "Some Chemistry of Uranium" (2009), available as http://www.world-nuclear.org/education/chem.htm, includes the following passage:

> Refining and Conversion to UF6 prior to Enrichment
>
> (in Europe and North America)
>
> The mixed uranium oxide concentrate U3O8 received by the refinery is dissolved in nitric acid. The resulting solution of uranium nitrate UO2(NO3)2.6H2O is fed into a countercurrent solvent extraction process, using tributyl phosphate dissolved in kerosene or dodecane. The uranium is collected by the organic extractant, from which it can be washed out by dilute nitric acid solution and then concentrated by evaporation. The solution is then calcined (heated strongly) to produce pure UO3.
>
> Most nuclear reactors require uranium to be enriched from its natural isotopic composition of 0.7% U-235 (most of the rest being U-238) to 3.5-4% U-235. The uranium therefore needs to be in a gaseous form and the most convenient way of achieving this is to convert the uranium oxides to uranium hexafluoride.
>
> After purification, the uranium oxide UO3 is reduced in a kiln by hydrogen to UO2.
>
> UO3 + H2 ====> UO2 + H2O .... delta H = -109 kJ/mole
>
> This reduced oxide is then reacted with gaseous hydrogen fluoride in another kiln to form uranium tetrafluoride, UF4, though in some places this is made with aqueous HF by a wet process.
>
> UO2 + 4HF ====> UF4 + 2H2O .... delta H = -176 kJ/mole
>
> The tetrafluoride is then fed into a fluidised bed reactor with gaseous fluorine to produce uranium hexafluoride, UF6. Hexafluoride is condensed and stored.
>
> UF4 + F2 ====> UF6

This implies that the minimum energy for reducing and converting Uranium oxide to Uranium tetrafluoride is 285 kJ per mole of Uranium, or 1.20 MJ per kg Uranium metal. As a starting value, we assume that inefficiencies in the kilns used in these processes, plus the energy cost of converting UF_4 to UF_6, mean that the total energy needed for converting U_3O_8 to UF_6 is approximately 200% of the theoretical minimum, or about 2.39 MJ per kg Uranium metal.

4. The 2009 update to the "MIT Report" described in note 2 uses a conversion cost of $6 per kg U in 2007 dollars. The World Nuclear Association (2012), in "The Economics of Nuclear Power" (updated December, 2012, and available as http://www.world-nuclear.org/info/inf02.html), lists costs for UF6 conversion as of March 2011 as $13 per kg UO_2.

5. The WISE Uranium Project's (2009), "Nuclear Fuel Material Balance Calculator", available as http://www.wise-uranium.org/nfcm.html, lists default estimates for the amount of solid and liquid waste per unit Uranium metal handled in conversion plants as shown.

6. Initital estimate based on US 2006 reported average rail freight revenue, updated to 2009 dollars. Original data from Research and Innovative Technology Administration, U.S. Bureau of Transportation Statistics, U.S. Department of Transportation (US DOT), "Table 3-17: Average Freight Revenue Per Ton-mile", available as http://www.bts.gov/publications/national_transportation_statistics/html/table_03_17.html.

7. Initital estimate based on description of uranium oxide concentrate (UOC, or U_3O_8) shipping practices from Australia from Australian Government Department of Toursim, Industry and Resources brochure "SAFE AND EFFECTIVE TRANSPORT OF URANIUM", dated October, 2007, and available as www.ret.gov.au/.../uranium/.../Safe_and_Effective_Transport_of_Uranium.pdf.
This document suggests that UOC is shipped in standard 20-foot shipping containers in 205-liter drums. Photos in the brochure suggest that about 48 drums fit in a standard container. According to http://www.powderandbulk.com/resources/bulk_density/material_bulk_density_chart_u.htm, the bulk density of uranum oxide is 1.73 kg/liter, which suggests that each drum would hold 354.65 kg of product, and a shipping container would hold 17.02 metric tons of yellowcake.
Other sources give a range of bulk densities for U_3O_8 of 1.5 to 4.0 kg/liter, but several sources cited the same figure used in this calculation.
Shipping rates are difficult to estimate, and according to at least one reference, have varied by a factor of four just between 2005 and 2009. We use an average 2008 leasing rate for Panamax ships of about $ 26,000 per day for ships with capacity of 3500 TEU, with one "TEU" equaling the space for a standard 20-foot container unit.
Based on the document "Propulsion Trends in Container Vessels", by MAN B&W Diesel A/S, Copenhagen, Denmark, undated but probably about 2005, and available as http://www.manbw.com/files/news/filesof4672/P9028.pdf, the average design speed of a panamax ship is in the range of 20 knots, or 37.1 km/hr.
Assuming that the average speed of a ship during a voyage is 80% of design speed, and assuming that the ship operates at an average of 80% of capacity, and a tare (empty) weight for eac drum of 17 kg (e.g. from http://www.colyerfehr.com.au/logisticsAndTransport.html), the cost per tonne-km for shipping of U_3O_8 would be estimated at $ 0.00077 per tonne-km of yellowcake transported.
An alternative, and perhaps more accurate, way of estimating this cost is to base the cost roughly on published freight rates per container (TEU).
The Review of Maritime Transport 2008, published by the United Nations, United Nations Conference in Trade and Development Staff, and available to read through Google Books, includes in Table 34 the following data:

Table 34

Freight rates (market averages) per TEU on the three major liner trade routes
($ per TEU and percentage change)

	Transpacific		Europe–Asia		Transatlantic	
	Asia–USA	USA–Asia	Europe–Asia	Asia–Europe	USA–Europe	Europe–USA
2006						
First quarter	1 836	815	793	1 454	995	1 829
Change (%)	-2	-1	-4	-15	-1	1
Second quarter	1 753	828	804	1 408	1 010	1 829
Change (%)	-5	2	1	-3	2	0
Third quarter	1 715	839	806	1 494	1 041	1 854
Change (%)	-2	1	0	6	3	1
Fourth quarter	1 671	777	792	1 545	1 066	1 762
Change (%)	-3	-7	-2	3	2	-5
2007						
First quarter	1 643	737	755	1 549	1 032	1 692
Change (%)	-2	-5	-5	0	-3	-4
Second quarter	1 675	765	744	1 658	1 067	1 653
Change (%)	2	4	-1	7	3	-2
Third quarter	1 707	780	777	1 952	1 115	1 725
Change (%)	2	2	4	18	4	4
Fourth quarter	1 707	794	905	2 054	1 147	1 766
Change (%)	0	2	16	5	3	2
2008						
First quarter	1 725	861	968	2 021	1 193	1 700
Change (%)	1	8	7	-2	4	-4
Second quarter	1 837	999	1 061	1 899	1 326	1 652
Change (%)	6	16	10	-6	11	-3

Source: UNCTAD secretariat based upon *Containerisation International Online*, www.ci-online.co.uk.

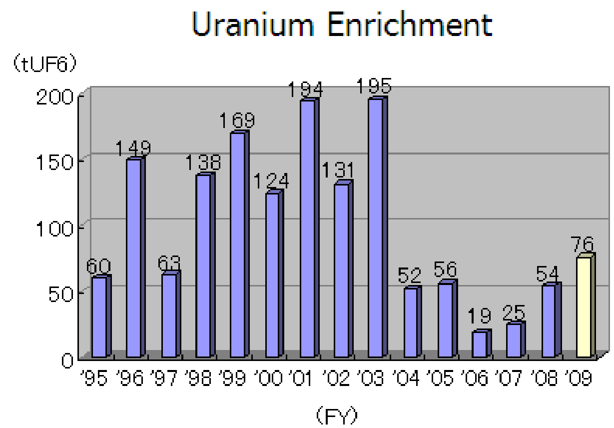
Notes: The freight rates shown are all-in, that is they include currency adjustment factors and bunker adjustment factors, plus terminal handling charges where gate/gate rates have been agreed, and inland haulage where container yard/container yard rates have been agreed. All rates are average rates of all commodities carried by major carriers. Rates to and from the United States refer to the average for all three coasts.

Assuming, as an example, that Uranium bound for Northeast Asia is mined in Canada and enriched in France, a cross-Atlantic transport distance of about 6000 km is implied, which, at a per-container rate of $1,300, would imply a shipment cost per metric tonne of Uranium of $ 0.0127. We use this rough estimate in the calculations above.

8. See text of EASS Report for this scenario. Calculations assume that all DPRK enrichment takes place in the ROK, that Chinese enrichment ramps up from an assumed 10 percent of requirements in 2000 (which should be checked) to 1.5 million SWU/yr in 2009 and 3 million SWU/yr in 2015, that Japan's enrichment averages 300,000 SWU/yr through 2010, and that that the ROK begins enriching fuel in 2015. Assumptions for Japan and China based on http://www.world-nuclear.org/info/inf79.html ("Nuclear Power in Japan", World Nuclear Association, January, 2010) and World Nuclear Association (2015), "Uranium Enrichment", available as http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Uranium-Enrichment/, The latter lists enrichment capacity in China at "Hanzhun & Lanzhou" as 2200, 4220, and 7520 thousand SWU in 2013, 2015 and 2020, respectively.

9. The graph below, from Japan Nuclear Fuel Limited (JNFL) "Operational Progress (As of end of February 28, 2010)", available as http://www.jnfl.co.jp/english/progress.html, indicates the problems with centrifuge technologies encountered by Japan in the past decade. Data from this graph are used to calculate the fractions of enrichment provided in-country from 2000 through 2009, as shown above. Conversion of units (enriched fuel as UF_6 to enriched fuel as U) follow.

Year	te UF_6	te U	Natural U equivalent
2000	124	83.83	729.63
2001	194	131.15	1,141.53
2002	131	88.56	770.82
2003	195	131.82	1,147.41
2004	52	35.15	305.98
2005	56	37.86	329.51
2006	19	12.84	111.80
2007	25	16.90	147.10
2008	54	36.50	317.74
2009	76	51.38	447.20



10 Japan sources its uranium from a number of different countries, most notably Australia, Kazakhstan, and Canada. We assume most of this uranium is carried by ship, and an average shipping distance is 8000 km. For U origin for Japan, see, for example, World Nuclear Organization (2016), "Japan's Nuclear Fuel Cycle", dated January, 2016, and available as http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-fuel-cycle.aspx.

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FUTURE REGIONAL NUCLEAR FUEL CYCLE COOPERATION IN EAST ASIA: ENERGY SECURITY COSTS AND BENEFITS

Calculations for East Asia Science and Security (EASS) and Related Follow-on (2012-2016) Projects, funded by MacArthur Foundation

Estimates of Reactor Fuel Fabrication and Transport Requirements: "National Enrichment, National Reprocessing" Scenario (Regional Scenario 1)

Using Nuclear Fuel Requirements Estimates from "Business-as-Usual" Capacity Expansion Case

Prepared by: David Von Hippel
Last Modified: 1/26/2016

General Assumptions

All costs in approximately **2009 US Dollars** unless otherwise noted

Fraction of mixed-oxide (MOx) fuel used in first reactor cores using MOx	20%	(*See **Note 1***), except	30%	in Japan
Fraction of mixed-oxide (MOx) fuel used in reactors using MOx by target year	20%	(*See **Note 1***), except	30%	in Japan
Year that target fraction of MOx fuel in reactor cores using MOx is reached	2030	(*See **Note 1***).		
Average distance from fuel fabrication facility for imported fuel assemblies made of uranium (and MOx) not enriched in-country (km)	13,000	Rough Estimate (See ***Note 11***)		
Average cost of UOx fabricated fuel transport, rail ($/tonne-km heavy metal)	$ 2.75	(*See **Note 7***).		
Average cost of UOx fabricated fuel transport, ocean freight ($/tonne-km heavy metal)	$ 6.88	(*See **Note 7***).		
Average cost of MOx fabricated fuel transport, rail ($/tonne-km heavy metal)	$ 4.13	(*See **Note 7***).		
Average cost of MOx fabricated fuel transport, ocean freight ($/tonne-km heavy metal)	$ 10.32	(*See **Note 7***).		
Cost of Uranium Oxide (UOx) fuel fabrication	$ 272	per kg heavy metal	(See ***Note 6***)	
Cost of Uranium/Plutonium Blending and MOx fuel fabrication	$ 1,800	per kg heavy metal	(See ***Note 5***)	
Fraction of MOx fuel as Plutonium (% of Heavy Metals)	9.5%	(See ***Note 4***)		
Losses in uranium conversion (from UF_6 to UO_2) and fuel fabrication	1.0%	(total) of incoming enriched UF_6 (as in country workbooks)		
Solid waste from Uranium Oxide (UOx) fuel fabrication	0.5	t/t U	(See ***Note 3***)	
Liquid waste from Uranium Oxide (UOx) fuel fabriction	9	m^3/t U	(See ***Note 3***)	
Solid waste from Mixed Oxide (MOx) fuel fabrication	0.5	t/t heavy metal	(See ***Note 8***)	
Liquid waste from Mixed Oxide (MOx) fuel fabrication	9	m^3/t heavy metal	(See ***Note 8***)	
Fossil fuel use in Uranium Oxide (UOx) fuel fabrication	2709	GJ/t U	(See ***Note 9***)	
Electricity use in Uranium Oxide (UOx) fuel fabrication	300.9	MWhe/t U	(See ***Note 9***)	
Fossil fuel use in Mixed Oxide (MOx) fuel fabrication	2709	GJ/t heavy metal	(See ***Note 10***)	
Electricity use in Mixed Oxide (MOx) fuel fabrication	300.9	MWhe/t heavy metal	(See ***Note 10***)	

	Australia	China	DPRK	Indonesia	Japan	ROK	RFE	Taiwan	Vietnam	
Average distance from domestic fuel fabrication facilities to reactors (km)	1000	1000	300	1000	500	500	2000	500	500	All Placeholders
Predominant transport mode for domestic fuel assemblies	Ship	Rail	Rail	Ship	Ship	Ship	Rail	Ship	Ship	All Placeholders
Ultimate target fraction of reactors that will use mixed-oxide (MOx) Fuel	0%	40%	50%	0%	40%	50%	0%	0%	0%	(See ***Note 2***)
Year use of MOx fuel starts	2025	2025	2025	2025	2010	2025	2025	2025	2025	(See ***Note 2***)
Year use of MOx fuel reaches target level	2050	2050	2050	2050	2030	2050	2050	2050	2050	(See ***Note 2***)

NOTES AND SOURCES

1. Our understanding, based on conversations with US and European experts (F.N. von Hippel and K. Janberg, personal communications, 2009) is that the use of MOx fuel in current light-water reactor cores is limited by the characteristics of MOx fuel to 20% of the reactor core for safety and reactor control reasons.
The information from these experts is contradicted somewhat by a passage in the "MIT Report" (see referece below), page 121, which reads (in part), "In practice, current reactors employing UOX and MOX are fueled with a 2:1 ratio of UOX to MOX fuel".
Other references suggest that France is currently using approximately 30% MOx in some of its reactors, that the US DOE calls for reactors using 40% MOx cores, and that future reactors capable of using 50% (Europe) and 100% (Japan) MOx cores are under design. See, for example,
A. Sowder (2009), "Readiness of Current and New U.S. Reactors for MOX Fuel", presentation at North Carolina and Virginia Health Physics Societies Joint 2009 Spring Meeting, New Bern, North Carolina, 13 March 2009 (Sowder is from the US Electric Power Research Institute, or EPRI), available as http://hpschapters.org/northcarolina/spring2009/FAM.4.pdf.
Although at present we have no reason to believe that the 20% limit described above will increase in the future as an average across reactors in the region, we include in this worksheet algorithms for increasing the limit gradually over time in case technological improvements allow higher fractions of MOx to be used.

2 See text of EASS Report for this scenario for a description of these assumptions. Calculations assume that DPRK use of MOx fuel is tha same as in the ROK, because the ROK is essentially operating the DPRK's reactors.

3. The WISE Uranium Project's (2009), "Nuclear Fuel Material Balance Calculator", available as http://www.wise-uranium.org/nfcm.html, lists default estimates for the amount of solid and liquid waste per unit Uranium metal handled in fuel fabrication plants as shown.

4. 7 % is reported in "MIT Report", The Future of Nuclear Power, An Interdisciplinary MIT Study, 2003, compiled by a team of reearchers mostly from the Massachusetts Institute of Technology (MIT), Cambridge, MA USA. Data from page 121. Report available as http://web.mit.edu/nuclearpower/pdf/nuclearpower-full.pdf. http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Fuel-Recycling/Mixed-Oxide-Fuel-MOX/ reports an average of 9.5% Pu in MOX fuel.

5. Initial value from lecture notes from 2004 MIT course "Nuclear Energy Economics and Policy Analysis", available as http://ocw.mit.edu/NR/rdonlyres/Nuclear-Engineering/22-812JSpring2004/55ABD4F2-4FF8-4386-9055-D8F1C38A2193/0/lec15note.pdf
Original source probably Matthew Bunn et al, "The Economics of Reprocessing vs. the Direct Disposal of Spent Fuel", Project on Managing the Atom, Kennedy School of Government, Harvard University, December 2003, but the latter document hasn't been consulted yet.
The same value has been found in the MIT Report (see reference above), page 147, where the reference seems to be to 2002 costs.
We therefore assume that the cost in 2009 dollars is about $ 1,800
For Japan, the CINC (Citizens' Nuclear Information Center) entitled "Rokkasho Reprocessing Plant and other Nuclear Facilities", available as http://www.cnic.jp/english/topics/cycle/rokkasho/rokkashodata.html, citing a JNFL press release from April, 2009, lists the cost (assumedly in 2009) of the MOX fuel fabrication facility at Rokkasho as 190 billion Yen, with a capacity of 130 tonnes of MOX fuel per year. At an interest rate of 5% annually and an assumed facility lifetime of 30 years, this would imply annualized capital costs (only) of 95,075 Yen per kg processed, or, at the then-prevailing exchange rates of about 95 Yen per dollar, about $ 1,001 for annualized capital costs alone. This appears reasonably consistent with the MIT figure referenced above, since additional operating costs would also be incurred.

6. Initial value, based on World Nuclear Association (2010) "The Economics of Nuclear Power", available as http://www.world-nuclear.org/info/inf02.html.
Quoted cost of $240 per kg UO_2 fuel as of January 2010 was converted to a $ per kg heavy metal (U) basis.
This value is in the range of the "$200 to $400/kg" indicated in the WISE Uranium Project (2009), "Nuclear Fuel Energy Balance Calculator - HELP", available as http://www.wise-uranium.org/nfceh.html, but substantially less than the value of $460/kg U calculated with the WISE Uranium Project (2009) "Nuclear Fuel Cost Calculator", available as http://www.wise-uranium.org/nfcc.html.
The MIT Report (see reference above), gives, on page 146, an estimate for fuel fabrication costs of $275 per kg heavy metal, probably in 2002 dollars, which would imply a cost of $ 330.00 in 2009 dollars.

7. These values are pure guesses at present. It is assumed that due to requirements for specialized ships, shipping containers, and handling procedures, the costs of transporting UOx fuel will be much higher than the costs of transporting yellowcake, which can travel in fairly standard cargo vessels and containers. It is assumed that costs for transporting MOx fuels will be higher still, due to the added security and radiological hazards associated with MOx. Research is needed to better estimate these costs.
As a order of magnitude estimate, assume that a ship carries an average of 10 transport casks, each of which cost $2 million and can hold 16 BWR assemblies of 0.183 tHM each. Assume that each ship has a capital cost of $30 million, and an operating life of. 30 years.
(Might be a ship similar to those used by Nuclear Fuel Transport Limited of Japan, see http://www.nft.co.jp/yusou/english/business/vessels.html.)
Assume an interest rate of 7% per year, and 40 trips per year. Then the annualized capital cost per tonne of spent fuel for a journey of 500 km (as in Japan) would be $4.03 million per year, or $100,733 per trip, or $ 3,440 per tonne of fuel or $ 6.88 per tonne-km of fuel transported. Fuel, personnel, and related costs would also apply, but are assumed to be small relative to capital costs for these specialized transport modes and containers. As noted, this is a very rough estimate at best.
For rail transport (or road) transport, a rough calculation based on the capital cost of a transport cask, with otherwise the same assumptions as above, would yield $ 161,173 dollars per year per cask, or $ 4,029 per trip, or $ 1,376 per tHM, or $ 2.75 per tHM-km.

8. No specific data on waste generation from MOx fuel preparation and fabrication is available at present, so values for UOx fuel preparation (see Note 3) are used as a placeholder. It seems likely that MOx fuel preparation will generate at least as much waste as UOx fuel fabrication, given the additional blending step required.

9. The WISE Uranium Project's (2009), "Nuclear Fuel Energy Balance Calculator", available as http://www.wise-uranium.org/nfce.html lists default estimates for the amount of fossil fuel and electricity needed per unit Uranium metal handled in fuel fabrication plants as shown.

10. No specific data for fuels and electricity use in MOx fuel fabrication were immediately available, so values for UOx fuel fabrication from source above (WISE Uranium Project) are used as placeholders.

11. Rough estimate assuming that imported enriched fuel would come from Eastern North America or Western Europe (about 16,000 km by sea) or from Russia (Urals region or Irkutsk region), which is a shorter distance, and partially overland.

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FUTURE REGIONAL NUCLEAR FUEL CYCLE COOPERATION IN EAST ASIA: ENERGY SECURITY COSTS AND BENEFITS

Calculations for East Asia Science and Security (EASS) and Related Follow-on (2012-2016) Projects, funded by MacArthur Foundation

Estimates of Reprocessing and Spent Fuel Management Requirements: "National Enrichment, National Reprocessing" Scenario (Regional Scenario 1)

Using Nuclear Fuel Requirements Estimates from "Business-as-Usual" Capacity Expansion Case

Prepared by:	David Von Hippel
Last Modified:	1/22/2016

General Assumptions

All costs in approximately **2009 US Dollars** unless otherwise noted

Effective average lag time between when fabricated fuel is placed in service in reactor and when it is removed from at-reactor spent-fuel pool for reprocessing, storage, and/or disposal	8	years	*(See **Note 8**).*
Average loading of spent fuel pools (relative to capacity) before fuel is discharged to storage and/or disposal	90%	Assumption	
Average distance from reactors to international reprocessing facility (km)	13,000	Rough Estimate (See ***Note 20***)	
Average distance from reactors to regional spent fuel storage or disposal facility (km)	3,000	Placeholder only	
Average mass of spent fuel per shipping cask--ocean or rail transport	6.71	t HM	*(See **Note 3**).*
Average number of shipping casks per shipload in ocean transport	20		*(See **Note 3**).*
Average cost of spent fuel transport, rail ($/tonne-km heavy metal)	$ 79.00	*(See **Note 4**).*	
Average cost of spent fuel transport, ocean freight ($/tonne-km heavy metal)	$ 39.50	*(See **Note 4**).*	
Average cost of reprocessing at international facilities	$ 1,200	per kg heavy metal	(See ***Notes 1, 9, and 15***)
Volume of high-level waste (as vitrified) from reprocessing operations	0.115	m^3/t HM processed	(See ***Note 1***)
Cost of treatment and disposal of high-level waste (via vitrification) from reprocessing operations	$ 150,000	$/t HM processed	(See ***Note 1***)
Fossil fuel requirements for treatment/disposal of high level wastes from reprocessing	1.00	GJ/t HM processed	Placeholder only
Electricity requirements for treatment/disposal of high level wastes from reprocessing	3.45	MWhe/t HM processed	(Very rough estimate, see ***Note 19***)
Volume of medium-level waste from reprocessing operations	0.2	m^3/t HM processed	(See ***Note 1***)
Cost of disposal of medium-level waste from reprocessing operations	$ 62,179	$/t HM processed	Rough estimate (See ***Note 22***)
Volume of low-level waste from reprocessing operations	1.4	m^3/t HM processed	(See ***Note 1***)
Cost of disposal of low-level waste from reprocessing operations	$ 26,500	$/t HM processed	Rough estimate (See ***Note 21***)
Volume of solid wastes from reprocessing operations	0.15	m^3/t HM processed	(See ***Note 1***)
Cost of disposal of solid wastes from reprocessing operations	$ 144	$/t HM processed	Rough estimate (See ***Note 23***)
Mass of Plutonium separated from reprocessing operations	11.00	kg/t HM processed	(See ***Note 1***)
Cost of storage/safeguarding/disposal of plutonium from reprocessing operations (fraction not used as MOx)	$ 3,000	$/kg Pu-yr	(See ***Note 5***)

(Depleted) Uranium separated during reprocessing operations	0.94	t/t HM processed	(See ***Note 1***)
Cost of disposal of depleted Uranium from reprocessing operations (fraction not used in MOx)	$ 8,572	$/t U	Rough estimate (See ***Note 24***)
Fossil fuel requirements for reprocessing	26,736.00	GJ/t HM processed	(See ***Note 27***)
Electricity requirements for reprocessing	1,110.00	MWhe/t HM processed	(See ***Note 27***)
Average cost of cask for dry cask storage of spent nuclear fuel (UOx)	$ 800,000	per cask	Rough estimate (See ***Note 17***), except Japan (See ***Note 28***)
Average cost of cask for dry cask storage of spent nuclear fuel (MOx)	$ 800,000	per cask	Placeholder only--Assumed same as UOx for now
Average capacity of cask for dry cask storage, spent UOx Fuel	10.00	t HM processed	Rough estimate--capacity varies by cask design
Average capacity of cask for dry cask storage, spent MOx Fuel	10.00	t HM processed	Placeholder only--Assumed same as UOx for now
Average cost of permanent disposal of spent fuel (UOx or MOx)	$ 1,000,000	$/t HM processed	(See ***Note 6***)
Average operating and maintenance costs for dry cask storage of spent UOx Fuel	$ 10,000	per cask-yr	Order-of-magnitude estimate (See ***Note 18***), except Japan (See ***Note 28***)
Average operating and maintenance costs for dry cask storage of spent MOx Fuel	$ 10,000	per cask-yr	Placeholder only--Assumed same as UOx for now
Average cost of interim storage of spent fuel	$ 360,000	$/t HM processed	(See ***Note 7***)
Annual Cost of Storing Spent Cooled UOx Fuel in Pools	$ 11,708	$/t HM processed	(See ***Note 29***)
Annual Cost of Storing Spent Cooled MOx Fuel in Pools	$ 11,708	$/t HM processed	Placeholder only--Assumed same as UOx for now, though could be higher

	Australia	China	DPRK	Indonesia	Japan	ROK	RFE	Taiwan	Vietnam	
Average distance from reactors to domestic reprocessing facilities (km)	1000	1000	300	1000	500	500	2000	500	500	All Placeholders
Predominant transport mode to domestic reprocessing facilities	Ship	Rail	Rail	Ship	Ship	Ship	Rail	Ship	Ship	All Placeholders
Inventory of LWR spent fuel as of 2000 (metric tons heavy metal--MTHM)	-	225	-	-	4,176	2,058	9	1,434	-	From national workbooks for this nuclear path--year 2000 values
Inventory of CANDU spent fuel as of 2000 (metric tons heavy metal--MTHM)	-	-	-	-	-	2,206	-	-	-	From national workbooks for this nuclear path--year 2000 values
Inventory of plutonium from spent fuel reprocessed internationally or domestically, as of 2000 (MTHM)	0	0	0	0	34.00	0	0	0	0	(See ***Note 10***)
Inventory of high level wastes from spent fuel reprocessed internationally as of 2000 (m^3 as vitrified solid)	0	0	0	0	355.45	0	0	0	0	(See ***Note 13***)
Year reprocessing at international facilities starts	2030	2030	2030	2030	2000	2030	2030	2030	2030	(See ***Note 14***)
Initial fraction of spent fuel reprocessed at international facilities	0%	0%	0%	0%	50%	0%	0%	0%	0%	(See ***Note 16*** for
Ultimate target fraction of annual cooled spent UOx reactor fuel that is reprocessed internationally	0%	0%	0%	0%	0%	0%	0%	0%	0%	(See ***Note 16*** for estimated Japan value)
Year international reprocessing of spent fuel reaches target level	2050	2050	2050	2050	2005	2050	2050	2050	2050	(See ***Note 16*** for estimated Japan value)
Ultimate target fraction of spent UOx reactor fuel that is reprocessed domestically	0%	60%	60%	0%	80%	60%	25%	0%	0%	*(Assumption)*
Year domestic fuel reprocessing starts	2025	2025	2025	2025	2018	2025	2021	2025	2025	*(Assumption)*
Year domestic reprocessing of fuel reaches target level	2050	2030	2030	2050	2020	2030	2022	2050	2050	*(Assumption)*
Average cost of reprocessing at domestic facilities ($/kg U in incoming spent fuel)	$ 1,200	$ 1,200	$ 1,200	$ 1,200	$ 3,400	$ 1,200	$ 1,200	$ 1,200	$ 1,200	(See ***Note 11***)
Average cost of direct disposal at domestic facilities ($/kg HM in incoming spent fuel)	$ 1,000	$ 1,000	$ 1,000	$ 1,000	$ 1,000	$ 1,000	$ 1,000	$ 1,000	$ 1,000	(See ***Note 12***)
Average distance from reactors to domestic spent fuel storage/disposal facilities (km)	1000	1000	300	1000	500	500	2000	500	500	All Placeholders
Predominant transport mode to domestic fuel storage/disposal facilities	Ship	Rail	Rail	Ship	Ship	Ship	Rail	Ship	Ship	All Placeholders
Average cost of interim domestic storage of spent fuel	$ 360,000	$ 360,000	$ 360,000	$ 360,000	$ 360,000	$ 360,000	$ 360,000	$ 360,000	$ 360,000	$/t HM processed--Placeholder assuming same as international costs for now
Average cost of permanent domestic disposal of spent fuel (UOx or MOx)	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000	$1,000,000	$ 1,000,000	$ 1,000,000	$/t HM processed--Placeholder assuming same as international costs for now

(Depleted) Uranium separated during reprocessing operations	0.94	t/t HM processed	(See ***Note 1***)
Cost of disposal of depleted Uranium from reprocessing operations (fraction not used in MOx)	$ 8,572	$/t U	Rough estimate (See ***Note 24***)
Fossil fuel requirements for reprocessing	26,736.00	GJ/t HM processed	(See ***Note 27***)
Electricity requirements for reprocessing	1,110.00	MWhe/t HM processed	(See ***Note 27***)
Average cost of cask for dry cask storage of spent nuclear fuel (UOx)	$ 800,000	per cask	Rough estimate (See ***Note 17***), except Japan (See ***Note 28***)
Average cost of cask for dry cask storage of spent nuclear fuel (MOx)	$ 800,000	per cask	Placeholder only--Assumed same as UOx for now
Average capacity of cask for dry cask storage, spent UOx Fuel	10.00	t HM processed	Rough estimate--capacity varies by cask design
Average capacity of cask for dry cask storage, spent MOx Fuel	10.00	t HM processed	Placeholder only--Assumed same as UOx for now
Average cost of permanent disposal of spent fuel (UOx or MOx)	$ 1,000,000	$/t HM processed	(See ***Note 6***)
Average operating and maintenance costs for dry cask storage of spent UOx Fuel	$ 10,000	per cask-yr	Order-of-magnitude estimate (See ***Note 18***), except Japan (See ***Note 28***)
Average operating and maintenance costs for dry cask storage of spent MOx Fuel	$ 10,000	per cask-yr	Placeholder only--Assumed same as UOx for now
Average cost of interim storage of spent fuel	$ 360,000	$/t HM processed	(See ***Note 7***)
Annual Cost of Storing Spent Cooled UOx Fuel in Pools	$ 11,708	$/t HM processed	(See ***Note 29***)
Annual Cost of Storing Spent Cooled MOx Fuel in Pools	$ 11,708	$/t HM processed	Placeholder only--Assumed same as UOx for now, though could be higher

	Australia	China	DPRK	Indonesia	Japan	ROK	RFE	Taiwan	Vietnam	
Average distance from reactors to domestic reprocessing facilities (km)	1000	1000	300	1000	500	500	2000	500	500	All Placeholders
Predominant transport mode to domestic reprocessing facilities	Ship	Rail	Rail	Ship	Ship	Ship	Rail	Ship	Ship	All Placeholders
Inventory of LWR spent fuel as of 2000 (metric tons heavy metal--MTHM)	-	225	-	-	4,176	2,058	9	1,434	-	From national workbooks for this nuclear path--year 2000 values
Inventory of CANDU spent fuel as of 2000 (metric tons heavy metal--MTHM)	-	-	-	-	-	2,206	-	-	-	From national workbooks for this nuclear path--year 2000 values
Inventory of plutonium from spent fuel reprocessed internationally or domestically, as of 2000 (MTHM)	0	0	0	0	34.00	0	0	0	0	(See ***Note 10***)
Inventory of high level wastes from spent fuel reprocessed internationally as of 2000 (m^3 as vitrified solid)	0	0	0	0	355.45	0	0	0	0	(See ***Note 13***)
Year reprocessing at international facilities starts	2030	2030	2030	2030	2000	2030	2030	2030	2030	(See ***Note 14***)
Initial fraction of spent fuel reprocessed at international facilities	0%	0%	0%	0%	50%	0%	0%	0%	0%	(See ***Note 16*** for
Ultimate target fraction of annual cooled spent UOx reactor fuel that is reprocessed internationally	0%	0%	0%	0%	0%	0%	0%	0%	0%	(See ***Note 16*** for estimated Japan value)
Year international reprocessing of spent fuel reaches target level	2050	2050	2050	2050	2005	2050	2050	2050	2050	(See ***Note 16*** for estimated Japan value)
Ultimate target fraction of spent UOx reactor fuel that is reprocessed domestically	0%	60%	60%	0%	80%	60%	25%	0%	0%	*(Assumption)*
Year domestic fuel reprocessing starts	2025	2025	2025	2025	2018	2025	2021	2025	2025	*(Assumption)*
Year domestic reprocessing of fuel reaches target level	2050	2030	2030	2050	2020	2030	2022	2050	2050	*(Assumption)*

	Australia	China	DPRK	Indonesia	Japan	ROK	RFE	Taiwan	Vietnam	
Average cost of reprocessing at domestic facilities ($/kg U in incoming spent fuel)	$ 1,200	$ 1,200	$ 1,200	$ 1,200	$ 3,400	$ 1,200	$ 1,200	$ 1,200	$ 1,200	(See ***Note 11***)
Average cost of direct disposal at domestic facilities ($/kg HM in incoming spent fuel)	$ 1,000	$ 1,000	$ 1,000	$ 1,000	$ 1,000	$ 1,000	$ 1,000	$ 1,000	$ 1,000	(See ***Note 12***)
Average distance from reactors to domestic spent fuel storage/disposal facilities (km)	1000	1000	300	1000	500	500	2000	500	500	All Placeholders
Predominant transport mode to domestic fuel storage/disposal facilities	Ship	Rail	Rail	Ship	Ship	Ship	Rail	Ship	Ship	All Placeholders
Average cost of interim domestic storage of spent fuel	$ 360,000	$ 360,000	$ 360,000	$ 360,000	$ 360,000	$ 360,000	$ 360,000	$ 360,000	$ 360,000	$/t HM processed--Placeholder assuming same as international costs for now
Average cost of permanent domestic disposal of spent fuel (UOx or MOx)	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000	$1,000,000	$ 1,000,000	$ 1,000,000	$/t HM processed--Placeholder assuming same as international costs for now

Type of Spent Fuel Storage or Disposal Used for Cooled Fuel Not Reprocessed (and Cooled Spent MOx Fuel), by Country				
	Australia	Dry Cask Storage	China	Domestic Interim Storage
	DPRK	Dry Cask Storage	Indonesia	Dry Cask Storage
	Japan	Dry Cask Storage	ROK	Domestic Interim Storage
	RFE	Domestic Interim Storage	Taiwan	Dry Cask Storage
	Vietnam	Dry Cask Storage		

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NOTES AND SOURCES

1. The following data were prepared and compiled by T. Katsuta for the EASS project and are used as the source for several initial estimates in the calculations above. Note that these data have not been thoroughly cross-checked against other, more recent, sources, and need to be updated to reflect more recent currency years or for updated technologies. Source, memo "EASSC: Estimation of the unit cost and the material flow", by Tadahiro KATSUTA, dated 5/1/2009.

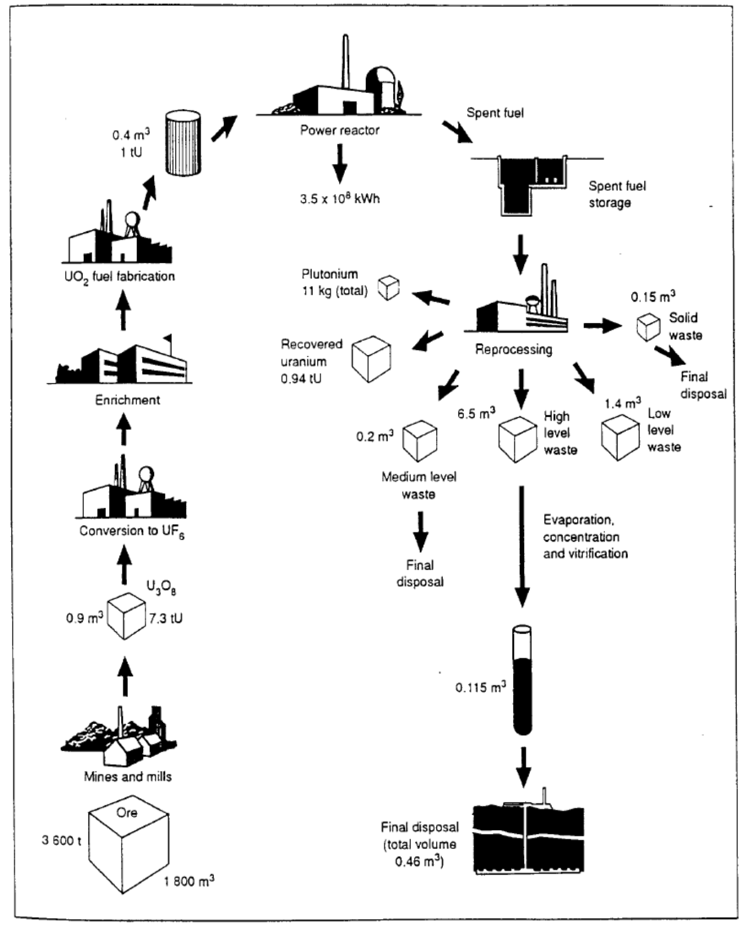
	Case 1	Case 2, 3 or 4[1]
(Frontend)		
Uranium ore purchase	$50/kgU	
Conversion	$8kgU	
Enrichment	$110/SWU	
UOX Fabrication	$275/kgU	
(Backend)		
Reprocessing option		
Transport	$50/kgU	
Reprocessing	$3,400/kgU [2]	$720/kgU
HLW disposal	$90/kgU	
MOX fuel fabrication	$1,100/kgU	
Direct disposal option		
Transport/Storage	$600/kgU[3]	$230/kgU
Disposal	$610/kgU	

Values in this table that are from OECD/NEA (1994) are in "early-1991" US dollars.

[1] Nuclear Energy Agency of the Organization for Economic Cooperation and Development, The Economics of the Nuclear Fuel Cycle, OECD/NEA (1994)
[2] In the case of Rokkasho plant, 32,000tons of spent fuel is reprocessed using 110 US billion $.
[3] In the case of Mutsu intrim storage, 24,000 tons of spent fuel is transported and stored using 60US billion $

Figure at right is source of initial estimates of material flows from reprocessing, as included in the Katsuta memo referenced above. Original source is OECD/NEA 1994 reference noted above.

Figure 3.1 **Material flow of the PWR reprocessing option**
(the figure is an example and the numbers are approximate only)



Recovered uranium and plutonium can be recycled.
Source: COGEMA, HORIZON 2000.

2. These values are pure guesses at present. It is assumed that due to requirements for specialized ships, shipping containers, and handling procedures, the costs of transporting UOx fuel will be much higher than the costs of transporting yellowcake, which can travel in fairly standard cargo vessels and containers. We may ultimately wish to use a transport cost estimate that is not based on distance, or only partially based on distance, if that is appropriate and cost data are available.

3. Assumptions for fuel transport by rail or ocean freight assume the use of shipping casks similar to those produced/used by Japan's Nuclear Fuel Transport Company Ltd..
These casks, which weigh on the order of 100 tons empty, and 115-120 tons full, hold 38 BWR or 14 PWR fuel assemblies
(see http://www.nft.co.jp/english/business/packages_1.html).
Other casks are in use in reactor fuel transport (generic casks shown in documents from the US Nuclear Regulatory Commission for use in rail--and presumably ship--transport as shown in http://www.nrc.gov/waste/spent-fuel-storage/diagram-typical-trans-cask-system-2.pdf, for example, have similar dimensions, but capacity for more fuel assemblies) but the Japanese casks are used as an example here because they are provided and presumably in use by a company in the region.
Japan's Nuclear Fuel Transport Company Ltd., also lists two dedicated ships for handling spent fuel. The vessel with higher capacity (the "ROKUEI MARU"), can handle a maximum of 20 spent fuel packages (casks). We assume that this is a reasonable average for ship capacity in the coming decades.
(Data on ships from http://www.nft.co.jp/english/business/vessels.html).
The website http://www.nucleartourist.com/basics/hlwaste.htm, using data from the USDOE, reports the following information on the contents of PWR and BWR fuel assemblies:

Characteristics	BWR[a]	PWR[b]
Overall assembly length, m	4.47	4.059
Cross section, cm	13.9 x 13.9	21.4 x 21.4
Fuel rod length, m	4.064	3.851
Active fuel height, m	3.759	3.658
Fuel rod outer diameter, cm	1.252	0.95
Fuel rod array	8 x 8	17 x 17
Fuel rods per assembly	63	264
Assembly total weight, kg	319.9	657.9
Uranium/assembly, kg	183.3	461.4
UO_2/assembly, kg	208	523.4
Zircaloy/assembly, kg	103.3[c]	108.4[d]
Hardware/assembly, kg	8.6[e]	26.1[f]
Total metal/assembly, kg	111.9	134.5
Nominal volume/assembly, m^3	0.0864[g]	0.186[g]

[a] Ref. 5. U.S. Environmental Protection Agency, "*Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes*," Code of Federal Regulations, 40 CFR Part 191 (July 1, 1996).

[b] Ref. 6. U.S. Department of Energy, DOE Order 5820.2A, *Radioactive Waste Management,* Washington, D.C., Sept. 26, 1988.

[c] Includes Zircaloy fuel-rod spacers and fuel channel.

[d] Includes Zircaloy control-rod guide thimbles.

[e] Includes stainless steel tie-plates, Inconel springs, and plenum springs.

[f] Includes stainless steel nozzles and Inconel-718 grids.

[g] Based on overall outside dimension. Includes spacing between the stacked fuel rods of an assembly.

These data, together with the data above, suggest a mass of 6.46 t HM per PWR cask, or
6.97 t HM per BWR cask.

At present, PWRs dominate the reactor fleet in the ROK, while BWRs make up about two thirds of the reactor fleets in Japan and Taiwan. We make the rough approximation that 50% of spent fuel is/will be of the PWR type in the period under study, implying an average of 6.71 t HM per cask.

4. As a first approximation of the costs of shipping spent nuclear fuel, we use the estimate of shipping costs of $50 kg U (or heavy metal) from the 1994 OECD/NEA study referenced in note 1, above. In 2009 dollars, this is $ 79.00 kg U (or heavy metal). The 1994 OECD/NEA study indicates (section 4.3.2.1) that this cost is indicative of transport within the (Western) European area, which we assume means an average transport distance of about 1000 km, and also means transport predominantly by rail. This implies a transport cost of abou $ 79.00 per t (HM)-km. If we assume that ocean shipping costs about 50% as much, that cost would be $ 39.50 per t (HM)-km, which, with an average capacity as indicated in note 3, above, and an average ship speed of 20 km/hr, implies a daily transport cost of $ 2,545,380 This seems somewhat high, but is perhaps reasonable given the special nature of the materials shipped. It is also somewhat unclear whether this cost includes elements such as preparation of fuel for transport, loading of casks, and the casks themselves (if they are not reusable)..

5. As an initial estimate, the 1994 OECD/NEA study referenced in note 1, above, includes (section 4.3.2.6) an estimate that costs of storing plutonium are "in the region of $1 to $2 per gram of total plutonium [Pu(t)] per year" in 1991 dollars. We use the higher end of this estimate, and update to 2009 dollars, pending receipt of more up-to-date data.

6. As an initial estimate, the 1994 OECD/NEA study referenced in note 1, above, includes (table 5.5) provides an estimate that costs of a "Direct disposal option, encapsulation & disposal" are $610/kg U in 1991 dollars. We use this figure, converted (roughly) to 2009 dollars, as an initial estimate pending receipt of more up-to-date information. An alternative figure for the cost of spent fuel disposal of $400 per kg HM was used in the study <u>THE ECONOMICS OF REPROCESSING VS. DIRECT DISPOSAL OF SPENT NUCLEAR FUEL</u> Final Report, 8/12/1999-7/30/2003, by Matthew Bunn, Steve Fetter, John P. Holdren, and Bob van der Zwaan, available as http://belfercenter.ksg.harvard.edu/publication/2089/economics_of_reprocessing_vs_direct_disposal_of_spent_nuclear_fuel.html This cost in 2009 dollars would equate to $ 468,000 per t HM processed.

7. As an initial estimate, the 1994 OECD/NEA study referenced in note 1, above, includes (table 5.5) provides an estimate that costs of a "Direct disposal option, spent fuel transport & storage" are $230/kg U in 1991 dollars. We use this figure, converted (roughly) to 2009 dollars, as an initial estimate pending receipt of more up-to-date information.

8. Rough, initial estimate based on a number of sources, including the 1994 OECD/NEA study referenced in note 1 above (table 5.3). In practice, spent fuel needs to be placed in reactor fuels for a minimum of 5 years, but can stay much longer, and the amount of time a fuel element spends in a typical LWR seems to be 1 to 2 years.

9. The "MIT Report", <u>The Future of Nuclear Power, An Interdisciplinary MIT Study</u>, 2003, compiled by a team of researchers mostly from the Massachusetts Institute of Technology (MIT), Cambridge, MA USA, lists an estimated reprocessing cost of $1000 per kg heavy metal, presumably in approximately 2002 dollars (p. 147). Available as http://web.mit.edu/nuclearpower/pdf/nuclearpower-full.pdf. This value, equivalent to $ 1,200 in 2009 dollars, is very simlar to (in comparable dollars) to the value from the OECD/NEA 1994 document referred to in Note 1.

10. Estimated based on Figures 3.3 and 3.4 in "Japan's Civilian Nuclear Fuel Cycle and Nuclear Spent Fuel Management Issue", by Tadahiro Katsuta1 and Tatsujiro Suzuki, dated June 2006 Prepared for the INTERNATIONAL PANEL ON FISSILE MATERIAL. Of the total mass of Pu, approximately 7 tonnes was at Tokai, with the remainder at international reprocessing facilities in the UK and France. Available as http://nautilus.org/wp-content/uploads/2012/01/copy_of_IPFMFact200606b13.pdf.

11. Japan value is assumed for now to be similar to the estimate prepared by Katsuta (see Note 1, above). Reprocessing at other countries is assumed, pending country-specific information, to be at similar cost to international reprocessing.

12. Cost of domestic direct disposal of spent fuels is assumed, pending country-specific information, to be at similar cost to international disposal.

13. Japan value is estimated, at present, based on mass of Plutonium in inventories and average production of plutonium and vitrified high-level wastes from international reprocessing operations (factors assumed in this worksheet).

14. Reprocessing of Japanese spent fuel at international facilities in France and the UK was ongoing as of 2000. Values for other years are placeholders, and do not affect results since no international reprocessing of spent fuels from countries other than Japan is assumed to take place in this scenario.

15. F. N. von Hippel, in "Why reprocessing persists in some countries and not in others:The Costs and Benefits of Reprocessing" (prepared 9 April 2009, and available as http://www.npec-web.org/Essays/vonhippel%20-%20TheCostsandBenefits.pdf, notes that the cost of reprocessing of Japanese spent fuel (and, other spent fuel) in France as "..perhaps $2 million per ton..", which would be significantly higher than the values cited in notes 1 and 9, above.

16. A straightforward statement of the amount of Japanese spent fuel reprocessed internationally (in the UK and France) was not immediately available. The World Nuclear Association (2010), in "Japanese Waste and MOX Shipments From Europe", (available as http://www.world-nuclear.org/info/inf39.html, updated January, 2010), notes that "From 1969-1990, some 2940 tonnes of used fuel in total was shipped (in over 160 shipments) by these utilities to France for reprocessing. Shipments of about 4100 tonnes were to the UK, and by mid 2007 more than 2600 tonnes of oxide fuel had been reprocessed there, plus a small amount of Japanese Magnox used fuel."
This suggests that at least 7000 tonnes of spent fuel had been sent to Europe for reprocessing by 2007, and possibly more.
This represents about 189% of the cooled spent fuel available by 2007, or possibly slightly less, since the World Nuclear Association figures seem to be in terms of Uranium oxides, as opposed to tonnes of heavy metal. Since Japanese shipments to reprocessing centers in Europe were winding down in the 2000s, we use 50 percent reprocessing as a starting value for approximately 2000, pending receipt of better data, and an end date for European reprocessing of Japanese spent fuel of 2012.

17. An older reference, US Department of Energy (1994), <u>Multi-purpose Canister Evaluation: A Systems Engineering Approach</u>. Report DOE/RW-0445, September, 1994, describes a multipurpose canister (interim storage, transport, and final disposal) designed for PWR spent fuel, costing about $350,000 in (presumably) 1994 US dollars. Escalated to 2009 dollars, this would be about $500,000. Pending receipt of more definitive costs, we increase this estimate to $800,000 per cask to reflect increases in materials costs (steel and concrete) as well as other refinements. This is consistent with references to costs of "about $1 million each" for dry casks that we have seen in other summary descriptions of the technology.

18. Rough, order-of-magnitude estimate, pending development of more up-to-date information, based on older data descrbed as "Midrange" estimates for costs of O&M of dry storage facilities at operating and shut-down reactors from TRW Environmental Safety Systems, Inc., <u>At Reactor Dry Storage Issues</u>, Report # E00000000-01717-2200-00002, September, 1993.

19. Though electricity is a key input to the process of vitrifying high-level nuclear wastes (HLW), firm figures on the electricity requirements for HLW vitrification have been difficult to find. Electricity is used in numerous operations in HLW processing, but seems to be used most intensively in the process of "calcining"--reducing liquid HLW to a powder for mixture with glass, and "melting", in which the powdered HLW is melted together with glass "frit" to form molten glass, which is then poured into steel flaskes for indefinite storage. The melting step requires the most electricity. Of the many documents reviewed to date on HLW vitrification, few provide sufficient data to calculate a per-unit electricity consumption for the process. One document with potentially applicable data is the Pacific Northwest National Laboratory (report # PNNL-13582) report High-Level Waste Melter Study Report, by J.M. Perez, et al, dated July 2001, and available as http://www.osti.gov/bridge/servlets/purl/786808-mi2P3c/native/786808.pdf. In a discussion of a German HLW pilot test included in this document (e.g., page 6-16), "installed electrical power" to the test melter is described as being 80 kVA, with average glass output of 7 kg/hr. Assuming (in a full production facility) a mass ratio of 25% HLW oxides within the final glass product (the German test actually used a lower value, 16%, but 25% seems more common in the literature), this implies an average power input of 45.71 kWh per kg heavy metal oxides, or somewhat more than that per kg heavy metal. This calculation is highly approximate, as 1) the "installed electrical power" is highly likely to have been greater then the average draw on the system, but 2) this only counts power to the melter, not to the calciner or to the many other processes that are required for HLW vitrification. Another (imperfect) point of reference for this parameter is a report on a pilot project for a different type of vitrification system: "AVS ADVANCED VITRIFICATION SYSTEM Additional Testing Project DE-AC26-00NT40801", Presentation to Industry Partnerships for Environmental Science and Technology Conference, November 1 [2001] at NETL, Morgantown WV, by James Powell, available as www.netl.doe.gov/publications/proceedings/01/indpartner/em5-1.pdf. The "AVS" system involves heating a sludge-like mixture of glass and concentrated HLW directly in a crucible, which also ultimately serves as the disposal vessel. Slide 8 of the Powell presentation lists electricity input of 10 MWh to produce 2100 kg of glass. In the AVS test, higher ratios of HLW to glass were used than is typical in the literature. If one takes the same 25% HLW oxides used above (rather than the 35% to 62% for the AVS system), the estimated use of electricity per unit input HLW (mostly heavy metal oxides) woul 19.05 kWh per kg heavy metal oxides, or somewhat more than that per kg heavy metal. The average electricity use for vitrification in existing and operating facilities is known to someone, and can doubtless be divined through further research. For the time being We take the above as indicative that electricity input to HLW vitrification is in the range of tens of kWh per tonne HLW oxides, and use the value 40 kWh per kg HLW solids in the incoming HLW feed. Assuming a glass density 3 kg/liter (from Powell presentation), and the vitrified HLW volume of 0.115 m^3/t HM processed, as assumed above, or 0.08625 tonnes HLW solids (presumably mostly oxides) per t HM processed, this implies about 3.45 MWh for HLW vitrification per t HM processed in a reprocessing center. Again, this is at best a crude estimate.

20. Rough estimate assuming that imported reprocessing centers accepting spent fuel would be in Eastern North America or Western Europe (about 16,000 km by sea) or in Russia (Urals region or Siberia region), which is a shorter distance, and partially overland.

21. Recent estimates of the U.S. costs of disposal of low-level radioactive wastes were not immediately available, but cost figures provided in Porter, R.C (2002), The Economics of Waste, Resources for the Future, Table 16-2, shows estimates by other authors ranging from $91 to $218 per cubic foot of waste (1997 dollars). The U.S. DOE (1998) document Report to Congress: Equity of Commercial Low-Level Radioactive Waste Disposal Fees, dated February, 1998, and available as http://www.osti.gov/bridge/servlets/purl/587909-T8VLO4/webviewable/587909.pdf, lists a range of costs for disposing of a hypothetical shipment of LLRW at several existing and (then) proposed US sites of $111 to $613 per cubic foot (Table 2--presumably also in 1997 dollars). Assuming escalation of LLW disposal costs in the decade-plus since these estimates were published, we take a value at the higher end of the range, $400 per cubic foot in 1997 dollars, or $ 18,929 2009 dollars per cubic meter LLW. In an extract from the book Nukenomics: The commercialisation of Britain's nuclear industry, available as "Radwaste management:Buried costs", in Nuclear Engineering International, 27 March, 2008, available as http://www.neimagazine.com/story.asp?storyCode=2049209, I. Jackson states that the "price for disposal of low-level waste at the NDA's Low Level Waste Repository (LLWR) at Drigg in Cumbria is only around £2000/m3". This would be about $ 4,145 2009 dollars per cubic meter LLW. For the moment, we assume that the US estimate is more applicable, as it averages in newer facilities, so we assume a cost of $26,500 per t heavy metal processed.

22. The conclusion to the article by I. Jackson cited in Note 21 reads" The bottom line is that nuclear energy utilities probably need fixed waste disposal 'prices' for repository disposal capped somewhere in the range from £12,200 to £24,400/m3, but the NDA's true marginal 'cost' is nearer to £67,000/m3, and the commercial 'value' of the repository asset could approach £201,000m3 if operated as a fully private sector venture." This passage, which refers to the costs of Intermediate-level waste disposal in the United Kingdom, suggests a range of costs from true marginal costs of disposal to the value to foreign (mostly Asian, in this case) utilities of waste disposal services of 67 to 201 thousand British pounds per cubic meter. As an order-of magnitude estimate, we choose a value at the upper end ot this scale as probably representative of either commercial or Asian disposal costs, at 150,000 2007 British pounds per cubic meter of ILW, $ 62,179 per t heavy metal processed.

23. A U.S. commercial provider of solid waste disposal services lists a cost for disposing of industrial waste of $200 per 55-gallon drum. (See http://www.accpwasteremoval.com/COST.html.) This equates to a cost of $ 962.00 per cubic meter.
Y. Nakamura (2007), WASTE MANAGEMENT AND RECYCLING BUSINESS IN THE UNITED STATES AND JAPAN, USJP (Harvard University) Occasional Paper 07-09, cites a range of disposal costs in "highly regulated landfills" of "from ¥20,000 ($169) to ¥40,000 ($338) per ton". (Source available as www.wcfia.harvard.edu/us-japan/research/pdf/07-09.Nakamura.pdf). If the wastes were refered to in the Nakamura article were, for example, a mixture of paper, cloth, sludges, and other components, a bulk density of 0.2 to 0.4 per liter might not be unreasonable, which would suggest that the Japanese costs are of a similar magnitude, on a per unit volume basis, as the costs from the US. We therefore use the latter as a rough estimate. The U.S. estimate equates to $ 144 per t heavy metal processed.

24. No specific cost estimate for the disposal of deplete Uranium from reprocessing operations was immediately available, but it stands to reason that the cost of disposal of depleted U cannot be less, on a volumetric basis, than the cost of low-level radioactive waste, since it is, after all, such a waste. Assuming a bulk density for depleted Uranium of about 3.0 (as, for example, U3O8, UF4, or UO2F2--see http://www.eoearth.org/article/uranium), then the cost of disposing of depleted U would be about $ 8,572 per tonne U.

25. Various sources, including "Construction and Operation Experience of Rokkasho Reprocessing Plant", presented at the conference "2009 Fuel Cycle Information Exchange (FCIX)", June 25, 2009, by Kazuhiko Hiruta and Toshiyuki Zama of Japan Nuclear Fuel Limited, report that 430 tonnes of spent fuel were used in a trial reprocessing run at Japan's Rokkasho plant between 2006 and 2009. It is somewhat unclear whether the 430 tonnes refers to the total mass of spent fuel, or just to the heavy metals content, but we assume the latter. The source document is available (via Google search) on www.nrc.gov.
We model the use of the 430 tonnes of spent fuel in Rokkasho as occuring in equal portions over the four years of the trial.

26. An estimate of the amount of spent fuel reprocessed each year at the experimental Tokai plant in the year 2000 through its closure in early 2006 was not immediately available, but we estimate the annual amounts as follows: For 2000 and 2001, specific annual data are available from IAEA (2005), Status and trends in spent fuel reprocessing, Report # IAEA-TECDOC-1467, dated September, 2005, and available as www-pub.iaea.org/MTCD/publications/PDF/te_1467_web.pdf (page 68). For other years, the amount of spent fuel reprocessed was estimated by assuming that a similar amount of spent fuel was reprocessed in 2002 through 2005 as was reported reprocessed in 2001. This assumption is more or less consistent with the amount of spent fuel reported as transported or to be transport to Tokai over the period 2000 through 2005, (spent fuel data and projections from M. Mori (2001?), "Spent Fuel Transport Experience in Japan", figure 3, available as www-pub.iaea.org/MTCD/publications/PDF/te_1467_web.pdf)

27. The document NETL Life Cycle Inventory Data Process Documentation File, by the US DOE National Energy Technology Laboratory, for "Spent Fuel Reprocessing", dated August 11, 2011, and available as http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Life%20Cycle%20Analysis/UP_Library/DF_Stage3_O_Spent_Fuel_Reprocessing_2011-01.pdf, includes the following data:

Electricity consumption by reprocessing (PUREX) process:	1.11	MWh per kgHM				
Thermal enenergy use (gas)	5.57	MWh per kgHM or	20.05	GJ per kgHM, which assuming a	75%	boiler efficiency
suggests an estimated	26.74	GJ natural gas per kgHM				
Water requirements for cooling	631,000	liters per kgHM, 99% of which is returned to the source, meaning that				
Water consumption for cooling is	6310	liters per kgHM				

28. At a cost for casks of $800,000 each, annual O&M costs of $ 10,000 per cask/yr, cask capacity of 10.00 tHM, and an assumed storage period of 40 years, and a discount rate of 5% annually, the implied discounted cost of dry cask storage is $ 97,159 per tHM, of which $ 17,159 , or about 17.7% , are O&M costs. This is roughly consistent with the proportion of dry cask storage costs accounted for by O&M costs as included in "Metal Cask Storage as Compared with Pool Storage of Spent Nuclear Fuel in Japan", prepared by Toshiari Saegusa (CRIEPI) for a Nautilus Institute Workshop in September, 2015.
Although the year in which the overall costs presented in the Dr. Saegusa's paper is unclear, assuming that it is 2015, the overall discounted storage cost per tHM presented, about 30 million Y per tHM, assuming an exchange rate of 118 Y per $, is the equivalent of $ 254,237 per THM in 2015 dollars, or $ 228,814 in 2009, a factor of 2.36 higher than the international/basis costs calculated above. It is possible that Dr. Saegusa's study used figures from around 1999, and it is not clear that they have been adjusted for inflation, though inflation in Japan has been limited. Also, dry cask costs may have changed in the interim. Lacking additional information on dry cask costs in Japan, we use the calculated ratio of costs above to increase dry cask costs for Japan.
An alternative estimate for dry cask storage cost in Japan can be derived based on the cost of the Mustu dry storage facility built in 2010-2013, and scheduled to be put in service in 2016.
Based on the World Nuclear Association (2015) document "Japan's Nuclear Fuel Cycle", dated October, 2015, and available as http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/Japan--Nuclear-Fuel-Cycle/, the Mustu spent storage facility cost 100 billion yen, of which 70% was said to be cost for casks, with a total capacity of 3000 THM. This implies a cask cost of 23,333,333 Yen per metric tonne or about 233,333,333 Yen per Cask. At 2013 exchange rates of about 93 Yen per USD, this would be $ 2,508,961 per cask, significantly higher than the international cost above, but close to the cost estimated above based on the presentation by Dr. Saegusa.

29 A recent estimate for the operating costs of spent fuel pools was not immediately available, but an older (1991) US study, S.R. Rod (1991), *Cost Estimates of Operating Onsite Spent Fuel Pools After Final Reactor Shutdown*, Report Number PNL-7778, dated August, 1991, and available as http://www.osti.gov/scitech/servlets/purl/5349359/, lists an average (mean) cost of operating spent fuel pools of $7.41 per kg U-yr, presumably in 1991 dollars or similar, which imp $ 11.71 per kg U-yr in 2009 dollars.
By way of comparison, the operating costs for spent fuel pools implied by data in Dr. Saegusa's study, as referenced in *Note 28* above, was appro 25000 Yen per kg U for a storage volume of 3000 tU (see Figure 11 of Dr. Saegusa's paper), which is the capacity of the Rokkasho spent fuel pools, and similar to the aggregate size of the largest at-reactor pools in Japan for a single complex.
Assuming that the total cost per unit storage was calculated based on a storage t 50 years and using a discount rate of 5% /yr, the value above implies an annual cost of 1,369.42 Yen per kg U/yr, which, assuming the exchange rates above, implies $ 11.61 per kg U in 2015 dollars or $ 10.44 per kg U-yr in 2009 dollars, that is, very close to the PNL estimate provided above when expressed in comparble units. The value for operating costs estimated from Dr. Saegusa's paper includes "administration", "maintenance", "personnel", and "utilities".

30 A recent article by Hui Zhang (2015), "Reprocessing in China: A long, risky journey", *Bulletin of the Atomic Scientists*, dated 10 April 2015, and available as http://thebulletin.org/reprocessing-poised-growth-or-deaths-door/reprocessing-china-long-risky-journey indicates that China produced less than 14 kg of Pu during a hot test of its pilot civilian reprocessing plant at the Jiuquan nuclear complex in Gansu province during 2010, but as of early 2015, reprocessing at the (nominally) 50 tHM/yr facility had not resumed.

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ANNEX 4B: Selected Additional Results

FUTURE REGIONAL NUCLEAR FUEL CYCLE COOPERATION IN EAST ASIA: ENERGY SECURITY COSTS AND BENEFITS

Calculations for East Asia Science and Security (EASS) and Related Follow-on (2012-2016) Projects, funded by MacArthur Foundation

Cost Totals: Summaries for All Regional Scenarios

Prepared by:	David Von Hippel
Last Modified:	3/11/2016

All costs in millions of 2009 US Dollars. Cumulative costs are not discounted.

Results for BAU Nuclear Capacity Expansion Path

	Annual Costs in 2050				Cumulative Costs, 2000-2050			
Cost Category	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Uranium (Yellowcake) Production/Purchase	$ 4,536	$ 4,536	$ 4,332	$ 4,692	$160,865	$160,863	$ 159,516	$165,029
Uranium Transport to Enrichment Plants	$ 2	$ 6	$ 5	$ 6	$ 80	$ 183	$ 175	$ 182
Conversion of U_3O_8 to UF_6 for Enrichment	$ 623	$ 623	$ 637	$ 690	$ 20,659	$ 20,630	$ 21,596	$ 22,374
Uranium Enrichment Services	$ 3,506	$ 3,506	$ 3,584	$ 3,881	$125,885	$125,705	$ 131,662	$136,204
UOx Fuel Transport	$ 61	$ 199	$ 392	$ 432	$ 4,082	$ 6,418	$ 12,912	$ 13,628
MOx Fuel Transport	$ 2	$ 25	$ 48	$ -	$ 29	$ 365	$ 692	$ 1
UOx Fuel Fabrication	$ 1,315	$ 1,315	$ 1,344	$ 1,455	$ 43,703	$ 43,642	$ 45,680	$ 47,320
MOx Fuel Fabrication	$ 720	$ 720	$ 737	$ -	$ 10,639	$ 10,639	$ 10,853	$ 12
Spent UOx Fuel Transport to Reprocessing	$ 134	$ 495	$ 1,284	$ -	$ 3,122	$ 9,222	$ 23,980	$ 623
Reprocessing	$ 3,776	$ 3,005	$ 3,001	$ -	$ 90,788	$ 69,848	$ 70,164	$ 3,495
Treatment/Disposal of HLW from Reprocessing*	$ 351	$ 376	$ 375	$ -	$ 8,015	$ 8,037	$ 8,076	$ 733
Storage of Plutonium from Reprocessing*	$ 79	$ 84	$ 58	$ 159	$ 10,371	$ 9,772	$ 9,660	$ 7,949
Disposal of MLW from Reprocessing	$ 145	$ 156	$ 155	$ -	$ 3,130	$ 3,139	$ 3,156	$ 112
Disposal of LLW from Reprocessing	$ 62	$ 66	$ 66	$ -	$ 1,334	$ 1,338	$ 1,345	$ 48
Disposal of Solid Wastes from Reprocessing	$ 0	$ 0	$ 0	$ -	$ 7	$ 7	$ 7	$ 0
Disposal/Use of Depleted U from Reprocessing	$ 16	$ 17	$ 17	$ -	$ 360	$ 361	$ 362	$ 14
Storage/Disposal of UOx Spent Fuel	$ 372	$ 583	$ 582	$ 625	$ 7,572	$ 19,666	$ 19,552	$ 16,455
Storage/Disposal of MOx Spent Fuel	$ 87	$ 104	$ 106	$ -	$ 784	$ 1,120	$ 1,139	$ 2
Spent Fuel Pool O&M, Cooled UOx Spent Fuel	$ 335	$ 74	$ 74	$ 74	$ 9,561	$ 3,790	$ 3,790	$ 3,790
Spent Fuel Pool O&M, Cooled MOx Spent Fuel	$ 73	$ 73	$ 74	$ 0	$ 559	$ 559	$ 566	$ 5
Spent UOx Fuel Transport to Storage/Disposal	$ 64	$ 195	$ 192	$ 23	$ 912	$ 6,865	$ 6,790	$ 595
Spent MOx Fuel Transport to Storage/Disposal	$ 14	$ 34	$ 35	$ -	$ 113	$ 369	$ 375	$ 0
TOTAL of Above	$ 16,271	$ 16,191	$ 17,100	$ 12,037	$502,570	$502,538	$ 532,049	$418,570

* Note: Includes Pu and HLW stocks accumulated by Japan by 2000, mostly from fuel reprocessed internationally.

Total of U/Enrichment/Transport Costs	$ 10,763	$ 10,928	$ 11,079	$ 11,155	$365,941	$368,446	$ 383,087	$384,749

Net Present Value Cost Results for BAU Nuclear Capacity Expansion Path, 2010-2050

	Real Discount Rate:		0%	/yr	Real Discount Rate:		2.5%	/yr	Real Discount Rate:		5.0%	/yr
Cost Category	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Uranium (Yellowcake) Production/Purchase	$148,722	$148,720	$ 147,373	$ 152,886	$ 84,386	$ 84,384	$ 84,630	$ 87,199	$ 51,983	$ 51,982	$ 52,787	$ 54,045
Uranium Transport to Enrichment Plants	$ 66	$ 169	$ 161	$ 167	$ 40	$ 93	$ 90	$ 93	$ 27	$ 56	$ 55	$ 56
Conversion of U_3O_8 to UF_6 for Enrichment	$ 18,966	$ 18,938	$ 19,904	$ 20,681	$ 10,618	$ 10,598	$ 11,226	$ 11,586	$ 6,453	$ 6,439	$ 6,874	$ 7,049
Uranium Enrichment Services	$114,476	$114,296	$ 120,253	$ 124,795	$ 65,009	$ 64,884	$ 68,796	$ 70,911	$ 40,109	$ 40,021	$ 42,752	$ 43,787
UOx Fuel Transport	$ 2,990	$ 5,911	$ 11,820	$ 12,536	$ 1,970	$ 3,265	$ 6,605	$ 6,950	$ 1,404	$ 1,952	$ 4,005	$ 4,180
MOx Fuel Transport	$ 29	$ 365	$ 692	$ 1	$ 14	$ 169	$ 320	$ 1	$ 7	$ 83	$ 155	$ 1
UOx Fuel Fabrication	$ 40,011	$ 39,950	$ 41,988	$ 43,628	$ 22,399	$ 22,357	$ 23,683	$ 24,442	$ 13,612	$ 13,583	$ 14,501	$ 14,871
MOx Fuel Fabrication	$ 10,639	$ 10,639	$ 10,853	$ 12	$ 4,938	$ 4,938	$ 5,033	$ 11	$ 2,412	$ 2,412	$ 2,456	$ 11
Spent UOx Fuel Transport to Reprocessing	$ 2,499	$ 8,976	$ 23,357	$ 0	$ 1,193	$ 4,215	$ 10,961	$ 0	$ 597	$ 2,069	$ 5,374	$ 0
Reprocessing	$ 87,294	$ 66,355	$ 66,670	$ 2	$ 43,920	$ 33,628	$ 33,815	$ 1	$ 23,375	$ 18,093	$ 18,204	$ 1
Treatment/Disposal of HLW from Reprocessing	$ 7,282	$ 7,303	$ 7,343	$ 0	$ 3,558	$ 3,531	$ 3,555	$ 0	$ 1,831	$ 1,799	$ 1,813	$ 0
Storage of Plutonium from Reprocessing*	$ 8,961	$ 8,361	$ 8,250	$ 6,539	$ 5,338	$ 5,032	$ 4,992	$ 4,062	$ 3,452	$ 3,291	$ 3,277	$ 2,758
Disposal of MLW from Reprocessing	$ 3,018	$ 3,027	$ 3,044	$ 0	$ 1,475	$ 1,464	$ 1,473	$ 0	$ 759	$ 746	$ 751	$ 0
Disposal of LLW from Reprocessing	$ 1,286	$ 1,290	$ 1,297	$ 0	$ 628	$ 624	$ 628	$ 0	$ 323	$ 318	$ 320	$ 0
Disposal of Solid Wastes from Reprocessing	$ 7	$ 7	$ 7	$ 0	$ 3	$ 3	$ 3	$ 0	$ 2	$ 2	$ 2	$ 0
Disposal/Use of Depleted U from Reprocessing	$ 345	$ 346	$ 348	$ (0)	$ 170	$ 168	$ 169	$ (0)	$ 88	$ 86	$ 87	$ (0)
Storage/Disposal of UOx Spent Fuel	$ 7,391	$ 16,825	$ 16,711	$ 14,362	$ 3,822	$ 9,995	$ 9,930	$ 8,031	$ 2,162	$ 6,577	$ 6,540	$ 5,002
Storage/Disposal of MOx Spent Fuel	$ 784	$ 1,120	$ 1,139	$ 2	$ 329	$ 484	$ 492	$ 2	$ 143	$ 217	$ 221	$ 2
Spent Fuel Pool O&M, Cooled UOx Spent Fuel	$ 9,077	$ 3,047	$ 3,047	$ 3,047	$ 5,165	$ 1,892	$ 1,892	$ 1,892	$ 3,222	$ 1,285	$ 1,285	$ 1,285
Spent Fuel Pool O&M, Cooled MOx Spent Fuel	$ 559	$ 559	$ 566	$ 5	$ 232	$ 232	$ 235	$ 3	$ 100	$ 100	$ 101	$ 2
Spent UOx Fuel Transport to Storage/Disposal	$ 902	$ 5,930	$ 5,855	$ 492	$ 417	$ 3,547	$ 3,509	$ 281	$ 206	$ 2,338	$ 2,318	$ 182
Spent MOx Fuel Transport to Storage/Disposal	$ 113	$ 369	$ 375	$ 0	$ 47	$ 159	$ 162	$ 0	$ 20	$ 72	$ 73	$ 0
TOTAL of Above	$465,418	$462,503	$ 491,053	$ 379,154	$255,670	$ 255,663	$ 272,201	$ 215,466	$ 152,287	$153,518	$ 163,949	$ 133,232

* Note: "Storage of Plutonium from Reprocessing" Includes Pu and HLW stocks accumulated by Japan by 2000, mostly from fuel reprocessed internationally.

Total of U/Enrichment/Transport Costs	$335,898	$338,988	$ 353,044	$ 354,706	$189,374	$ 190,689	$ 200,383	$ 201,194	$ 116,007	$116,527	$ 123,584	$ 124,000
Fraction of total cost of highest-cost scenario	94.8%	94.2%	100.0%	77.2%	93.9%	93.9%	100.0%	79.2%	92.9%	93.6%	100.0%	81.3%
Fraction of total cost of lowest-cost scenario	122.8%	122.0%	129.5%	100.0%	118.7%	118.7%	126.3%	100.0%	114.3%	115.2%	123.1%	100.0%

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Results for MAX Nuclear Capacity Expansion Path

	Annual Costs in 2050				Cumulative Costs, 2000-2050			
Cost Category	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Uranium (Yellowcake) Production/Purchase	$ 8,397	$ 8,397	$ 8,069	$ 8,731	$233,342	$233,338	$ 232,809	$242,285
Uranium Transport to Enrichment Plants	$ 3	$ 10	$ 10	$ 11	$ 106	$ 270	$ 270	$ 281
Conversion of U_3O_8 to UF_6 for Enrichment	$ 1,154	$ 1,154	$ 1,193	$ 1,291	$ 30,199	$ 30,156	$ 32,020	$ 33,367
Uranium Enrichment Services	$ 10,873	$ 10,873	$ 11,241	$ 12,164	$246,982	$246,669	$ 261,495	$273,175
UOx Fuel Transport	$ 124	$ 369	$ 775	$ 848	$ 4,912	$ 9,457	$ 20,029	$ 21,239
MOx Fuel Transport	$ 3	$ 45	$ 94	$ -	$ 48	$ 628	$ 1,250	$ 1
UOx Fuel Fabrication	$ 2,434	$ 2,434	$ 2,516	$ 2,723	$ 63,828	$ 63,738	$ 67,669	$ 70,512
MOx Fuel Fabrication	$ 1,322	$ 1,322	$ 1,365	$ -	$ 18,294	$ 18,293	$ 18,807	$ 12
Spent UOx Fuel Transport to Reprocessing	$ 286	$ 927	$ 2,405	$ -	$ 5,404	$ 15,532	$ 40,263	$ 623
Reprocessing	$ 6,892	$ 5,630	$ 5,620	$ -	$151,987	$119,199	$ 119,476	$ 3,495
Treatment/Disposal of HLW from Reprocessing*	$ 674	$ 704	$ 702	$ -	$ 13,339	$ 13,282	$ 13,317	$ 733
Storage of Plutonium from Reprocessing*	$ 38	$ 26	$ (48)	$ 159	$ 11,679	$ 10,832	$ 10,356	$ 7,949
Disposal of MLW from Reprocessing	$ 280	$ 292	$ 291	$ -	$ 5,337	$ 5,314	$ 5,328	$ 112
Disposal of LLW from Reprocessing	$ 119	$ 124	$ 124	$ -	$ 2,275	$ 2,265	$ 2,271	$ 48
Disposal of Solid Wastes from Reprocessing	$ 1	$ 1	$ 1	$ -	$ 12	$ 12	$ 12	$ 0
Disposal/Use of Depleted U from Reprocessing	$ 31	$ 32	$ 32	$ -	$ 613	$ 610	$ 609	$ 14
Storage/Disposal of UOx Spent Fuel	$ 334	$ 646	$ 644	$ 932	$ 2,978	$ 18,388	$ 18,263	$ 21,068
Storage/Disposal of MOx Spent Fuel	$ 122	$ 172	$ 177	$ -	$ 1,057	$ 1,853	$ 1,894	$ 2
Spent Fuel Pool O&M, Cooled UOx Spent Fuel	$ 396	$ 74	$ 74	$ 74	$ 9,412	$ 3,790	$ 3,790	$ 3,790
Spent Fuel Pool O&M, Cooled MOx Spent Fuel	$ 121	$ 121	$ 123	$ 0	$ 951	$ 951	$ 966	$ 5
Spent UOx Fuel Transport to Storage/Disposal	$ 56	$ 218	$ 212	$ 37	$ 285	$ 6,805	$ 6,690	$ 836
Spent MOx Fuel Transport to Storage/Disposal	$ 23	$ 57	$ 58	$ -	$ 174	$ 610	$ 624	$ 0
TOTAL of Above	$ 33,681	$ 33,625	$ 35,679	$ 26,970	$803,214	$801,991	$ 858,207	$679,547

* Note: Includes Pu and HLW stocks accumulated by Japan by 2000, mostly from fuel reprocessed internationally.

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Results for MIN Nuclear Capacity Expansion Path

Cost Category	Annual Costs in 2050				Cumulative Costs, 2000-2050			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Uranium (Yellowcake) Production/Purchase	$ 2,692	$ 2,692	$ 2,570	$ 2,795	$113,716	$113,716	$ 112,627	$115,948
Uranium Transport to Enrichment Plants	$ 1	$ 3	$ 3	$ 3	$ 52	$ 128	$ 116	$ 119
Conversion of U_3O_8 to UF_6 for Enrichment	$ 370	$ 370	$ 371	$ 403	$ 14,571	$ 14,570	$ 14,972	$ 15,434
Uranium Enrichment Services	$ 1,469	$ 1,469	$ 1,473	$ 1,602	$ 77,127	$ 77,122	$ 79,488	$ 81,570
UOx Fuel Transport	$ 17	$ 118	$ 214	$ 233	$ 2,848	$ 4,481	$ 8,496	$ 8,822
MOx Fuel Transport	$ 1	$ 16	$ 28	$ -	$ 17	$ 221	$ 395	$ 1
UOx Fuel Fabrication	$ 780	$ 780	$ 782	$ 851	$ 30,860	$ 30,858	$ 31,707	$ 32,680
MOx Fuel Fabrication	$ 454	$ 454	$ 454	$ -	$ 6,448	$ 6,448	$ 6,448	$ 12
Spent UOx Fuel Transport to Reprocessing	$ 93	$ 257	$ 762	$ -	$ 2,383	$ 5,182	$ 15,257	$ 623
Reprocessing	$ 1,727	$ 1,565	$ 1,781	$ -	$ 37,322	$ 33,480	$ 37,693	$ 3,495
Treatment/Disposal of HLW from Reprocessing*	$ 216	$ 196	$ 223	$ -	$ 4,962	$ 4,481	$ 5,008	$ 733
Storage of Plutonium from Reprocessing*	$ 71	$ (35)	$ 81	$ 159	$ 8,146	$ 6,643	$ 7,986	$ 7,949
Disposal of MLW from Reprocessing	$ 89	$ 81	$ 92	$ -	$ 1,865	$ 1,665	$ 1,884	$ 112
Disposal of LLW from Reprocessing	$ 38	$ 35	$ 39	$ -	$ 795	$ 710	$ 803	$ 48
Disposal of Solid Wastes from Reprocessing	$ 0	$ 0	$ 0	$ -	$ 4	$ 4	$ 4	$ 0
Disposal/Use of Depleted U from Reprocessing	$ 10	$ 9	$ 10	$ -	$ 214	$ 188	$ 216	$ 14
Storage/Disposal of UOx Spent Fuel	$ 264	$ 498	$ 433	$ 353	$ 7,266	$ 20,584	$ 19,320	$ 12,988
Storage/Disposal of MOx Spent Fuel	$ 58	$ 59	$ 59	$ -	$ 547	$ 676	$ 676	$ 2
Spent Fuel Pool O&M, Cooled UOx Spent Fuel	$ 270	$ 74	$ 74	$ 74	$ 9,044	$ 3,790	$ 3,790	$ 3,790
Spent Fuel Pool O&M, Cooled MOx Spent Fuel	$ 44	$ 44	$ 44	$ 0	$ 346	$ 346	$ 346	$ 5
Spent UOx Fuel Transport to Storage/Disposal	$ 40	$ 164	$ 143	$ 6	$ 757	$ 6,787	$ 6,360	$ 401
Spent MOx Fuel Transport to Storage/Disposal	$ 10	$ 20	$ 20	$ -	$ 86	$ 223	$ 223	$ 0
TOTAL of Above	$ 8,715	$ 8,870	$ 9,657	$ 6,480	$319,375	$332,303	$ 353,814	$284,745

* Note: Includes Pu and HLW stocks accumulated by Japan by 2000, mostly from fuel reprocessed internationally.

Aggregated Results for BAU Nuclear Capacity Expansion Path

	Annual Costs in 2050				Cumulative Costs, 2000-2050			
Cost Category	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Uranium Production/Purchase	$ 4,536	$ 4,536	$ 4,332	$ 4,692	$160,865	$160,863	$ 159,516	$165,029
Uranium/Fuel/SF Transport	$ 276	$ 953	$ 1,956	$ 460	$ 8,338	$ 23,422	$ 44,925	$ 15,028
Uranium Conversion/Enrichment	$ 4,129	$ 4,129	$ 4,221	$ 4,571	$146,543	$146,335	$ 153,258	$158,578
Fuel Fabrication	$ 2,034	$ 2,034	$ 2,081	$ 1,455	$ 54,342	$ 54,281	$ 56,533	$ 47,332
Reprocessing	$ 3,776	$ 3,005	$ 3,001	$ -	$ 90,788	$ 69,848	$ 70,164	$ 3,495
Waste Treatment/Pu Storage*	$ 653	$ 699	$ 673	$ 159	$ 23,218	$ 22,653	$ 22,606	$ 8,857
Spent Fuel Storage/Disposal	$ 867	$ 834	$ 837	$ 700	$ 18,476	$ 25,134	$ 25,047	$ 20,252
TOTAL of Above	$ 16,271	$ 16,191	$ 17,100	$ 12,037	$502,570	$502,538	$ 532,049	$418,570
* Note: Includes Pu and HLW stocks accumulated by Japan by 2000, mostly from fuel reprocessed internationally.								
Total Uranium/fuel supply costs	$ 10,975	$ 11,652	$ 12,590	$ 11,178	$370,088	$384,902	$ 414,232	$385,966

Aggregated Results for MAX Nuclear Capacity Expansion Path

	Annual Costs in 2050				Cumulative Costs, 2000-2050			
Cost Category	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Uranium Production/Purchase	$ 8,397	$ 8,397	$ 8,069	$ 8,731	$233,342	$233,338	$ 232,809	$242,285
Uranium/Fuel/SF Transport	$ 496	$ 1,626	$ 3,554	$ 896	$ 10,929	$ 33,302	$ 69,125	$ 22,979
Uranium Conversion/Enrichment	$ 12,026	$ 12,026	$ 12,434	$ 13,455	$277,181	$276,825	$ 293,515	$306,542
Fuel Fabrication	$ 3,755	$ 3,755	$ 3,881	$ 2,723	$ 82,122	$ 82,031	$ 86,476	$ 70,524
Reprocessing	$ 6,892	$ 5,630	$ 5,620	$ -	$151,987	$119,199	$ 119,476	$ 3,495
Waste Treatment/Pu Storage*	$ 1,142	$ 1,178	$ 1,102	$ 159	$ 33,255	$ 32,314	$ 31,893	$ 8,857
Spent Fuel Storage/Disposal	$ 973	$ 1,013	$ 1,018	$ 1,007	$ 14,398	$ 24,982	$ 24,914	$ 24,865
TOTAL of Above	$ 33,681	$ 33,625	$ 35,679	$ 26,970	$803,214	$801,991	$ 858,207	$679,547

* Note: Includes Pu and HLW stocks accumulated by Japan by 2000, mostly from fuel reprocessed internationally.

Aggregated Results for MIN Nuclear Capacity Expansion Path

	Annual Costs in 2050				Cumulative Costs, 2000-2050			
Cost Category	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Uranium Production/Purchase	$ 2,692	$ 2,692	$ 2,570	$ 2,795	$113,716	$113,716	$ 112,627	$115,948
Uranium/Fuel/SF Transport	$ 162	$ 579	$ 1,169	$ 242	$ 6,144	$ 17,022	$ 30,845	$ 9,965
Uranium Conversion/Enrichment	$ 1,839	$ 1,839	$ 1,844	$ 2,006	$ 91,698	$ 91,692	$ 94,461	$ 97,004
Fuel Fabrication	$ 1,234	$ 1,234	$ 1,236	$ 851	$ 37,307	$ 37,305	$ 38,154	$ 32,692
Reprocessing	$ 1,727	$ 1,565	$ 1,781	$ -	$ 37,322	$ 33,480	$ 37,693	$ 3,495
Waste Treatment/Pu Storage*	$ 424	$ 285	$ 445	$ 159	$ 15,985	$ 13,692	$ 15,901	$ 8,857
Spent Fuel Storage/Disposal	$ 637	$ 676	$ 611	$ 427	$ 17,204	$ 25,397	$ 24,133	$ 16,785
TOTAL of Above	$ 8,715	$ 8,870	$ 9,657	$ 6,480	$319,375	$332,303	$ 353,814	$284,745

* Note: Includes Pu and HLW stocks accumulated by Japan by 2000, mostly from fuel reprocessed internationally.

Comparison of Further Aggregated Annual Costs in 2050 by Scenario and Path

Cost Category	Scenario 1--BAU	Scenario 1--MAX	Scenario 1--MIN	Scenario 2--BAU	Scenario 2--MAX	Scenario 2--MIN	Scenario 3--BAU	Scenario 3--MAX	Scenario 3--MIN	Scenario 4--BAU	Scenario 4--MAX	Scenario 4--MIN
Front-end Costs	$ 10,763	$ 24,309	$ 5,784	$ 10,928	$ 24,603	$ 5,903	$ 11,079	$ 25,264	$ 5,895	$ 11,155	$ 25,767	$ 5,888
Back-end Costs	$ 5,508	$ 9,373	$ 2,931	$ 5,262	$ 9,022	$ 2,967	$ 6,021	$ 10,415	$ 3,762	$ 882	$ 1,203	$ 592
TOTAL	$ 16,271	$ 33,681	$ 8,715	$ 16,191	$ 33,625	$ 8,870	$ 17,100	$ 35,679	$ 9,657	$ 12,037	$ 26,970	$ 6,480

Comparison of Further Aggregated Cumulative 2000 - 2050 Costs by Scenario and Path

Cost Category	Scenario 1--BAU	Scenario 1--MAX	Scenario 1--MIN	Scenario 2--BAU	Scenario 2--MAX	Scenario 2--MIN	Scenario 3--BAU	Scenario 3--MAX	Scenario 3--MIN	Scenario 4--BAU	Scenario 4--MAX	Scenario 4--MIN
Front-end Costs	$ 365,941	$ 597,711	$ 245,638	$ 368,446	$ 602,549	$ 247,543	$ 383,087	$ 634,349	$ 254,248	$ 384,749	$ 640,872	$ 254,585
Back-end Costs	$ 136,629	$ 205,503	$ 73,737	$ 134,092	$ 199,442	$ 84,760	$ 148,962	$ 223,858	$ 99,566	$ 33,821	$ 38,675	$ 30,160
TOTAL	$502,570	$803,214	$ 319,375	$ 502,538	$801,991	$332,303	$ 532,049	$858,207	$ 353,814	$418,570	$ 679,547	$ 284,745

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FUTURE REGIONAL NUCLEAR FUEL CYCLE COOPERATION IN EAST ASIA: ENERGY SECURITY COSTS AND BENEFITS

Calculations for East Asia Science and Security (EASS) and Related Follow-on (2012-2016) Projects, funded by MacArthur Foundation

Estimates of Uranium Mining and Milling Volumes: Summaries for All Regional Scenarios

Prepared by:	David Von Hippel
Last Modified:	3/11/2016

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Metric Tons Natural Uranium (as U) Mined In-country for Use in Domestic Reactors	2010	1,320	1,136	1,136	1,136
	2030	11,668	1,106	1,105	1,140
	2050	17,229	1,053	1,053	1,140
	Cumulative, 2000-2050	457,150	52,637	52,653	54,041
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Metric Tons Natural Uranium (as U) Mined In-country for Use in Domestic Reactors	2010	1,320	1,136	1,136	1,136
	2030	19,772	1,670	1,670	1,728
	2050	36,427	3,915	3,916	4,237
	Cumulative, 2000-2050	793,068	91,705	91,779	95,475
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Metric Tons Natural Uranium (as U) Mined In-country for Use in Domestic Reactors	2010	1,320	1,136	1,136	1,136
	2030	8,396	1,111	1,110	1,140
	2050	10,642	1,048	1,048	1,140
	Cumulative, 2000-2050	318,598	52,663	52,672	54,041

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Annual Total Metric Tons Natural Uranium (as U) Imported for Use in Domestic Reactors	2010	12,788	12,971	12,971	12,971
	2030	24,529	35,091	34,223	35,296
	2050	27,247	43,423	43,611	47,227
	Cumulative, 2000-2050	1,037,451	1,441,949	1,490,019	1,543,444

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		MAX Capacity Expansion Paths			
Annual Total Metric Tons Natural Uranium (as U) Imported for Use in Domestic Reactors	2010	12,788	12,971	12,971	12,971
	2030	33,433	51,536	51,368	53,133
	2050	45,910	78,422	79,168	85,665
	Cumulative, 2000-2050	1,381,370	2,082,702	2,171,480	2,261,984

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		MIN Capacity Expansion Paths			
Annual Total Metric Tons Natural Uranium (as U) Imported for Use in Domestic Reactors	2010	12,788	12,971	12,971	12,971
	2030	16,011	23,296	22,580	23,187
	2050	15,760	25,354	25,423	27,654
	Cumulative, 2000-2050	736,199	1,002,133	1,030,861	1,062,471

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Annual Total Metric Tons Natural Uranium (as U) Imported plus Domestic Production	2010	14,107	14,107	14,107	14,107
	2030	36,197	36,197	35,328	36,436
	2050	44,476	44,476	44,664	48,367
	Cumulative, 2000-2050	1,494,601	1,494,586	1,542,672	1,597,485

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		MAX Capacity Expansion Paths			
Annual Total Metric Tons Natural Uranium (as U) Imported plus Domestic Production	2010	14,107	14,107	14,107	14,107
	2030	53,206	53,206	53,038	54,861
	2050	82,337	82,337	83,083	89,901
	Cumulative, 2000-2050	2,174,439	2,174,406	2,263,259	2,357,459

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		MIN Capacity Expansion Paths			
Annual Total Metric Tons Natural Uranium (as U) Imported plus Domestic Production	2010	14,107	14,107	14,107	14,107
	2030	24,407	24,407	23,690	24,327
	2050	26,402	26,402	26,471	28,794
	Cumulative, 2000-2050	1,054,796	1,054,796	1,083,533	1,116,512

Parameter	YEAR	BAU Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Thousand te Uranium Ore to Supply Uranium Mined In-country for Use in Domestic Reactors	2010	763	657	657	657
	2030	6,973	640	639	659
	2050	10,371	609	609	659
	Cumulative, 2000-2050	272,354	30,445	30,454	31,257

Parameter	YEAR	MAX Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Thousand te Uranium Ore to Supply Uranium Mined In-country for Use in Domestic Reactors	2010	763	657	657	657
	2030	11,994	1,063	1,063	1,100
	2050	22,322	2,752	2,752	2,978
	Cumulative, 2000-2050	478,057	59,712	59,762	62,282

Parameter	YEAR	MIN Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Thousand te Uranium Ore to Supply Uranium Mined In-country for Use in Domestic Reactors	2010	763	657	657	657
	2030	4,943	643	642	659
	2050	6,237	606	606	659
	Cumulative, 2000-2050	186,302	30,460	30,465	31,257

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Thousand Metric Tons Uranium Ore (from In-country and outside mines) to Supply All Domestic Uranium Needs	2010	1,081	980	980	980
	2030	7,584	1,513	1,491	1,537
	2050	11,049	1,689	1,694	1,834
	Cumulative, 2000-2050	298,158	66,310	67,515	69,647
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Thousand Metric Tons Uranium Ore (from In-country and outside mines) to Supply All Domestic Uranium Needs	2010	1,081	980	980	980
	2030	12,825	2,344	2,341	2,421
	2050	23,464	4,703	4,721	5,109
	Cumulative, 2000-2050	512,416	111,515	113,773	118,544
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Thousand Metric Tons Uranium Ore (from In-country and outside mines) to Supply All Domestic Uranium Needs	2010	1,081	980	980	980
	2030	5,341	1,222	1,204	1,236
	2050	6,629	1,237	1,239	1,347
	Cumulative, 2000-2050	204,613	55,386	56,105	57,684

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used (Mining and Milling) for Uranium Produced In-country for Use in Domestic Reactors (GWh)	2010	63	54	54	54
	2030	566	53	53	54
	2050	837	50	50	54
	Cumulative, 2000-2050	22,098	2,515	2,515	2,582
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used (Mining and Milling) for Uranium Produced In-country for Use in Domestic Reactors (GWh)	2010	63	54	54	54
	2030	936	56	56	57
	2050	1,642	65	65	70
	Cumulative, 2000-2050	36,539	2,712	2,714	2,795
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used (Mining and Milling) for Uranium Produced In-country for Use in Domestic Reactors (GWh)	2010	63	54	54	54
	2030	406	53	53	54
	2050	513	50	50	54
	Cumulative, 2000-2050	15,322	2,516	2,516	2,582

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used (Mining and Milling) for Uranium Imported In-country for Use in Domestic Reactors (GWh)	2010	115	117	117	117
	2030	222	317	309	319
	2050	246	392	394	427
	Cumulative, 2000-2050	9,370	13,023	13,457	13,939
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used (Mining and Milling) for Uranium Imported In-country for Use in Domestic Reactors (GWh)	2010	115	117	117	117
	2030	302	465	464	480
	2050	415	708	715	774
	Cumulative, 2000-2050	12,476	18,810	19,611	20,429
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used (Mining and Milling) for Uranium Imported In-country for Use in Domestic Reactors (GWh)	2010	115	117	117	117
	2030	145	210	204	209
	2050	142	229	230	250
	Cumulative, 2000-2050	6,649	9,051	9,310	9,596

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used (Mining and Milling) for Domestic and Imported Production (GWh)	2010	179	171	171	171
	2030	788	370	362	373
	2050	1,083	442	444	481
	Cumulative, 2000-2050	31,467	15,537	15,972	16,521

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used (Mining and Milling) for Domestic and Imported Production (GWh)	2010	179	171	171	171
	2030	1,238	521	519	537
	2050	2,057	773	780	844
	Cumulative, 2000-2050	49,014	21,522	22,325	23,224

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used (Mining and Milling) for Domestic and Imported Production (GWh)	2010	179	171	171	171
	2030	550	263	257	264
	2050	655	279	280	304
	Cumulative, 2000-2050	21,971	11,566	11,826	12,177

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Fossil Fuel (likely mostly diesel) Used (Mining and Milling) for Uranium Produced In-country for Use in Domestic Reactors (TJ)	2010	70	60	60	60
	2030	628	58	58	60
	2050	932	56	56	60
	Cumulative, 2000-2050	24,573	2,777	2,777	2,851
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Fossil Fuel (likely mostly diesel) Used (Mining and Milling) for Uranium Produced In-country for Use in Domestic Reactors (TJ)	2010	70	60	60	60
	2030	1,224	242	242	251
	2050	2,742	983	983	1,064
	Cumulative, 2000-2050	53,191	15,463	15,477	16,281
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Fossil Fuel (likely mostly diesel) Used (Mining and Milling) for Uranium Produced In-country for Use in Domestic Reactors (TJ)	2010	70	60	60	60
	2030	448	59	59	60
	2050	566	55	55	60
	Cumulative, 2000-2050	16,923	2,778	2,778	2,851

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Total Fossil Fuel (likely mostly diesel) Used (Mining and Milling) for Uranium Imported In-country for Use in Domestic Reactors (TJ)	2010	316	320	320	320
	2030	605	866	844	871
	2050	672	1,071	1,076	1,165
	Cumulative, 2000-2050	25,597	35,577	36,763	38,082
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Total Fossil Fuel (likely mostly diesel) Used (Mining and Milling) for Uranium Imported In-country for Use in Domestic Reactors (TJ)	2010	316	320	320	320
	2030	825	1,272	1,267	1,311
	2050	1,133	1,935	1,953	2,114
	Cumulative, 2000-2050	34,083	51,387	53,577	55,810
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Total Fossil Fuel (likely mostly diesel) Used (Mining and Milling) for Uranium Imported In-country for Use in Domestic Reactors (TJ)	2010	316	320	320	320
	2030	395	575	557	572
	2050	389	626	627	682
	Cumulative, 2000-2050	18,164	24,726	25,435	26,215

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Total Fossil Fuel (likely mostly diesel) Used (Mining and Milling) for Domestic and Imported Uranium Production (TJ)	2010	385	380	380	380
	2030	1,234	924	903	931
	2050	1,605	1,127	1,132	1,225
	Cumulative, 2000-2050	50,170	38,354	39,541	40,932
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Total Fossil Fuel (likely mostly diesel) Used (Mining and Milling) for Domestic and Imported Uranium Production (TJ)	2010	385	380	380	380
	2030	2,049	1,514	1,510	1,562
	2050	3,875	2,918	2,937	3,178
	Cumulative, 2000-2050	87,274	66,849	69,054	72,091
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Total Fossil Fuel (likely mostly diesel) Used (Mining and Milling) for Domestic and Imported Uranium Production (TJ)	2010	385	380	380	380
	2030	843	633	616	632
	2050	955	681	683	742
	Cumulative, 2000-2050	35,087	27,504	28,213	29,065

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Water Use for Milling (including in-situ leaching) of Uranium Produced In-country for Use in Domestic Reactors (million cubic meters)	2010	1	1	1	1
	2030	12	1	1	1
	2050	17	1	1	1
	Cumulative, 2000-2050	457	53	53	54

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Water Use for Milling (including in-situ leaching) of Uranium Produced In-country for Use in Domestic Reactors (million cubic meters)	2010	1	1	1	1
	2030	20	2	2	2
	2050	36	4	4	4
	Cumulative, 2000-2050	793	92	92	95

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Water Use for Milling (including in-situ leaching) of Uranium Produced In-country for Use in Domestic Reactors (million cubic meters)	2010	1.3	1.1	1.1	1.1
	2030	8.4	1.1	1.1	1.1
	2050	10.6	1.0	1.0	1.1
	Cumulative, 2000-2050	319	53	53	54

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Water Use for Milling (including in-situ leaching) of Uranium Imported In-country for Use in Domestic Reactors (million cubic meters)	2010	13	13	13	13
	2030	25	35	34	35
	2050	27	43	44	47
	Cumulative, 2000-2050	1,037	1,442	1,490	1,543
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Water Use for Milling (including in-situ leaching) of Uranium Imported In-country for Use in Domestic Reactors (million cubic meters)	2010	13	13	13	13
	2030	33	52	51	53
	2050	46	78	79	86
	Cumulative, 2000-2050	1,381	2,083	2,171	2,262
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Water Use for Milling (including in-situ leaching) of Uranium Imported In-country for Use in Domestic Reactors (million cubic meters)	2010	13	13	13	13
	2030	16	23	23	23
	2050	16	25	25	28
	Cumulative, 2000-2050	736	1,002	1,031	1,062

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Water Use for Milling (including in-situ leaching) for Production of Domestic and Imported Uranium (million cubic meters)	2010	14	14	14	14
	2030	36	36	35	36
	2050	44	44	45	48
	Cumulative, 2000-2050	1,495	1,495	1,543	1,597
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Water Use for Milling (including in-situ leaching) for Production of Domestic and Imported Uranium (million cubic meters)	2010	14	14	14	14
	2030	53	53	53	55
	2050	82	82	83	90
	Cumulative, 2000-2050	2,174	2,174	2,263	2,357
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Water Use for Milling (including in-situ leaching) for Production of Domestic and Imported Uranium (million cubic meters)	2010	14	14	14	14
	2030	24	24	24	24
	2050	26	26	26	29
	Cumulative, 2000-2050	1,055	1,055	1,084	1,117

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost (or value) of Uranium Produced In-country for Use in Domestic Reactors (Million 2009 dollars)	2010	$ 157	$ 135	$ 135	$ 135
	2030	$ 1,286	$ 122	$ 122	$ 126
	2050	$ 1,757	$ 107	$ 107	$ 116
	Cumulative, 2000-2050	$ 49,490	$ 5,868	$ 5,870	$ 6,017

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost (or value) of Uranium Produced In-country for Use in Domestic Reactors (Million 2009 dollars)	2010	$ 157	$ 135	$ 135	$ 135
	2030	$ 2,179	$ 184	$ 184	$ 190
	2050	$ 3,715	$ 399	$ 399	$ 432
	Cumulative, 2000-2050	$ 85,259	$ 10,002	$ 10,010	$ 10,400

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost (or value) of Uranium Produced In-country for Use in Domestic Reactors (Million 2009 dollars)	2010	$ 157	$ 135	$ 135	$ 135
	2030	$ 925	$ 122	$ 122	$ 126
	2050	$ 1,085	$ 107	$ 107	$ 116
	Cumulative, 2000-2050	$ 34,677	$ 5,871	$ 5,872	$ 6,017

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost (or value) of Uranium Imported for Use in Domestic Reactors (Million 2009 dollars)	2010	$ 1,522	$ 1,544	$ 1,544	$ 1,544
	2030	$ 2,703	$ 3,866	$ 3,582	$ 3,694
	2050	$ 2,779	$ 4,428	$ 4,225	$ 4,575
	Cumulative, 2000-2050	$ 111,375	$ 154,995	$ 153,646	$ 159,012

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost (or value) of Uranium Imported for Use in Domestic Reactors (Million 2009 dollars)	2010	$ 1,522	$ 1,544	$ 1,544	$ 1,544
	2030	$ 3,684	$ 5,678	$ 5,377	$ 5,562
	2050	$ 4,682	$ 7,997	$ 7,670	$ 8,299
	Cumulative, 2000-2050	$ 148,083	$ 223,336	$ 222,799	$ 231,885

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost (or value) of Uranium Imported for Use in Domestic Reactors (Million 2009 dollars)	2010	$ 1,522	$ 1,544	$ 1,544	$ 1,544
	2030	$ 1,764	$ 2,567	$ 2,363	$ 2,427
	2050	$ 1,607	$ 2,586	$ 2,463	$ 2,679
	Cumulative, 2000-2050	$ 79,039	$ 107,844	$ 106,755	$ 109,931

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost (or value) of Uranium Produced Domestically or Imported for Use in Reactors in the Region (Million 2009 dollars)	2010	$ 1,679	$ 1,679	$ 1,679	$ 1,679
	2030	$ 3,988	$ 3,988	$ 3,704	$ 3,820
	2050	$ 4,536	$ 4,536	$ 4,332	$ 4,692
	Cumulative, 2000-2050	$ 160,865	$ 160,863	$ 159,516	$ 165,029
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost (or value) of Uranium Produced Domestically or Imported for Use in Reactors in the Region (Million 2009 dollars)	2010	$ 1,679	$ 1,679	$ 1,679	$ 1,679
	2030	$ 5,862	$ 5,862	$ 5,561	$ 5,752
	2050	$ 8,397	$ 8,397	$ 8,069	$ 8,731
	Cumulative, 2000-2050	$ 233,342	$ 233,338	$ 232,809	$ 242,285
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost (or value) of Uranium Produced Domestically or Imported for Use in Reactors in the Region (Million 2009 dollars)	2010	$ 1,679	$ 1,679	$ 1,679	$ 1,679
	2030	$ 2,689	$ 2,689	$ 2,486	$ 2,553
	2050	$ 2,692	$ 2,692	$ 2,570	$ 2,795
	Cumulative, 2000-2050	$ 113,716	$ 113,716	$ 112,627	$ 115,948

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Radioactivity in Mill Tailings from Uranium Produced In-country for Use in Domestic Reactors (TBq)	2010	131	113	113	113
	2030	1,191	110	109	113
	2050	1,780	104	104	113
	Cumulative, 2000-2050	46,788	5,214	5,215	5,353

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Radioactivity in Mill Tailings from Uranium Produced In-country for Use in Domestic Reactors (TBq)	2010	131	113	113	113
	2030	2,055	176	176	182
	2050	3,814	442	442	478
	Cumulative, 2000-2050	82,162	9,826	9,834	10,243

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Radioactivity in Mill Tailings from Uranium Produced In-country for Use in Domestic Reactors (TBq)	2010	131	113	113	113
	2030	839	110	110	113
	2050	1,062	104	104	113
	Cumulative, 2000-2050	31,759	5,216	5,217	5,353

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	BAU Capacity Expansion Paths				
Annual Radioactivity in Mill Tailings from Uranium Imported for Use in Domestic Reactors (TBq)	2010	1,161	1,158	1,158	1,158
	2030	3,168	2,938	2,868	2,958
	2050	3,976	3,604	3,619	3,919
	Cumulative, 2000-2050	130,406	121,435	125,311	129,754
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Radioactivity in Mill Tailings from Uranium Imported for Use in Domestic Reactors (TBq)	2010	1,161	1,158	1,158	1,158
	2030	4,750	4,330	4,316	4,465
	2050	7,514	6,763	6,823	7,383
	Cumulative, 2000-2050	193,500	177,692	184,856	192,559
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Radioactivity in Mill Tailings from Uranium Imported for Use in Domestic Reactors (TBq)	2010	1,161	1,158	1,158	1,158
	2030	2,130	1,988	1,930	1,982
	2050	2,332	2,147	2,153	2,342
	Cumulative, 2000-2050	91,096	85,988	88,304	90,988

Parameter	YEAR	BAU Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Radioactivity in Mill Tailings from Uranium Produced Domestically and Imported for Use in Reactors in the Region (TBq)	2010	1,292	1,271	1,271	1,271
	2030	4,359	3,047	2,977	3,071
	2050	5,757	3,708	3,724	4,032
	Cumulative, 2000-2050	177,194	126,648	130,526	135,107

Parameter	YEAR	MAX Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Radioactivity in Mill Tailings from Uranium Produced Domestically and Imported for Use in Reactors in the Region (TBq)	2010	1,292	1,271	1,271	1,271
	2030	6,805	4,506	4,493	4,647
	2050	11,328	7,205	7,265	7,861
	Cumulative, 2000-2050	275,662	187,518	194,690	202,802

Parameter	YEAR	MIN Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Radioactivity in Mill Tailings from Uranium Produced Domestically and Imported for Use in Reactors in the Region (TBq)	2010	1,292	1,271	1,271	1,271
	2030	2,969	2,098	2,040	2,095
	2050	3,394	2,251	2,257	2,455
	Cumulative, 2000-2050	122,855	91,204	93,521	96,340

TABLES BELOW ALL FOR BAU CAPACITY EXPANSION CASE

		Scenario 1		Scenario 2		Scenario 3		Scenario 4	
Parameter	YEAR	Uranium Mined In-Country	Uranium Imported	Uranium Mined In-Country	Uranium Imported	Uranium Mined In-Country	Uranium Imported	Uranium Mined In-Country	Uranium Imported
Annual Total Metric Tons Natural Uranium (as U) Mined for Use in Domestic Reactors	2010	1,321	12,782	1,138	12,965	1,138	12,965	1,138	12,965
	2030	11,637	25,282	1,140	35,091	1,101	34,247	1,140	35,296
	2050	17,065	29,503	1,140	43,423	1,042	43,667	1,140	47,227
	Cumulative, 2000-2050	454,783	1,072,450	53,971	1,441,982	52,444	1,491,221	54,041	1,543,441
Annual Total Thousand Metric Tons Uranium Ore Mined for Use in Domestic Reactors*	2010	764	318	658	322	658	322	658	322
	2030	6,955	629	659	873	637	852	659	878
	2050	10,273	734	659	1,080	603	1,086	659	1,175
	Cumulative, 2000-2050	270,935	26,675	31,217	35,866	30,334	37,091	31,257	38,390

* Excludes Uranium mined via in-situ leaching.

The Nautilus Institute
for Security and Sustainability

FUTURE REGIONAL NUCLEAR FUEL CYCLE COOPERATION IN EAST ASIA: ENERGY SECURITY
Calculations for East Asia Science and Security (EASS) and Related Follow-on (2012-2016) Projects, funded by MacArthur Foundation

Estimates of Uranium Transport and Enrichment Parameters: Summaries for All Regional Scenarios

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Last Modified:	3/11/2016

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Metric Tons Natural Uranium (as UF6, but expressed as U) Enriched In-country for Use in Domestic Reactors	2010	3,643	3,643	3,643	3,643
	2030	32,663	-	5,762	4,925
	2050	39,684	-	5,286	4,925
	Cumulative, 2000-2050	1,095,240	47,413	222,475	202,495
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Tons Natural Uranium (as UF6, but expressed as U) Enriched In-country for Use in Domestic Reactors	2010	3,643	3,643	3,643	3,643
	2030	47,745	-	6,216	4,925
	2050	72,366	-	5,551	4,925
	Cumulative, 2000-2050	1,712,475	49,257	235,537	203,361
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Tons Natural Uranium (as UF6, but expressed as U) Enriched In-country for Use in Domestic Reactors	2010	3,643	3,643	3,643	3,643
	2030	23,188	-	5,127	4,925
	2050	25,406	-	4,555	4,925
	Cumulative, 2000-2050	773,461	47,006	202,784	202,143

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Metric Tons Natural Uranium (as UF6, but expressed as U) Enriched Outside the Country for Use in Domestic Reactors	2010	9,841	9,841	9,841	9,841
	2030	2,799	35,462	29,214	31,147
	2050	4,569	44,253	39,954	44,067
	Cumulative, 2000-2050	369,891	1,417,702	1,311,244	1,386,430

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Metric Tons Natural Uranium (as UF6, but expressed as U) Enriched Outside the Country for Use in Domestic Reactors	2010	9,841	9,841	9,841	9,841
	2030	4,644	52,390	47,608	50,748
	2050	9,560	81,926	79,152	86,730
	Cumulative, 2000-2050	432,203	2,092,368	2,038,442	2,166,327

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Metric Tons Natural Uranium (as UF6, but expressed as U) Enriched Outside the Country for Use in Domestic Reactors	2010	9,841	9,841	9,841	9,841
	2030	916	24,104	18,263	19,094
	2050	864	26,270	21,784	23,725
	Cumulative, 2000-2050	261,334	987,726	860,530	893,943

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Metric Tons Natural Uranium (as UF6, but expressed as U) Enriched Inside and Outside the Country for Use in Domestic Reactors	2010	13,484	13,484	13,484	13,484
	2030	35,462	35,462	34,976	36,072
	2050	44,253	44,253	45,240	48,992
	Cumulative, 2000-2050	1,465,130	1,465,116	1,533,719	1,588,925

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Metric Tons Natural Uranium (as UF6, but expressed as U) Enriched Inside and Outside the Country for Use in Domestic Reactors	2010	13,484	13,484	13,484	13,484
	2030	52,390	52,390	53,824	55,673
	2050	81,926	81,926	84,704	91,655
	Cumulative, 2000-2050	2,144,678	2,141,626	2,273,979	2,369,688

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Metric Tons Natural Uranium (as UF6, but expressed as U) Enriched Inside and Outside the Country for Use in Domestic Reactors	2010	13,484	13,484	13,484	13,484
	2030	24,104	24,104	23,390	24,019
	2050	26,270	26,270	26,339	28,650
	Cumulative, 2000-2050	1,034,795	1,034,732	1,063,313	1,096,086

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Million Tonne-km U3O8 Transport to In-country Enrichment for Use in Domestic Reactors	2010	12.0	12.0	12.0	12.0
	2030	64.5	-	12.7	13.1
	2050	62.9	-	10.5	11.4
	Cumulative, 2000-2050	2,056	119	476	491
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Million Tonne-km U3O8 Transport to In-country Enrichment for Use in Domestic Reactors	2010	12	12	12	12
	2030	95	-	16	17
	2050	103	-	13	14
	Cumulative, 2000-2050	3,131	129	583	603
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Million Tonne-km U3O8 Transport to In-country Enrichment for Use in Domestic Reactors	2010	12	12	12	12
	2030	32	-	7	8
	2050	24	-	5	5
	Cumulative, 2000-2050	1,054	115	317	325

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Million Tonne-km U3O8 Transport to Out-of-country Enrichment for Use in Domestic Reactors	2010	99	99	99	99
	2030	28	356	294	303
	2050	46	445	402	435
	Cumulative, 2000-2050	3,738	14,248	13,178	13,661

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Million Tonne-km U3O8 Transport to Out-of-country Enrichment for Use in Domestic Reactors	2010	99	99	99	99
	2030	47	527	478	495
	2050	96	823	795	861
	Cumulative, 2000-2050	4,344	21,029	20,487	21,368

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Million Tonne-km U3O8 Transport to Out-of-country Enrichment for Use in Domestic Reactors	2010	99	99	99	99
	2030	9	242	184	188
	2050	9	264	219	238
	Cumulative, 2000-2050	2,626	9,927	8,649	8,917

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Million Tonne-km U3O8 Transport to In-country and Out-of-country Enrichment for Use in Domestic Reactors	2010	111	111	111	111
	2030	93	356	306	316
	2050	109	445	412	446
	Cumulative, 2000-2050	5,794	14,367	13,654	14,153
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Million Tonne-km U3O8 Transport to In-country and Out-of-country Enrichment for Use in Domestic Reactors	2010	111	111	111	111
	2030	142	527	495	512
	2050	199	823	808	874
	Cumulative, 2000-2050	7,475	21,158	21,070	21,972
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Million Tonne-km U3O8 Transport to In-country and Out-of-country Enrichment for Use in Domestic Reactors	2010	111	111	111	111
	2030	42	242	191	196
	2050	33	264	224	243
	Cumulative, 2000-2050	3,680	10,042	8,966	9,241

Parameter	YEAR	BAU Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Cost (Million 2009 USD) of U3O8 Transport to In-country Enrichment for Use in Domestic Reactors	2010	$ 0.17	$ 0.17	$ 0.17	$ 0.17
	2030	$ 0.99	$ -	$ 0.20	$ 0.21
	2050	$ 1.05	$ -	$ 0.17	$ 0.19
	Cumulative, 2000-2050	$ 32.46	$ 1.83	$ 7.59	$ 7.83

Parameter	YEAR	MAX Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Cost (Million 2009 USD) of U3O8 Transport to In-country Enrichment for Use in Domestic Reactors	2010	$ 0.17	$ 0.17	$ 0.17	$ 0.17
	2030	$ 1.48	$ -	$ 0.25	$ 0.26
	2050	$ 1.79	$ -	$ 0.20	$ 0.21
	Cumulative, 2000-2050	$ 50.44	$ 1.97	$ 8.95	$ 9.26

Parameter	YEAR	MIN Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Cost (Million 2009 USD) of U3O8 Transport to In-country Enrichment for Use in Domestic Reactors	2010	$ 0.17	$ 0.17	$ 0.17	$ 0.17
	2030	$ 0.54	$ -	$ 0.13	$ 0.14
	2050	$ 0.48	$ -	$ 0.10	$ 0.11
	Cumulative, 2000-2050	$ 18.20	$ 1.78	$ 5.57	$ 5.71

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Cost (Million 2009 USD) of U3O8 Transport to Out-of-country Enrichment for Use in Domestic Reactors	2010	$ 1.26	$ 1.26	$ 1.26	$ 1.26
	2030	$ 0.36	$ 4.54	$ 3.74	$ 3.85
	2050	$ 0.58	$ 5.66	$ 5.11	$ 5.53
	Cumulative, 2000-2050	$ 47.57	$ 181.35	$ 167.73	$ 173.88

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Cost (Million 2009 USD) of U3O8 Transport to Out-of-country Enrichment for Use in Domestic Reactors	2010	$ 1.26	$ 1.26	$ 1.26	$ 1.26
	2030	$ 0.59	$ 6.70	$ 6.09	$ 6.30
	2050	$ 1.22	$ 10.48	$ 10.12	$ 10.96
	Cumulative, 2000-2050	$ 55.29	$ 267.65	$ 260.75	$ 271.97

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Cost (Million 2009 USD) of U3O8 Transport to Out-of-country Enrichment for Use in Domestic Reactors	2010	$ 1.26	$ 1.26	$ 1.26	$ 1.26
	2030	$ 0.12	$ 3.08	$ 2.34	$ 2.40
	2050	$ 0.11	$ 3.36	$ 2.79	$ 3.03
	Cumulative, 2000-2050	$ 33.43	$ 126.35	$ 110.08	$ 113.49

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Cost (Million 2009 USD) of U3O8 Transport to In-country and Out-of-country Enrichment for Use in Domestic Reactors	2010	$ 1.43	$ 1.43	$ 1.43	$ 1.43
	2030	$ 1.35	$ 4.54	$ 3.94	$ 4.06
	2050	$ 1.63	$ 5.66	$ 5.28	$ 5.72
	Cumulative, 2000-2050	$ 80.03	$ 183.18	$ 175.32	$ 181.71
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Cost (Million 2009 USD) of U3O8 Transport to In-country and Out-of-country Enrichment for Use in Domestic Reactors	2010	$ 1.43	$ 1.43	$ 1.43	$ 1.43
	2030	$ 2.08	$ 6.70	$ 6.34	$ 6.56
	2050	$ 3.01	$ 10.48	$ 10.32	$ 11.17
	Cumulative, 2000-2050	$ 105.72	$ 269.62	$ 269.70	$ 281.23
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Cost (Million 2009 USD) of U3O8 Transport to In-country and Out-of-country Enrichment for Use in Domestic Reactors	2010	$ 1.43	$ 1.43	$ 1.43	$ 1.43
	2030	$ 0.66	$ 3.08	$ 2.47	$ 2.54
	2050	$ 0.59	$ 3.36	$ 2.88	$ 3.14
	Cumulative, 2000-2050	$ 51.63	$ 128.13	$ 115.65	$ 119.20

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Annual Total Fossil Fuel Used in Converting U3O8 to UF6 for Uranium Enriched In-country (TJ)	2010	9	9	9	9
	2030	79	-	14	14
	2050	96	-	13	14
	Cumulative, 2000-2050	2,636	114	535	553
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Fossil Fuel Used in Converting U3O8 to UF6 for Uranium Enriched In-country (TJ)	2010	9	9	9	9
	2030	115	-	15	15
	2050	174	-	13	14
	Cumulative, 2000-2050	4,121	119	567	586
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Fossil Fuel Used in Converting U3O8 to UF6 for Uranium Enriched In-country (TJ)	2010	9	9	9	9
	2030	56	-	12	13
	2050	61	-	11	12
	Cumulative, 2000-2050	1,861	113	488	503

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Annual Total Fossil Fuel Used in Converting U3O8 to UF6 for Uranium Enriched Out-of-country (TJ)	2010	24	24	24	24
	2030	7	85	70	73
	2050	11	107	96	104
	Cumulative, 2000-2050	895	3,412	3,156	3,271
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Fossil Fuel Used in Converting U3O8 to UF6 for Uranium Enriched Out-of-	2010	24	24	24	24
	2030	11	126	115	119
	2050	23	197	190	206
	Cumulative, 2000-2050	1,040	5,036	4,906	5,117
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Fossil Fuel Used in Converting U3O8 to UF6 for Uranium Enriched Out-of-	2010	24	24	24	24
	2030	2	58	44	45
	2050	2	63	52	57
	Cumulative, 2000-2050	629	2,377	2,071	2,135

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	BAU Capacity Expansion Paths				
Annual Total Fossil Fuel Used in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (TJ)	2010	32	32	32	32
	2030	85	85	84	87
	2050	107	107	109	118
	Cumulative, 2000-2050	3,531	3,526	3,691	3,824
	MAX Capacity Expansion Paths				
Annual Total Fossil Fuel Used in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (TJ)	2010	32	32	32	32
	2030	126	126	130	134
	2050	197	197	204	221
	Cumulative, 2000-2050	5,162	5,154	5,473	5,703
	MIN Capacity Expansion Paths				
Annual Total Fossil Fuel Used in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (TJ)	2010	32	32	32	32
	2030	58	58	56	58
	2050	63	63	63	69
	Cumulative, 2000-2050	2,490	2,490	2,559	2,638

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	BAU Capacity Expansion Paths				
Annual Total Electricity Used in Converting U3O8 to UF6 for Uranium Enriched In-country (GWh)	2010	4	4	4	4
	2030	33	-	6	6
	2050	40	-	5	6
	Cumulative, 2000-2050	1,101	48	224	231
	MAX Capacity Expansion Paths				
Annual Total Electricity Used in Converting U3O8 to UF6 for Uranium Enriched In-country (GWh)	2010	4	4	4	4
	2030	48	-	6	6
	2050	73	-	6	6
	Cumulative, 2000-2050	1,721	50	237	245
	MIN Capacity Expansion Paths				
Annual Total Electricity Used in Converting U3O8 to UF6 for Uranium Enriched In-country (GWh)	2010	4	4	4	4
	2030	23	-	5	5
	2050	26	-	5	5
	Cumulative, 2000-2050	777	47	204	210

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used in Converting U3O8 to UF6 for Uranium Enriched Out-of-country (GWh)	2010	10	10	10	10
	2030	3	36	29	30
	2050	5	44	40	43
	Cumulative, 2000-2050	374	1,425	1,318	1,366
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used in Converting U3O8 to UF6 for Uranium Enriched Out-of-country (GWh)	2010	10	10	10	10
	2030	5	53	48	49
	2050	10	82	80	86
	Cumulative, 2000-2050	434	2,103	2,049	2,137
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used in Converting U3O8 to UF6 for Uranium Enriched Out-of-country (GWh)	2010	10	10	10	10
	2030	1	24	18	19
	2050	1	26	22	24
	Cumulative, 2000-2050	263	993	865	892

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Electricity Used in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (GWhe)	2010	14	14	14	14
	2030	36	36	35	36
	2050	44	44	45	49
	Cumulative, 2000-2050	1,475	1,472	1,541	1,597
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Electricity Used in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (GWhe)	2010	14	14	14	14
	2030	53	53	54	56
	2050	82	82	85	92
	Cumulative, 2000-2050	2,155	2,152	2,285	2,382
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Electricity Used in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (GWhe)	2010	14	14	14	14
	2030	24	24	24	24
	2050	26	26	26	29
	Cumulative, 2000-2050	1,040	1,040	1,069	1,102

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Annual Total Cost of Conversion of U3O8 to UF6 for Uranium Enriched In-country (million dollars)	2010	$ 51	$ 51	$ 51	$ 51
	2030	$ 460	$ -	$ 81	$ 84
	2050	$ 559	$ -	$ 74	$ 81
	Cumulative, 2000-2050	$ 15,422	$ 668	$ 3,133	$ 3,233
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Conversion of U3O8 to UF6 for Uranium Enriched In-country (million dollars)	2010	$ 51	$ 51	$ 51	$ 51
	2030	$ 672	$ -	$ 88	$ 91
	2050	$ 1,019	$ -	$ 78	$ 85
	Cumulative, 2000-2050	$ 24,113	$ 694	$ 3,317	$ 3,429
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Conversion of U3O8 to UF6 for Uranium Enriched In-country (million dollars)	2010	$ 51	$ 51	$ 51	$ 51
	2030	$ 327	$ -	$ 72	$ 74
	2050	$ 358	$ -	$ 64	$ 70
	Cumulative, 2000-2050	$ 10,891	$ 662	$ 2,855	$ 2,941

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Annual Total Cost of Conversion of U3O8 to UF6 for Uranium Enriched Out-of-country (million dollars)	2010	$ 139	$ 139	$ 139	$ 139
	2030	$ 39	$ 499	$ 411	$ 424
	2050	$ 64	$ 623	$ 563	$ 609
	Cumulative, 2000-2050	$ 5,237	$ 19,963	$ 18,464	$ 19,140
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Conversion of U3O8 to UF6 for Uranium Enriched Out-of-country (million dollars)	2010	$ 139	$ 139	$ 139	$ 139
	2030	$ 65	$ 738	$ 670	$ 693
	2050	$ 135	$ 1,154	$ 1,115	$ 1,206
	Cumulative, 2000-2050	$ 6,086	$ 29,462	$ 28,703	$ 29,938
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Conversion of U3O8 to UF6 for Uranium Enriched Out-of-country (million dollars)	2010	$ 139	$ 139	$ 139	$ 139
	2030	$ 13	$ 339	$ 257	$ 264
	2050	$ 12	$ 370	$ 307	$ 334
	Cumulative, 2000-2050	$ 3,680	$ 13,908	$ 12,117	$ 12,493

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Conversion of U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (million dollars)	2010	$ 190	$ 190	$ 190	$ 190
	2030	$ 499	$ 499	$ 492	$ 508
	2050	$ 623	$ 623	$ 637	$ 690
	Cumulative, 2000-2050	$ 20,659	$ 20,630	$ 21,596	$ 22,374

		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Conversion of U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (million dollars)	2010	$ 190	$ 190	$ 190	$ 190
	2030	$ 738	$ 738	$ 758	$ 784
	2050	$ 1,154	$ 1,154	$ 1,193	$ 1,291
	Cumulative, 2000-2050	$ 30,199	$ 30,156	$ 32,020	$ 33,367

		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Conversion of U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (million dollars)	2010	$ 190	$ 190	$ 190	$ 190
	2030	$ 339	$ 339	$ 329	$ 338
	2050	$ 370	$ 370	$ 371	$ 403
	Cumulative, 2000-2050	$ 14,571	$ 14,570	$ 14,972	$ 15,434

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched In-country (metric tons)	2010	2,563	2,563	2,563	2,563
	2030	22,979	-	4,054	4,181
	2050	27,919	-	3,719	4,027
	Cumulative, 2000-2050	770,520	33,356	156,515	161,547

		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched In-country (metric tons)	2010	2,563	2,563	2,563	2,563
	2030	33,590	-	4,373	4,523
	2050	50,911	-	3,906	4,226
	Cumulative, 2000-2050	1,204,756	34,653	165,704	171,331

		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched In-country (metric tons)	2010	2,563	2,563	2,563	2,563
	2030	16,313	-	3,607	3,704
	2050	17,874	-	3,205	3,486
	Cumulative, 2000-2050	544,143	33,070	142,662	146,958

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched Out-of-country (metric tons)	2010	6,924	6,924	6,924	6,924
	2030	1,969	24,948	20,552	21,197
	2050	3,214	31,133	28,109	30,440
	Cumulative, 2000-2050	261,646	997,378	922,483	956,290
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched Out-of-country (metric tons)	2010	6,924	6,924	6,924	6,924
	2030	3,267	36,857	33,493	34,644
	2050	6,725	57,636	55,685	60,255
	Cumulative, 2000-2050	304,062	1,472,018	1,434,080	1,495,786
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched Out-of-country (metric tons)	2010	6,924	6,924	6,924	6,924
	2030	644	16,957	12,848	13,194
	2050	608	18,481	15,325	16,670
	Cumulative, 2000-2050	183,853	694,882	605,398	624,157

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (metric tons)	2010	9,486	9,486	9,486	9,486
	2030	24,948	24,948	24,606	25,378
	2050	31,133	31,133	31,827	34,467
	Cumulative, 2000-2050	1,032,166	1,030,735	1,078,998	1,117,837
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Produced in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (metric tons)	2010	9,486	9,486	9,486	9,486
	2030	36,857	36,857	37,866	39,167
	2050	57,636	57,636	59,590	64,481
	Cumulative, 2000-2050	1,508,818	1,506,671	1,599,784	1,667,117
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Produced in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (metric tons)	2010	9,486	9,486	9,486	9,486
	2030	16,957	16,957	16,456	16,898
	2050	18,481	18,481	18,530	20,156
	Cumulative, 2000-2050	727,996	727,952	748,060	771,115

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched In-country (cubic meters)	2010	23,796	23,796	23,796	23,796
	2030	213,375	-	37,644	38,823
	2050	259,245	-	34,531	37,395
	Cumulative, 2000-2050	7,154,831	309,736	1,453,355	1,500,080
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched In-country (cubic meters)	2010	23,796	23,796	23,796	23,796
	2030	311,904	-	40,606	42,001
	2050	472,743	-	36,266	39,242
	Cumulative, 2000-2050	11,187,024	321,782	1,538,683	1,590,935
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched In-country (cubic meters)	2010	23,796	23,796	23,796	23,796
	2030	151,479	-	33,496	34,397
	2050	165,971	-	29,758	32,369
	Cumulative, 2000-2050	5,052,758	307,077	1,324,717	1,364,609

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched Out-of-country (cubic meters)	2010	64,291	64,291	64,291	64,291
	2030	18,287	231,662	190,844	196,826
	2050	29,849	289,093	261,009	282,653
	Cumulative, 2000-2050	2,429,571	9,261,370	8,565,913	8,879,835
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched Out-of-country (cubic meters)	2010	64,291	64,291	64,291	64,291
	2030	30,339	342,244	311,005	321,694
	2050	62,450	535,193	517,074	559,510
	Cumulative, 2000-2050	2,823,433	13,668,737	13,316,454	13,889,439
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched Out-of-country (cubic meters)	2010	64,291	64,291	64,291	64,291
	2030	5,983	157,462	119,306	122,514
	2050	5,642	171,614	142,307	154,794
	Cumulative, 2000-2050	1,707,206	6,452,480	5,621,552	5,795,748

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
BAU Capacity Expansion Paths					
Annual Liguid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (cubic meters)	2010	88,087	88,087	88,087	88,087
	2030	231,662	231,662	228,488	235,649
	2050	289,093	289,093	295,540	320,048
	Cumulative, 2000-2050	9,584,402	9,571,106	10,019,268	10,379,915
MAX Capacity Expansion Paths					
Annual Liguid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (cubic meters)	2010	88,087	88,087	88,087	88,087
	2030	342,244	342,244	351,611	363,696
	2050	535,193	535,193	553,340	598,751
	Cumulative, 2000-2050	14,010,457	13,990,519	14,855,137	15,480,374
MIN Capacity Expansion Paths					
Annual Liguid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (cubic meters)	2010	88,087	88,087	88,087	88,087
	2030	157,462	157,462	152,802	156,911
	2050	171,614	171,614	172,064	187,163
	Cumulative, 2000-2050	6,759,964	6,759,557	6,946,269	7,160,358

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Annual Total Enriched Fuel Requirements for Uranium Enriched In-country for Domestic Use (metric tons enriched fuel as U)	2010	401	401	401	401
	2030	3,599	-	635	655
	2050	4,373	-	583	631
	Cumulative, 2000-2050	120,741	5,269	24,561	25,349

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		MAX Capacity Expansion Paths			
Annual Total Enriched Fuel Requirements for Uranium Enriched In-country for Domestic Use (metric tons enriched fuel as U)	2010	401	401	401	401
	2030	5,262	-	685	709
	2050	7,975	-	612	662
	Cumulative, 2000-2050	188,761	5,472	26,000	26,882

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		MIN Capacity Expansion Paths			
Annual Total Enriched Fuel Requirements for Uranium Enriched In-country for Domestic Use (metric tons enriched fuel as U)	2010	401	401	401	401
	2030	2,555	-	565	580
	2050	2,800	-	502	546
	Cumulative, 2000-2050	85,280	5,224	22,391	23,064

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enriched Fuel Requirements for Uranium Enriched Out-of-country for Domestic Use (metric tons enriched fuel as U)	2010	1,085	1,085	1,085	1,085
	2030	308	3,908	3,219	3,320
	2050	504	4,877	4,403	4,768
	Cumulative, 2000-2050	41,393	156,641	144,909	150,205
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enriched Fuel Requirements for Uranium Enriched Out-of-country for Domestic Use (metric tons enriched fuel as U)	2010	1,085	1,085	1,085	1,085
	2030	512	5,773	5,246	5,427
	2050	1,053	9,028	8,723	9,439
	Cumulative, 2000-2050	48,038	230,991	225,048	234,714
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enriched Fuel Requirements for Uranium Enriched Out-of-country for Domestic Use (metric tons enriched fuel as U)	2010	1,085	1,085	1,085	1,085
	2030	101	2,656	2,013	2,067
	2050	95	2,895	2,401	2,611
	Cumulative, 2000-2050	29,207	109,257	95,240	98,179

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enriched Fuel Requirements for Uranium Enriched In-country or Out-of-country for Domestic Use (metric tons enriched fuel as U)	2010	1,486	1,486	1,486	1,486
	2030	3,908	3,908	3,854	3,975
	2050	4,877	4,877	4,986	5,399
	Cumulative, 2000-2050	162,134	161,910	169,470	175,554
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enriched Fuel Requirements for Uranium Enriched In-country or Out-of-country for Domestic Use (metric tons enriched fuel as U)	2010	1,486	1,486	1,486	1,486
	2030	5,773	5,773	5,931	6,135
	2050	9,028	9,028	9,334	10,101
	Cumulative, 2000-2050	236,799	236,463	251,048	261,596
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enriched Fuel Requirements for Uranium Enriched In-country or Out-of-country for Domestic Use (metric tons enriched fuel as U)	2010	1,486	1,486	1,486	1,486
	2030	2,656	2,656	2,578	2,647
	2050	2,895	2,895	2,903	3,157
	Cumulative, 2000-2050	114,488	114,481	117,631	121,242

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enrichment Requirements for Uranium Enriched In-country for Domestic Use (Million kg SWU)	2010	2.8	2.8	2.8	2.8
	2030	25.4	-	4.5	4.6
	2050	30.8	-	4.1	4.4
	Cumulative, 2000-2050	851	37	173	178

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enrichment Requirements for Uranium Enriched In-country for Domestic Use (Million kg SWU)	2010	2.8	2.8	2.8	2.8
	2030	37.1	-	4.8	5.0
	2050	56.2	-	4.3	4.7
	Cumulative, 2000-2050	1,330	38	183	189

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enrichment Requirements for Uranium Enriched In-country for Domestic Use (Million kg SWU)	2010	3	3	3	3
	2030	18	-	4	4
	2050	20	-	4	4
	Cumulative, 2000-2050	601	36	157	162

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enrichment Requirements for Uranium Enriched Out-of-country for Domestic Use (Million kg SWU)	2010	8	8	8	8
	2030	2	28	23	23
	2050	4	34	31	34
	Cumulative, 2000-2050	288	1,100	1,018	1,055
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enrichment Requirements for Uranium Enriched Out-of-country for Domestic Use (Million kg SWU)	2010	8	8	8	8
	2030	4	41	37	38
	2050	7	64	61	67
	Cumulative, 2000-2050	335	1,624	1,582	1,651
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enrichment Requirements for Uranium Enriched Out-of-country for Domestic Use (Million kg SWU)	2010	8	8	8	8
	2030	1	19	14	15
	2050	1	20	17	18
	Cumulative, 2000-2050	202	766	668	688

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enrichment Requirements for Uranium Enriched In-country or Out-of-country for Domestic Use (Million kg SWU)	2010	10	10	10	10
	2030	28	28	27	28
	2050	34	34	35	38
	Cumulative, 2000-2050	1,139	1,137	1,190	1,233

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enrichment Requirements for Uranium Enriched In-country or Out-of-country for Domestic Use (Million kg SWU)	2010	10	10	10	10
	2030	41	41	42	43
	2050	64	64	66	71
	Cumulative, 2000-2050	1,665	1,662	1,765	1,840

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enrichment Requirements for Uranium Enriched In-country or Out-of-country for Domestic Use (Million kg SWU)	2010	10	10	10	10
	2030	19	19	18	19
	2050	20	20	20	22
	Cumulative, 2000-2050	803	803	825	850

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Uranium Enrichment In-country for Fuel Used in Domestic Reactors (Million 2009 dollars)	2010	$ 421	$ 421	$ 421	$ 421
	2030	$ 2,807	$ -	$ 495	$ 511
	2050	$ 3,144	$ -	$ 419	$ 453
	Cumulative, 2000-2050	$ 92,285	$ 4,531	$ 19,287	$ 19,877

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Uranium Enrichment In-country for Fuel Used in Domestic Reactors (Million 2009 dollars)	2010	$ 421	$ 421	$ 421	$ 421
	2030	$ 5,239	$ -	$ 682	$ 705
	2050	$ 9,604	$ -	$ 737	$ 797
	Cumulative, 2000-2050	$ 200,856	$ 4,895	$ 26,338	$ 27,300

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Uranium Enrichment In-country for Fuel Used in Domestic Reactors (Million 2009 dollars)	2010	$ 421	$ 421	$ 421	$ 421
	2030	$ 1,690	$ -	$ 374	$ 384
	2050	$ 1,421	$ -	$ 255	$ 277
	Cumulative, 2000-2050	$ 53,852	$ 4,387	$ 15,175	$ 15,565

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Uranium Enrichment Services Imported for Fuel Used in Domestic Reactors (Million 2009 dollars)	2010	$ 1,139	$ 1,139	$ 1,139	$ 1,139
	2030	$ 241	$ 3,047	$ 2,510	$ 2,589
	2050	$ 362	$ 3,506	$ 3,165	$ 3,428
	Cumulative, 2000-2050	$ 33,600	$ 121,174	$ 112,375	$ 116,327

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Uranium Enrichment Services Imported for Fuel Used in Domestic Reactors (Million 2009 dollars)	2010	$ 1,139	$ 1,139	$ 1,139	$ 1,139
	2030	$ 510	$ 5,748	$ 5,224	$ 5,403
	2050	$ 1,269	$ 10,873	$ 10,505	$ 11,367
	Cumulative, 2000-2050	$ 46,126	$ 241,774	$ 235,157	$ 245,875

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Uranium Enrichment Services Imported for Fuel Used in Domestic Reactors (Million 2009 dollars)	2010	$ 1,139	$ 1,139	$ 1,139	$ 1,139
	2030	$ 67	$ 1,756	$ 1,331	$ 1,366
	2050	$ 48	$ 1,469	$ 1,218	$ 1,325
	Cumulative, 2000-2050	$ 23,275	$ 72,735	$ 64,314	$ 66,005

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Uranium Enrichment Services In-country or Imported for Fuel Used in Domestic Reactors (Million 2009 dollars)	2010	$ 1,560	$ 1,560	$ 1,560	$ 1,560
	2030	$ 3,047	$ 3,047	$ 3,006	$ 3,100
	2050	$ 3,506	$ 3,506	$ 3,584	$ 3,881
	Cumulative, 2000-2050	$ 125,885	$ 125,705	$ 131,662	$ 136,204
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Uranium Enrichment Services In-country or Imported for Fuel Used in Domestic Reactors (Million 2009 dollars)	2010	$ 1,560	$ 1,560	$ 1,560	$ 1,560
	2030	$ 5,748	$ 5,748	$ 5,906	$ 6,109
	2050	$ 10,873	$ 10,873	$ 11,241	$ 12,164
	Cumulative, 2000-2050	$ 246,982	$ 246,669	$ 261,495	$ 273,175
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Uranium Enrichment Services In-country or Imported for Fuel Used in Domestic Reactors (Million 2009 dollars)	2010	$ 1,560	$ 1,560	$ 1,560	$ 1,560
	2030	$ 1,756	$ 1,756	$ 1,704	$ 1,750
	2050	$ 1,469	$ 1,469	$ 1,473	$ 1,602
	Cumulative, 2000-2050	$ 77,127	$ 77,122	$ 79,488	$ 81,570

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used for Uranium Enrichment In-country for Fuel Used in Domestic Reactors (GWh)	2010	141	141	141	141
	2030	1,268	-	224	231
	2050	1,541	-	205	222
	Cumulative, 2000-2050	42,529	1,837	8,635	8,913
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used for Uranium Enrichment In-country for Fuel Used in Domestic Reactors (GWh)	2010	141	141	141	141
	2030	1,854	-	241	250
	2050	2,810	-	216	233
	Cumulative, 2000-2050	66,499	1,908	9,143	9,453
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used for Uranium Enrichment In-country for Fuel Used in Domestic Reactors (GWh)	2010	141	141	141	141
	2030	900	-	199	204
	2050	987	-	177	192
	Cumulative, 2000-2050	30,033	1,821	7,871	8,108

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used for Uranium Enrichment Out-of-country for Fuel Used in Domestic Reactors (GWh)	2010	5,068	5,068	5,068	5,068
	2030	109	1,377	1,135	1,170
	2050	177	1,719	1,552	1,680
	Cumulative, 2000-2050	118,676	192,044	189,574	191,748
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used for Uranium Enrichment Out-of-country for Fuel Used in Domestic Reactors (GWh)	2010	5,068	5,068	5,068	5,068
	2030	180	2,035	1,849	1,912
	2050	371	3,182	3,074	3,326
	Cumulative, 2000-2050	119,966	231,687	234,060	238,107
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used for Uranium Enrichment Out-of-country for Fuel Used in Domestic Reactors (GWh)	2010	5,068	5,068	5,068	5,068
	2030	36	936	709	728
	2050	34	1,020	846	920
	Cumulative, 2000-2050	107,043	163,034	157,495	158,739

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used for Uranium Enrichment In-country or Out-of-country for Fuel Used in Domestic Reactors (GWh)	2010	5,210	5,210	5,210	5,210
	2030	1,377	1,377	1,358	1,401
	2050	1,719	1,719	1,757	1,903
	Cumulative, 2000-2050	161,205	193,881	198,209	200,661
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used for Uranium Enrichment In-country or Out-of-country for Fuel Used in Domestic Reactors (GWh)	2010	5,210	5,210	5,210	5,210
	2030	2,035	2,035	2,090	2,162
	2050	3,182	3,182	3,289	3,559
	Cumulative, 2000-2050	186,466	233,595	243,202	247,560
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used for Uranium Enrichment In-country or Out-of-country for Fuel Used in Domestic Reactors (GWh)	2010	5,210	5,210	5,210	5,210
	2030	936	936	908	933
	2050	1,020	1,020	1,023	1,113
	Cumulative, 2000-2050	137,076	164,855	165,366	166,847

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Depleted Uranium Produced from Uranium Enrichment In-country for Fuel Used in Domestic Reactors (metric tons U)	2010	3,241	3,241	3,241	3,241
	2030	29,063	-	5,127	5,288
	2050	35,311	-	4,703	5,093
	Cumulative, 2000-2050	974,499	42,145	197,914	204,279
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Depleted Uranium Produced from Uranium Enrichment In-country for Fuel	2010	3,241	3,241	3,241	3,241
	2030	42,484	-	5,531	5,721
	2050	64,391	-	4,940	5,345
	Cumulative, 2000-2050	1,523,714	43,786	209,537	216,654
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Depleted Uranium Produced from Uranium Enrichment In-country for Fuel	2010	3,241	3,241	3,241	3,241
	2030	20,633	-	4,562	4,685
	2050	22,607	-	4,053	4,409
	Cumulative, 2000-2050	688,180	41,783	180,393	185,827

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Depleted Uranium Produced from Uranium Enrichment Out-of-country for Fuel Used in Domestic Reactors (metric tons U)	2010	8,757	8,757	8,757	8,757
	2030	2,491	31,554	25,994	26,809
	2050	4,066	39,377	35,551	38,500
	Cumulative, 2000-2050	330,518	1,261,061	1,166,334	1,209,093
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Depleted Uranium Produced from Uranium Enrichment Out-of-country for Fuel Used in Domestic Reactors (metric tons U)	2010	8,757	8,757	8,757	8,757
	2030	4,132	46,616	42,361	43,817
	2050	8,506	72,897	70,429	76,209
	Cumulative, 2000-2050	384,165	1,861,377	1,813,394	1,891,439
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Depleted Uranium Produced from Uranium Enrichment Out-of-country for Fuel Used in Domestic Reactors (metric tons U)	2010	8,757	8,757	8,757	8,757
	2030	815	21,447	16,250	16,687
	2050	769	23,375	19,383	21,084
	Cumulative, 2000-2050	232,126	878,469	765,290	789,017

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Depleted Uranium Produced from Uranium Enrichment In-country or Out-of-country for Fuel Used in Domestic Reactors (metric tons U)	2010	11,998	11,998	11,998	11,998
	2030	31,554	31,554	31,122	32,097
	2050	39,377	39,377	40,255	43,593
	Cumulative, 2000-2050	1,305,016	1,303,206	1,364,249	1,413,371
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Depleted Uranium Produced from Uranium Enrichment In-country or Out-of-country for Fuel Used in Domestic Reactors (metric tons U)	2010	11,998	11,998	11,998	11,998
	2030	46,616	46,616	47,892	49,538
	2050	72,897	72,897	75,369	81,554
	Cumulative, 2000-2050	1,907,879	1,905,163	2,022,931	2,108,093
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Depleted Uranium Produced from Uranium Enrichment In-country or Out-of-country for Fuel Used in Domestic Reactors (metric tons U)	2010	11,998	11,998	11,998	11,998
	2030	21,447	21,447	20,813	21,372
	2050	23,375	23,375	23,436	25,493
	Cumulative, 2000-2050	920,307	920,251	945,683	974,843

The Nautilus Institute
for Security and Sustainability

FUTURE REGIONAL NUCLEAR FUEL CYCLE COOPERATION IN EAST ASIA: ENERGY SECURITY COSTS AND BENEFITS

Calculations for East Asia Science and Security (EASS) and Related Follow-on (2012-2016) Projects, funded by MacArthur Foundation

Estimates of Fuel Fabrication and Transport Parameters: Summaries for All Regional Scenarios

Prepared by:	David Von Hippel
Last Modified:	3/11/2016

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	398	398	398	398
	2030	3,554	-	626	537
	2050	4,288	-	571	537
	Cumulative, 2000-2050	118,908	5,212	24,198	22,136
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	398	398	398	398
	2030	5,191	-	668	537
	2050	7,809	-	595	537
	Cumulative, 2000-2050	185,766	5,410	25,439	22,230
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	398	398	398	398
	2030	2,527	-	560	537
	2050	2,764	-	497	537
	Cumulative, 2000-2050	84,271	5,169	22,173	22,097

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated Outside the Country for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	1,073	1,073	1,073	1,073
	2030	315	3,869	3,189	3,398
	2050	540	4,828	4,365	4,808
	Cumulative, 2000-2050	41,605	155,078	143,578	151,663
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated Outside the Country for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	1,073	1,073	1,073	1,073
	2030	524	5,716	5,204	5,537
	2050	1,129	8,938	8,646	9,462
	Cumulative, 2000-2050	48,665	228,688	223,099	236,749
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated Outside the Country for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	1,073	1,073	1,073	1,073
	2030	103	2,630	1,992	2,083
	2050	103	2,866	2,376	2,588
	Cumulative, 2000-2050	29,071	108,167	94,281	97,933

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Requirements for UOx Fuel (excluding MOx) from All Sources (Metric tonnes heavy metal in fabricated fuel)	2010	1,471	1,471	1,471	1,471
	2030	3,869	3,869	3,816	3,935
	2050	4,828	4,828	4,936	5,345
	Cumulative, 2000-2050	160,513	160,291	167,775	173,799
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Requirements for UOx Fuel (excluding MOx) from All Sources (Metric tonnes heavy metal in fabricated fuel)	2010	1,471	1,471	1,471	1,471
	2030	5,716	5,716	5,872	6,074
	2050	8,938	8,938	9,241	10,000
	Cumulative, 2000-2050	234,431	234,098	248,538	258,980
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Requirements for UOx Fuel (excluding MOx) from All Sources (Metric tonnes heavy metal in fabricated fuel)	2010	1,471	1,471	1,471	1,471
	2030	2,630	2,630	2,552	2,621
	2050	2,866	2,866	2,874	3,126
	Cumulative, 2000-2050	113,343	113,336	116,454	120,030

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for MOx Fuel Blended and Fabricated In-Country for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	1	1	1	1
	2030	119	-	22	-
	2050	400	-	53	-
	Cumulative, 2000-2050	5,899	11	900	1

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for MOx Fuel Blended and Fabricated In-Country for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	1	1	1	1
	2030	198	-	33	-
	2050	734	-	61	-
	Cumulative, 2000-2050	10,152	19	1,176	1

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for MOx Fuel Blended and Fabricated In-Country for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	1	1	1	1
	2030	69	-	14	-
	2050	252	-	43	-
	Cumulative, 2000-2050	3,572	9	661	1

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for MOx Fuel Blended and Fabricated Out-of-Country for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	4	4	4	4
	2030	0	119	98	-
	2050	0	400	356	-
	Cumulative, 2000-2050	11	5,900	5,130	5
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for MOx Fuel Blended and Fabricated Out-of-Country for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	4	4	4	4
	2030	(0)	198	169	-
	2050	-	734	698	-
	Cumulative, 2000-2050	12	10,144	9,273	5
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for MOx Fuel Blended and Fabricated Out-of-Country for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	4	4	4	4
	2030	(0)	69	54	-
	2050	0	252	209	-
	Cumulative, 2000-2050	10	3,573	2,921	5

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for MOx Fuel Blended and Fabricated from All Sources for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	5	5	5	5
	2030	119	119	120	-
	2050	400	400	409	-
	Cumulative, 2000-2050	5,911	5,910	6,030	7
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for MOx Fuel Blended and Fabricated from All Sources for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	5	5	5	5
	2030	198	198	202	-
	2050	734	734	758	-
	Cumulative, 2000-2050	10,163	10,163	10,448	7
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for MOx Fuel Blended and Fabricated from All Sources for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	5	5	5	5
	2030	69	69	69	-
	2050	252	252	252	-
	Cumulative, 2000-2050	3,582	3,582	3,582	7

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Use of Plutonium for MOx Fuel Blended and Fabricated In-Country for Use in Domestic Reactors (Metric tonnes Pu in fabricated fuel)	2010	0.1	0.1	0.1	0.1
	2030	11.3	-	2.1	-
	2050	38.0	-	5.1	-
	Cumulative, 2000-2050	560.4	1.0	85.5	0.1

		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Plutonium for MOx Fuel Blended and Fabricated In-Country for Use in Domestic Reactors (Metric tonnes Pu in fabricated fuel)	2010	0.1	0.1	0.1	0.1
	2030	18.8	-	3.2	-
	2050	69.8	-	5.8	-
	Cumulative, 2000-2050	964.4	1.8	111.7	0.1

		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Use of Plutonium for MOx Fuel Blended and Fabricated In-Country for Use in Domestic Reactors (Metric tonnes Pu in fabricated fuel)	2010	0.1	0.1	0.1	0.1
	2030	6.5	-	1.3	-
	2050	24.0	-	4.1	-
	Cumulative, 2000-2050	339.4	0.9	62.8	0.1

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Implied Use of Plutonium for MOx Fuel Blended and Fabricated Out-of-Country for Use in Domestic Reactors (Metric tonnes Pu in fabricated fuel)	2010	0.4	0.4	0.4	0.4
	2030	0.0	11.3	9.3	-
	2050	0.0	38.0	33.8	-
	Cumulative, 2000-2050	1	560	487	0
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Use of Plutonium for MOx Fuel Blended and Fabricated Out-of-Country for Use in Domestic Reactors (Metric tonnes Pu in fabricated fuel)	2010	0	0	0	0
	2030	(0)	19	16	-
	2050	-	70	66	-
	Cumulative, 2000-2050	1	964	881	0
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Use of Plutonium for MOx Fuel Blended and Fabricated Out-of-Country for Use in Domestic Reactors (Metric tonnes Pu in fabricated fuel)	2010	0	0	0	0
	2030	(0)	7	5	-
	2050	0	24	20	-
	Cumulative, 2000-2050	1	339	277	0

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Use of Plutonium for MOx Fuel Blended and Fabricated from All Sources for Use in Domestic Reactors (Metric tonnes Pu in fabricated fuel)	2010	0.4	0.4	0.4	0.4
	2030	11.3	11.3	11.4	-
	2050	38.0	38.0	38.9	-
	Cumulative, 2000-2050	562	561	573	0.6
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Use of Plutonium for MOx Fuel Blended and Fabricated from All Sources for Use in Domestic Reactors (Metric tonnes Pu in fabricated fuel)	2010	0	0	0	0
	2030	19	19	19	-
	2050	70	70	72	-
	Cumulative, 2000-2050	966	965	993	1
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Use of Plutonium for MOx Fuel Blended and Fabricated from All Sources for Use in Domestic Reactors (Metric tonnes Pu in fabricated fuel)	2010	0	0	0	0
	2030	7	7	7	-
	2050	24	24	24	-
	Cumulative, 2000-2050	340	340	340	1

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Million dollars)	2010	$ 1.18	$ 1.18	$ 1.18	$ 1.18
	2030	$ 10.84	$ -	$ 1.79	$ 1.48
	2050	$ 12.87	$ -	$ 1.62	$ 1.48
	Cumulative, 2000-2050	$ 360.22	$ 15.39	$ 69.18	$ 61.70
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Million dollars)	2010	$ 1.18	$ 1.18	$ 1.18	$ 1.18
	2030	$ 15.71	$ -	$ 1.94	$ 1.48
	2050	$ 23.22	$ -	$ 1.71	$ 1.48
	Cumulative, 2000-2050	$ 558.95	$ 16.25	$ 73.45	$ 62.02
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Million dollars)	2010	$ 1.18	$ 1.18	$ 1.18	$ 1.18
	2030	$ 7.53	$ -	$ 1.56	$ 1.48
	2050	$ 8.00	$ -	$ 1.37	$ 1.48
	Cumulative, 2000-2050	$ 247.83	$ 15.25	$ 62.21	$ 61.57

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated Out-of-Country for Use in Domestic Reactors (Million dollars)	2010	$ 96.00	$ 44.31	$ 96.00	$ 96.00
	2030	$ 28.16	$ 159.72	$ 285.29	$ 303.96
	2050	$ 48.28	$ 199.32	$ 390.41	$ 430.04
	Cumulative, 2000-2050	$ 3,722	$ 6,402	$ 12,843	$ 13,566

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated Out-of-Country for Use in Domestic Reactors (Million dollars)	2010	$ 96.00	$ 44.31	$ 96.00	$ 96.00
	2030	$ 46.89	$ 235.97	$ 465.48	$ 495.24
	2050	$ 100.96	$ 369.00	$ 773.42	$ 846.38
	Cumulative, 2000-2050	$ 4,353	$ 9,441	$ 19,956	$ 21,177

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated Out-of-Country for Use in Domestic Reactors (Million dollars)	2010	$ 96.00	$ 44.31	$ 96.00	$ 96.00
	2030	$ 9.17	$ 108.57	$ 178.15	$ 186.34
	2050	$ 9.17	$ 118.32	$ 212.57	$ 231.53
	Cumulative, 2000-2050	$ 2,600	$ 4,466	$ 8,433	$ 8,760

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated for Use in Domestic Reactors, All Sources (Million dollars)	2010	$ 97.18	$ 45.49	$ 97.18	$ 97.18
	2030	$ 38.99	$ 159.72	$ 287.08	$ 305.44
	2050	$ 61.16	$ 199.32	$ 392.04	$ 431.52
	Cumulative, 2000-2050	$ 4,082	$ 6,418	$ 12,912	$ 13,628
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated for Use in Domestic Reactors, All Sources (Million dollars)	2010	$ 97.18	$ 45.49	$ 97.18	$ 97.18
	2030	$ 62.61	$ 235.97	$ 467.42	$ 496.72
	2050	$ 124.18	$ 369.00	$ 775.12	$ 847.86
	Cumulative, 2000-2050	$ 4,912	$ 9,457	$ 20,029	$ 21,239
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated for Use in Domestic Reactors, All Sources (Million dollars)	2010	$ 97.18	$ 45.49	$ 97.18	$ 97.18
	2030	$ 16.70	$ 108.57	$ 179.71	$ 187.82
	2050	$ 17.17	$ 118.32	$ 213.94	$ 233.01
	Cumulative, 2000-2050	$ 2,848	$ 4,481	$ 8,496	$ 8,822

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Implied Transport Costs for MOx Fuel for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Million dollars)	2010	$ 0.00	$ 0.00	$ 0.00	$ 0.00
	2030	$ 0.58	$ -	$ 0.10	$ -
	2050	$ 1.79	$ -	$ 0.23	$ -
	Cumulative, 2000-2050	$ 27.31	$ 0.06	$ 4.07	$ 0.01
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for MOx Fuel for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Million dollars)	2010	$ 0.00	$ 0.00	$ 0.00	$ 0.00
	2030	$ 0.96	$ -	$ 0.16	$ -
	2050	$ 3.26	$ -	$ 0.27	$ -
	Cumulative, 2000-2050	$ 46.73	$ 0.10	$ 5.49	$ 0.01
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for MOx Fuel for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Million dollars)	2010	$ 0.00	$ 0.00	$ 0.00	$ 0.00
	2030	$ 0.32	$ -	$ 0.06	$ -
	2050	$ 1.10	$ -	$ 0.18	$ -
	Cumulative, 2000-2050	$ 16.08	$ 0.05	$ 2.84	$ 0.01

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for MOx Fuel for Fuel Enriched and Fabricated Out-of-Country for Use in Domestic Reactors (Million dollars)	2010	$ 0.52	$ 0.24	$ 0.52	$ 0.52
	2030	$ 0.00	$ 7.35	$ 13.11	$ -
	2050	$ 0.00	$ 24.76	$ 47.75	$ -
	Cumulative, 2000-2050	$ 1.51	$ 365.34	$ 688.30	$ 0.69
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for MOx Fuel for Fuel Enriched and Fabricated Out-of-Country for Use in Domestic Reactors (Million dollars)	2010	$ 0.52	$ 0.24	$ 0.52	$ 0.52
	2030	$ (0.00)	$ 12.27	$ 22.62	$ -
	2050	$ -	$ 45.48	$ 93.61	$ -
	Cumulative, 2000-2050	$ 1.59	$ 628.18	$ 1,244.13	$ 0.69
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for MOx Fuel for Fuel Enriched and Fabricated Out-of-Country for Use in Domestic Reactors (Million dollars)	2010	$ 0.52	$ 0.24	$ 0.52	$ 0.52
	2030	$ (0.00)	$ 4.25	$ 7.31	$ -
	2050	$ 0.00	$ 15.61	$ 28.00	$ -
	Cumulative, 2000-2050	$ 1.31	$ 221.24	$ 391.86	$ 0.69

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Implied Transport Costs for MOx Fuel for Fuel Enriched and Fabricated for Use in Domestic Reactors, All Sources (Million dollars)	2010	$ 0.53	$ 0.24	$ 0.53	$ 0.53
	2030	$ 0.58	$ 7.35	$ 13.21	$ -
	2050	$ 1.79	$ 24.76	$ 47.98	$ -
	Cumulative, 2000-2050	$ 28.82	$ 365.39	$ 692.36	$ 0.69

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		MAX Capacity Expansion Paths			
Implied Transport Costs for MOx Fuel for Fuel Enriched and Fabricated for Use in Domestic Reactors, All Sources (Million dollars)	2010	$ 0.53	$ 0.24	$ 0.53	$ 0.53
	2030	$ 0.96	$ 12.27	$ 22.79	$ -
	2050	$ 3.26	$ 45.48	$ 93.88	$ -
	Cumulative, 2000-2050	$ 48.32	$ 628.28	$ 1,249.62	$ 0.69

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		MIN Capacity Expansion Paths			
Implied Transport Costs for MOx Fuel for Fuel Enriched and Fabricated for Use in Domestic Reactors, All Sources (Million dollars)	2010	$ 0.53	$ 0.24	$ 0.53	$ 0.53
	2030	$ 0.32	$ 4.25	$ 7.37	$ -
	2050	$ 1.10	$ 15.61	$ 28.18	$ -
	Cumulative, 2000-2050	$ 17.40	$ 221.29	$ 394.70	$ 0.69

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated In-country (metric tons)	2010	199	199	199	199
	2030	1,777	-	313	269
	2050	2,144	-	286	269
	Cumulative, 2000-2050	59,454	2,606	12,099	11,068
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated In-country (metric tons)	2010	199	199	199	199
	2030	2,596	-	334	269
	2050	3,905	-	297	269
	Cumulative, 2000-2050	92,883	2,705	12,719	11,115
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated In-country (metric tons)	2010	199	199	199	199
	2030	1,264	-	280	269
	2050	1,382	-	249	269
	Cumulative, 2000-2050	42,136	2,585	11,087	11,049

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated Out-of-country (metric tons)	2010	537	537	537	537
	2030	157	1,934	1,595	1,699
	2050	270	2,414	2,182	2,404
	Cumulative, 2000-2050	20,802	77,539	71,789	75,831
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated Out-of-country (metric tons)	2010	537	537	537	537
	2030	262	2,858	2,602	2,768
	2050	564	4,469	4,323	4,731
	Cumulative, 2000-2050	24,333	114,344	111,550	118,375
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated Out-of-country (metric tons)	2010	537	537	537	537
	2030	51	1,315	996	1,042
	2050	51	1,433	1,188	1,294
	Cumulative, 2000-2050	14,536	54,083	47,141	48,966

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated, All Sources (metric tons)	2010	736	736	736	736
	2030	1,934	1,934	1,908	1,968
	2050	2,414	2,414	2,468	2,673
	Cumulative, 2000-2050	80,256	80,145	83,888	86,899
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated, All Sources (metric tons)	2010	736	736	736	736
	2030	2,858	2,858	2,936	3,037
	2050	4,469	4,469	4,621	5,000
	Cumulative, 2000-2050	117,215	117,049	124,269	129,490
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated, All Sources (metric tons)	2010	736	736	736	736
	2030	1,315	1,315	1,276	1,310
	2050	1,433	1,433	1,437	1,563
	Cumulative, 2000-2050	56,671	56,668	58,227	60,015

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated In-country (cubic meters)	2010	3,581	3,581	3,581	3,581
	2030	31,987	-	5,638	4,836
	2050	38,594	-	5,140	4,836
	Cumulative, 2000-2050	1,070,172	46,912	217,778	199,221
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated In-country (cubic meters)	2010	3,581	3,581	3,581	3,581
	2030	46,723	-	6,014	4,836
	2050	70,285	-	5,352	4,836
	Cumulative, 2000-2050	1,671,892	48,691	228,948	200,071
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated In-country (cubic meters)	2010	3,581	3,581	3,581	3,581
	2030	22,745	-	5,043	4,836
	2050	24,872	-	4,474	4,836
	Cumulative, 2000-2050	758,443	46,525	199,560	198,874

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Annual Liquid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated Out-of-country (cubic meters)	2010	9,659	9,659	9,659	9,659
	2030	2,833	34,820	28,705	30,583
	2050	4,858	43,452	39,282	43,269
	Cumulative, 2000-2050	374,444	1,395,706	1,292,202	1,364,966

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		MAX Capacity Expansion Paths			
Annual Liquid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated Out-of-country (cubic meters)	2010	9,659	9,659	9,659	9,659
	2030	4,718	51,441	46,835	49,830
	2050	10,158	80,443	77,818	85,160
	Cumulative, 2000-2050	437,987	2,058,191	2,007,891	2,130,745

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		MIN Capacity Expansion Paths			
Annual Liquid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated Out-of-country (cubic meters)	2010	9,659	9,659	9,659	9,659
	2030	923	23,667	17,924	18,749
	2050	923	25,795	21,388	23,296
	Cumulative, 2000-2050	261,643	973,500	848,529	881,394

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated, All Sources (cubic meters)	2010	13,240	13,240	13,240	13,240
	2030	34,820	34,820	34,343	35,419
	2050	43,452	43,452	44,421	48,105
	Cumulative, 2000-2050	1,444,616	1,442,618	1,509,979	1,564,187
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated, All Sources (cubic meters)	2010	13,240	13,240	13,240	13,240
	2030	51,441	51,441	52,849	54,666
	2050	80,443	80,443	83,170	89,996
	Cumulative, 2000-2050	2,109,879	2,106,882	2,236,839	2,330,816
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated, All Sources (cubic meters)	2010	13,240	13,240	13,240	13,240
	2030	23,667	23,667	22,967	23,585
	2050	25,795	25,795	25,862	28,132
	Cumulative, 2000-2050	1,020,087	1,020,025	1,048,089	1,080,268

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
BAU Capacity Expansion Paths					
Annual Solid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated In-country (metric tons)	2010	0.4	0.4	0.4	0.4
	2030	59.4	-	11.0	-
	2050	199.9	-	26.7	-
	Cumulative, 2000-2050	2,949.7	5.4	449.8	0.7
MAX Capacity Expansion Paths					
Annual Solid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated In-country (metric tons)	2010	0.4	0.4	0.4	0.4
	2030	99.1	-	16.6	-
	2050	367.2	-	30.3	-
	Cumulative, 2000-2050	5,075.8	9.3	587.9	0.7
MIN Capacity Expansion Paths					
Annual Solid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated In-country (metric tons)	2010	0.4	0.4	0.4	0.4
	2030	34.3	-	7.1	-
	2050	126.1	-	21.7	-
	Cumulative, 2000-2050	1,786.1	4.6	330.7	0.7

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
BAU Capacity Expansion Paths					
Annual Solid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated Out-of-country (metric tons)	2010	1.9	1.9	1.9	1.9
	2030	0.0	59.4	48.8	-
	2050	0.0	199.9	177.9	-
	Cumulative, 2000-2050	6	2,950	2,565	3
MAX Capacity Expansion Paths					
Annual Solid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated Out-of-country (metric tons)	2010	2	2	2	2
	2030	(0)	99	84	-
	2050	-	367	349	-
	Cumulative, 2000-2050	6	5,072	4,636	3
MIN Capacity Expansion Paths					
Annual Solid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated Out-of-country (metric tons)	2010	2	2	2	2
	2030	(0)	34	27	-
	2050	0	126	104	-
	Cumulative, 2000-2050	5	1,786	1,460	3

Parameter	YEAR	BAU Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated, All Sources (metric tons)	2010	2.3	2.3	2.3	2.3
	2030	59.4	59.4	59.8	-
	2050	199.9	199.9	204.7	-
	Cumulative, 2000-2050	2,955	2,955	3,015	3.3

Parameter	YEAR	MAX Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated, All Sources (metric tons)	2010	2	2	2	2
	2030	99	99	101	-
	2050	367	367	379	-
	Cumulative, 2000-2050	5,082	5,081	5,224	3

Parameter	YEAR	MIN Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated, All Sources (metric tons)	2010	2	2	2	2
	2030	34	34	34	-
	2050	126	126	126	-
	Cumulative, 2000-2050	1,791	1,791	1,791	3

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	BAU Capacity Expansion Paths				
Annual Liquid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated In-country (cubic meters)	2010	7	7	7	7
	2030	1,069	-	197	-
	2050	3,599	-	481	-
	Cumulative, 2000-2050	53,095	97	8,097	13
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated In-country (cubic meters)	2010	7.0	7.0	7.0	7.0
	2030	1,783.9	-	298.9	-
	2050	6,609.3	-	546.2	-
	Cumulative, 2000-2050	91,364.4	168.1	10,583.0	13.1
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated In-country (cubic meters)	2010	7.0	7.0	7.0	7.0
	2030	617.7	-	127.5	-
	2050	2,269.4	-	391.3	-
	Cumulative, 2000-2050	32,150.0	83.4	5,952.7	13.1

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	BAU Capacity Expansion Paths				
Annual Liquid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated Out-of-country (cubic meters)	2010	35	35	35	35
	2030	0	1,069	879	-
	2050	0	3,599	3,203	-
	Cumulative, 2000-2050	101	53,096	46,169	46
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated Out-of-country (cubic meters)	2010	35	35	35	35
	2030	(0)	1,784	1,517	-
	2050	-	6,609	6,279	-
	Cumulative, 2000-2050	107	91,297	83,453	46
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated Out-of-country (cubic meters)	2010	35	35	35	35
	2030	(0)	618	490	-
	2050	0	2,269	1,878	-
	Cumulative, 2000-2050	88	32,155	26,285	46

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated, All Sources (cubic meters)	2010	42	42	42	42
	2030	1,069	1,069	1,076	-
	2050	3,599	3,599	3,684	-
	Cumulative, 2000-2050	53,196	53,193	54,267	59
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated, All Sources (cubic meters)	2010	42	42	42	42
	2030	1,784	1,784	1,816	-
	2050	6,609	6,609	6,826	-
	Cumulative, 2000-2050	91,471	91,465	94,036	59
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated, All Sources (cubic meters)	2010	42	42	42	42
	2030	618	618	618	-
	2050	2,269	2,269	2,269	-
	Cumulative, 2000-2050	32,238	32,238	32,238	59

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Million dollars)	2010	$ 108	$ 108	$ 108	$ 108
	2030	$ 968	$ -	$ 171	$ 146
	2050	$ 1,168	$ -	$ 155	$ 146
	Cumulative, 2000-2050	$ 32,375	$ 1,419	$ 6,588	$ 6,027
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Million dollars)	2010	$ 108	$ 108	$ 108	$ 108
	2030	$ 1,413	$ -	$ 182	$ 146
	2050	$ 2,126	$ -	$ 162	$ 146
	Cumulative, 2000-2050	$ 50,578	$ 1,473	$ 6,926	$ 6,053
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Million dollars)	2010	$ 108	$ 108	$ 108	$ 108
	2030	$ 688	$ -	$ 153	$ 146
	2050	$ 752	$ -	$ 135	$ 146
	Cumulative, 2000-2050	$ 22,945	$ 1,407	$ 6,037	$ 6,016

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated Out-of-Country for Use in Domestic Reactors (Million dollars)	2010	$ 292	$ 292	$ 292	$ 292
	2030	$ 86	$ 1,053	$ 868	$ 925
	2050	$ 147	$ 1,315	$ 1,188	$ 1,309
	Cumulative, 2000-2050	$ 11,328	$ 42,223	$ 39,092	$ 41,293
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated Out-of-Country for Use in Domestic Reactors (Million dollars)	2010	$ 292	$ 292	$ 292	$ 292
	2030	$ 143	$ 1,556	$ 1,417	$ 1,507
	2050	$ 307	$ 2,434	$ 2,354	$ 2,576
	Cumulative, 2000-2050	$ 13,250	$ 62,265	$ 60,743	$ 64,460
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated Out-of-Country for Use in Domestic Reactors (Million dollars)	2010	$ 292	$ 292	$ 292	$ 292
	2030	$ 28	$ 716	$ 542	$ 567
	2050	$ 28	$ 780	$ 647	$ 705
	Cumulative, 2000-2050	$ 7,915	$ 29,450	$ 25,670	$ 26,664

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated, All Sources, for Use in Domestic Reactors (Million dollars)	2010	$ 401	$ 401	$ 401	$ 401
	2030	$ 1,053	$ 1,053	$ 1,039	$ 1,072
	2050	$ 1,315	$ 1,315	$ 1,344	$ 1,455
	Cumulative, 2000-2050	$ 43,703	$ 43,642	$ 45,680	$ 47,320

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated, All Sources, for Use in Domestic Reactors (Million dollars)	2010	$ 401	$ 401	$ 401	$ 401
	2030	$ 1,556	$ 1,556	$ 1,599	$ 1,654
	2050	$ 2,434	$ 2,434	$ 2,516	$ 2,723
	Cumulative, 2000-2050	$ 63,828	$ 63,738	$ 67,669	$ 70,512

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated, All Sources, for Use in Domestic Reactors (Million dollars)	2010	$ 401	$ 401	$ 401	$ 401
	2030	$ 716	$ 716	$ 695	$ 713
	2050	$ 780	$ 780	$ 782	$ 851
	Cumulative, 2000-2050	$ 30,860	$ 30,858	$ 31,707	$ 32,680

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for MOx Fuel for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Million dollars)	2010	$ 1.4	$ 1.4	$ 1.4	$ 1.4
	2030	$ 214	$ -	$ 39	$ -
	2050	$ 720	$ -	$ 96	$ -
	Cumulative, 2000-2050	$ 10,619	$ 19	$ 1,619	$ 2.6

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for MOx Fuel for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Million dollars)	2010	$ 1.4	$ 1.4	$ 1.4	$ 1.4
	2030	$ 357	$ -	$ 60	$ -
	2050	$ 1,322	$ -	$ 109	$ -
	Cumulative, 2000-2050	$ 18,273	$ 34	$ 2,117	$ 3

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for MOx Fuel for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Million dollars)	2010	$ 1.4	$ 1.4	$ 1.4	$ 1.4
	2030	$ 124	$ -	$ 25	$ -
	2050	$ 454	$ -	$ 78	$ -
	Cumulative, 2000-2050	$ 6,430	$ 17	$ 1,191	$ 3

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for MOx Fuel for Fuel Enriched and Fabricated Out-of-Country for Use in Domestic Reactors (Million dollars)	2010	$ 7.0	$ 7.0	$ 7.0	$ 7.0
	2030	$ 0	$ 214	$ 176	$ -
	2050	$ 0	$ 720	$ 641	$ -
	Cumulative, 2000-2050	$ 20	$ 10,619	$ 9,234	$ 9
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for MOx Fuel for Fuel Enriched and Fabricated Out-of-Country for Use in Domestic Reactors (Million dollars)	2010	7	7	7	7
	2030	(0)	357	303	-
	2050	-	1,322	1,256	-
	Cumulative, 2000-2050	21	18,259	16,691	9
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for MOx Fuel for Fuel Enriched and Fabricated Out-of-Country for Use in Domestic Reactors (Million dollars)	2010	7	7	7	7
	2030	(0)	124	98	-
	2050	0	454	376	-
	Cumulative, 2000-2050	18	6,431	5,257	9

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for MOx Fuel, All Sources, for Use in Domestic Reactors (Million dollars)	2010	$ 8	$ 8	$ 8	$ 8
	2030	$ 214	$ 214	$ 215	$ -
	2050	$ 720	$ 720	$ 737	$ -
	Cumulative, 2000-2050	$ 10,639	$ 10,639	$ 10,853	$ 12

		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for MOx Fuel, All Sources, for Use in Domestic Reactors (Million dollars)	2010	$ 8	$ 8	$ 8	$ 8
	2030	$ 357	$ 357	$ 363	$ -
	2050	$ 1,322	$ 1,322	$ 1,365	$ -
	Cumulative, 2000-2050	$ 18,294	$ 18,293	$ 18,807	$ 12

		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for MOx Fuel, All Sources, for Use in Domestic Reactors (Million dollars)	2010	$ 8	$ 8	$ 8	$ 8
	2030	$ 124	$ 124	$ 124	$ -
	2050	$ 454	$ 454	$ 454	$ -
	Cumulative, 2000-2050	$ 6,448	$ 6,448	$ 6,448	$ 12

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating UOx Fuel for Fuel Enriched and Fabricated In-country (TJ)	2010	1,078	1,078	1,078	1,078
	2030	9,628	-	1,697	1,456
	2050	11,617	-	1,547	1,456
	Cumulative, 2000-2050	322,122	14,121	65,551	59,965
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating UOx Fuel for Fuel Enriched and Fabricated In-country (TJ)	2010	1,078	1,078	1,078	1,078
	2030	14,064	-	1,810	1,456
	2050	21,156	-	1,611	1,456
	Cumulative, 2000-2050	503,239	14,656	68,913	60,221
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating UOx Fuel for Fuel Enriched and Fabricated In-country (TJ)	2010	1,078	1,078	1,078	1,078
	2030	6,846	-	1,518	1,456
	2050	7,486	-	1,347	1,456
	Cumulative, 2000-2050	228,291	14,004	60,068	59,861

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating UOx Fuel for Fuel Enriched and Fabricated Out-of-country (TJ)	2010	2,907	2,907	2,907	2,907
	2030	853	10,481	8,640	9,206
	2050	1,462	13,079	11,824	13,024
	Cumulative, 2000-2050	112,708	420,107	388,953	410,855
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating UOx Fuel for Fuel Enriched and Fabricated Out-of-country (TJ)	2010	2,907	2,907	2,907	2,907
	2030	1,420	15,484	14,097	14,999
	2050	3,057	24,213	23,423	25,633
	Cumulative, 2000-2050	131,834	619,516	604,375	641,354
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating UOx Fuel for Fuel Enriched and Fabricated Out-of-country (TJ)	2010	2,907	2,907	2,907	2,907
	2030	278	7,124	5,395	5,643
	2050	278	7,764	6,438	7,012
	Cumulative, 2000-2050	78,755	293,024	255,407	265,300

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating UOx Fuel, All Sources (TJ)	2010	3,985	3,985	3,985	3,985
	2030	10,481	10,481	10,337	10,661
	2050	13,079	13,079	13,371	14,480
	Cumulative, 2000-2050	434,830	434,228	454,504	470,820
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating UOx Fuel, All Sources (TJ)	2010	3,985	3,985	3,985	3,985
	2030	15,484	15,484	15,908	16,454
	2050	24,213	24,213	25,034	27,089
	Cumulative, 2000-2050	635,074	634,171	673,289	701,576
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating UOx Fuel, All Sources (TJ)	2010	3,985	3,985	3,985	3,985
	2030	7,124	7,124	6,913	7,099
	2050	7,764	7,764	7,785	8,468
	Cumulative, 2000-2050	307,046	307,028	315,475	325,161

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating UOx Fuel for Fuel Enriched and Fabricated In-country (GWh)	2010	120	120	120	120
	2030	1,069	-	189	162
	2050	1,290	-	172	162
	Cumulative, 2000-2050	35,779	1,568	7,281	6,661
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating UOx Fuel for Fuel Enriched and Fabricated In-country (GWh)	2010	120	120	120	120
	2030	1,562	-	201	162
	2050	2,350	-	179	162
	Cumulative, 2000-2050	55,897	1,628	7,654	6,689
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating UOx Fuel for Fuel Enriched and Fabricated In-country (GWh)	2010	120	120	120	120
	2030	760	-	169	162
	2050	832	-	150	162
	Cumulative, 2000-2050	25,357	1,555	6,672	6,649

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating UOx Fuel for Fuel Enriched and Fabricated Out-of-country (GWh)	2010	323	323	323	323
	2030	95	1,164	960	1,023
	2050	162	1,453	1,313	1,447
	Cumulative, 2000-2050	12,519	46,663	43,203	45,635
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating UOx Fuel for Fuel Enriched and Fabricated Out-of-country (GWh)	2010	323	323	323	323
	2030	158	1,720	1,566	1,666
	2050	340	2,689	2,602	2,847
	Cumulative, 2000-2050	14,643	68,812	67,131	71,238
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating UOx Fuel for Fuel Enriched and Fabricated Out-of-country (GWh)	2010	323	323	323	323
	2030	31	791	599	627
	2050	31	862	715	779
	Cumulative, 2000-2050	8,748	32,547	28,369	29,468

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating UOx Fuel for Fuel Enriched and Fabricated, All Sources (GWh)	2010	443	443	443	443
	2030	1,164	1,164	1,148	1,184
	2050	1,453	1,453	1,485	1,608
	Cumulative, 2000-2050	48,298	48,232	50,484	52,296
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating UOx Fuel for Fuel Enriched and Fabricated, All Sources (GWh)	2010	443	443	443	443
	2030	1,720	1,720	1,767	1,828
	2050	2,689	2,689	2,781	3,009
	Cumulative, 2000-2050	70,540	70,440	74,785	77,927
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating UOx Fuel for Fuel Enriched and Fabricated, All Sources (GWh)	2010	443	443	443	443
	2030	791	791	768	789
	2050	862	862	865	941
	Cumulative, 2000-2050	34,105	34,103	35,041	36,117

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating MOx Fuel for Fuel Enriched and Fabricated In-country (TJ)	2010	2.1	2.1	2.1	2.1
	2030	321.7	-	59.4	-
	2050	1,083.2	-	144.8	-
	Cumulative, 2000-2050	15,981.5	29.1	2,437.2	3.9
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating MOx Fuel for Fuel Enriched and Fabricated In-country (TJ)	2010	2.1	2.1	2.1	2.1
	2030	536.9	-	90.0	-
	2050	1,989.4	-	164.4	-
	Cumulative, 2000-2050	27,500.7	50.6	3,185.5	3.9
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating MOx Fuel for Fuel Enriched and Fabricated In-country (TJ)	2010	2.1	2.1	2.1	2.1
	2030	185.9	-	38.4	-
	2050	683.1	-	117.8	-
	Cumulative, 2000-2050	9,677.1	25.1	1,791.8	3.9

Parameter	YEAR	BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating MOx Fuel for Fuel Enriched and Fabricated Out-of-country (TJ)	2010	10.5	10.5	10.5	10.5
	2030	0.0	321.7	264.6	-
	2050	0.0	1,083.2	964.0	-
	Cumulative, 2000-2050	30.5	15,982.0	13,897.0	13.9
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating MOx Fuel for Fuel Enriched and Fabricated Out-of-country (TJ)	2010	10.5	10.5	10.5	10.5
	2030	(0.0)	536.9	456.8	-
	2050	-	1,989.4	1,890.1	-
	Cumulative, 2000-2050	32.1	27,480.4	25,119.3	13.9
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating MOx Fuel for Fuel Enriched and Fabricated Out-of-country (TJ)	2010	10.5	10.5	10.5	10.5
	2030	(0.0)	185.9	147.6	-
	2050	0.0	683.1	565.3	-
	Cumulative, 2000-2050	26.6	9,678.5	7,911.8	13.9

Parameter	YEAR	BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating MOx Fuel, All Sources (TJ)	2010	13	13	13	13
	2030	322	322	324	-
	2050	1,083	1,083	1,109	-
	Cumulative, 2000-2050	16,012	16,011	16,334	18
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating MOx Fuel, All Sources (TJ)	2010	13	13	13	13
	2030	537	537	547	-
	2050	1,989	1,989	2,055	-
	Cumulative, 2000-2050	27,533	27,531	28,305	18
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating MOx Fuel, All Sources (TJ)	2010	13	13	13	13
	2030	186	186	186	-
	2050	683	683	683	-
	Cumulative, 2000-2050	9,704	9,704	9,704	18

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating MOx Fuel for Fuel Enriched and Fabricated In-country (GWh)	2010	0	0	0	0
	2030	36	-	7	-
	2050	120	-	16	-
	Cumulative, 2000-2050	1,775	3	271	0
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating MOx Fuel for Fuel Enriched and Fabricated In-country (GWh)	2010	0	0	0	0
	2030	60	-	10	-
	2050	221	-	18	-
	Cumulative, 2000-2050	3,055	6	354	0
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating MOx Fuel for Fuel Enriched and Fabricated In-country (GWh)	2010	0	0	0	0
	2030	21	-	4	-
	2050	76	-	13	-
	Cumulative, 2000-2050	1,075	3	199	0

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating MOx Fuel for Fuel Enriched and Fabricated Out-of-country (GWh)	2010	1.2	1.2	1.2	1.2
	2030	0.0	35.7	29.4	-
	2050	0.0	120.3	107.1	-
	Cumulative, 2000-2050	3.4	1,775.2	1,543.6	1.5
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating MOx Fuel for Fuel Enriched and Fabricated Out-of-country (GWh)	2010	1.2	1.2	1.2	1.2
	2030	(0.0)	59.6	50.7	-
	2050	-	221.0	209.9	-
	Cumulative, 2000-2050	3.6	3,052.4	2,790.1	1.5
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating MOx Fuel for Fuel Enriched and Fabricated Out-of-country (GWh)	2010	1	1	1	1
	2030	(0)	21	16	-
	2050	0	76	63	-
	Cumulative, 2000-2050	3	1,075	879	2

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating MOx Fuel from All Sources (GWh)	2010	1	1	1	1
	2030	36	36	36	-
	2050	120	120	123	-
	Cumulative, 2000-2050	1,779	1,778	1,814	2
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating MOx Fuel from All Sources (GWh)	2010	1	1	1	1
	2030	60	60	61	-
	2050	221	221	228	-
	Cumulative, 2000-2050	3,058	3,058	3,144	2
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating MOx Fuel from All Sources (GWh)	2010	1	1	1	1
	2030	21	21	21	-
	2050	76	76	76	-
	Cumulative, 2000-2050	1,078	1,078	1,078	2

The Nautilus Institute
for Security and Sustainability

FUTURE REGIONAL NUCLEAR FUEL CYCLE COOPERATION IN EAST ASIA: ENERGY SECURITY COSTS AND BENEFITS

Calculations for East Asia Science and Security (EASS) and Related Follow-on (2012-2016) Projects, funded by MacArthur Foundation

Estimates of Reprocessing and Spent Fuel Managment Parameters: Summaries for All Regional Scenarios

Prepared by:	David Von Hippel
Last Modified:	3/11/2016

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual New Spent LWR Fuel Cooled and Available for Reprocessing, Storage, or Disposal (excluding MOx spent fuel), Metric Tonnes Heavy Metal	2010	1,071	1,071	1,071	1,071
	2030	2,366	2,366	2,366	2,382
	2050	4,125	4,125	4,118	4,413
	Cumulative, 2000-2050	103,095	105,115	105,061	108,219

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual New Spent LWR Fuel Cooled and Available for Reprocessing, Storage, or Disposal (excluding MOx spent fuel), Metric Tonnes Heavy Metal	2010	1,071	1,071	1,071	1,071
	2030	2,865	2,865	2,865	2,904
	2050	6,486	6,486	6,472	6,963
	Cumulative, 2000-2050	134,513	136,533	136,419	141,674

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Spent MOx Fuel Cooled and Available for Storage or Disposal, Metric Tonnes Heavy Metal	2010	-	-	-	-
	2030	17	17	17	-
	2050	289	289	295	-
	Cumulative, 2000-2050	3,111	3,111	3,165	7
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Spent MOx Fuel Cooled and Available for Storage or Disposal, Metric Tonnes Heavy Metal	2010	-	-	-	-
	2030	39	39	39	-
	2050	478	478	492	-
	Cumulative, 2000-2050	5,148	5,148	5,262	7
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Spent MOx Fuel Cooled and Available for Storage or Disposal, Metric Tonnes Heavy Metal	2010	-	-	-	-
	2030	14	14	14	-
	2050	165	165	165	-
	Cumulative, 2000-2050	1,879	1,879	1,879	7

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Amount of Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (Metric tonnes heavy metal; based on annual amount of newly-cooled spent fuel available by year)	2010	1	1	1	1
	2030	1,603	241	241	-
	2050	2,340	-	-	-
	Cumulative, 2000-2050	49,153	4,212	4,212	609
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Amount of Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (Metric tonnes heavy metal; based on annual amount of newly-cooled spent fuel available by year)	2010	1	1	1	1
	2030	2,375	375	375	-
	2050	4,497	-	-	-
	Cumulative, 2000-2050	84,646	7,570	7,570	609
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Amount of Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (Metric tonnes heavy metal; based on annual amount of newly-cooled spent fuel available by year)	2010	1	1	1	1
	2030	1,018	-	-	-
	2050	1,439	-	-	-
	Cumulative, 2000-2050	28,799	609	609	609

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Amount of Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (Metric tonnes heavy metal; based on annual amount of newly-cooled spent fuel available by year)	2010	-	-	-	-
	2030	-	1,374	1,448	-
	2050	-	2,505	2,501	-
	Cumulative, 2000-2050	1,189	46,274	46,537	1,189
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Amount of Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (Metric tonnes heavy metal; based on annual amount of newly-cooled spent fuel available by year)	2010	-	-	-	-
	2030	-	2,011	2,101	-
	2050	-	4,691	4,683	-
	Cumulative, 2000-2050	1,189	77,886	78,117	1,189
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Amount of Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (Metric tonnes heavy metal; based on annual amount of newly-cooled spent fuel available by year)	2010	-	-	-	-
	2030	-	908	1,071	-
	2050	-	1,304	1,484	-
	Cumulative, 2000-2050	1,189	26,176	29,687	1,189

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Amount of Spent LWR Fuel (UOx only) Reprocessed in Total for Use in Domestic Reactors (Metric tonnes heavy metal)	2010	1	1	1	1
	2030	1,603	1,615	1,689	-
	2050	2,340	2,505	2,501	-
	Cumulative, 2000-2050	50,342	50,486	50,749	1,798

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Amount of Spent LWR Fuel (UOx only) Reprocessed in Total for Use in Domestic Reactors (Metric tonnes heavy metal)	2010	1	1	1	1
	2030	2,375	2,385	2,476	-
	2050	4,497	4,691	4,683	-
	Cumulative, 2000-2050	85,835	85,456	85,687	1,798

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Amount of Spent LWR Fuel (UOx only) Reprocessed in Total for Use in Domestic Reactors (Metric tonnes heavy metal)	2010	1	1	1	1
	2030	1,018	908	1,071	-
	2050	1,439	1,304	1,484	-
	Cumulative, 2000-2050	29,988	26,785	30,296	1,798

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (Million dollars)	2010	$ 0.10	$ 0.10	$ 0.10	$ 0.10
	2030	$ 80.96	$ 4.76	$ 4.76	$ -
	2050	$ 133.53	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 2,511	$ 83	$ 83	$ 12

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (Million dollars)	2010	$ 0.10	$ 0.10	$ 0.10	$ 0.10
	2030	$ 127.55	$ 7.40	$ 7.40	$ -
	2050	$ 286.41	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 4,794	$ 150	$ 150	$ 12

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (Million dollars)	2010	$ 0.10	$ 0.10	$ 0.10	$ 0.10
	2030	$ 61.86	$ -	$ -	$ -
	2050	$ 93.04	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 1,772	$ 12	$ 12	$ 12

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 271.35	$ 743.61	$ -
	2050	$ -	$ 494.64	$ 1,284.17	$ -
	Cumulative, 2000-2050	$ 611	$ 9,139	$ 23,897	$ 611

		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 397.10	$ 1,078.74	$ -
	2050	$ -	$ 926.57	$ 2,404.76	$ -
	Cumulative, 2000-2050	$ 611	$ 15,383	$ 40,113	$ 611

		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 179.31	$ 549.82	$ -
	2050	$ -	$ 257.50	$ 762.14	$ -
	Cumulative, 2000-2050	$ 611	$ 5,170	$ 15,244	$ 611

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (Million dollars)	2010	$ 0.10	$ 0.10	$ 0.10	$ 0.10
	2030	$ 80.96	$ 276.11	$ 748.36	$ -
	2050	$ 133.53	$ 494.64	$ 1,284.17	$ -
	Cumulative, 2000-2050	$ 3,122	$ 9,222	$ 23,980	$ 623
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (Million dollars)	2010	$ 0.10	$ 0.10	$ 0.10	$ 0.10
	2030	$ 127.55	$ 404.50	$ 1,086.14	$ -
	2050	$ 286.41	$ 926.57	$ 2,404.76	$ -
	Cumulative, 2000-2050	$ 5,404	$ 15,532	$ 40,263	$ 623
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (Million dollars)	2010	$ 0.10	$ 0.10	$ 0.10	$ 0.10
	2030	$ 61.86	$ 179.31	$ 549.82	$ -
	2050	$ 93.04	$ 257.50	$ 762.14	$ -
	Cumulative, 2000-2050	$ 2,383	$ 5,182	$ 15,257	$ 623

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Number of Ocean Voyages Annually for Transport of Cooled Spent LWR Fuel (UOx only) to In-country Reprocessing Centers	2010	-	-	-	-
	2030	5.70	1.79	1.79	-
	2050	6.36	-	-	-
	Cumulative, 2000-2050	170.63	31.37	31.37	4.53
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Number of Ocean Voyages Annually for Transport of Cooled Spent LWR Fuel (UOx only) to In-country Reprocessing Centers	2010	-	-	-	-
	2030	7	3	3	-
	2050	8	-	-	-
	Cumulative, 2000-2050	235	56	56	5
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Number of Ocean Voyages Annually for Transport of Cooled Spent LWR Fuel (UOx only) to In-country Reprocessing Centers	2010	-	-	-	-
	2030	2	-	-	-
	2050	3	-	-	-
	Cumulative, 2000-2050	64	5	5	5

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Number of Ocean Voyages Annually for Transport of Cooled Spent LWR Fuel (UOx only) to Out-of-country Reprocessing Centers	2010	-	-	-	-
	2030	-	10.23	10.79	-
	2050	-	18.66	18.63	-
	Cumulative, 2000-2050	8.86	344.68	346.64	8.86
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Number of Ocean Voyages Annually for Transport of Cooled Spent LWR Fuel (UOx only) to Out-of-country Reprocessing Centers	2010	-	-	-	-
	2030	-	14.98	15.65	-
	2050	-	34.95	34.88	-
	Cumulative, 2000-2050	8.86	580.16	581.88	8.86
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Number of Ocean Voyages Annually for Transport of Cooled Spent LWR Fuel (UOx only) to Out-of-country Reprocessing Centers	2010	-	-	-	-
	2030	-	6.76	7.98	-
	2050	-	9.71	11.06	-
	Cumulative, 2000-2050	8.86	194.98	221.14	8.86

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Number of Ocean Voyages Annually for Transport of Cooled Spent LWR Fuel (UOx only) to All Reprocessing Centers	2010	-	-	-	-
	2030	5.7	12.0	12.6	-
	2050	6.4	18.7	18.6	-
	Cumulative, 2000-2050	179.5	376.1	378.0	13.4

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Number of Ocean Voyages Annually for Transport of Cooled Spent LWR Fuel (UOx only) to All Reprocessing Centers	2010	-	-	-	-
	2030	7.5	17.8	18.4	-
	2050	8.3	34.9	34.9	-
	Cumulative, 2000-2050	244.0	636.5	638.3	13.4

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Number of Ocean Voyages Annually for Transport of Cooled Spent LWR Fuel (UOx only) to All Reprocessing Centers	2010	-	-	-	-
	2030	2.4	6.8	8.0	-
	2050	2.6	9.7	11.1	-
	Cumulative, 2000-2050	72.8	199.5	225.7	13.4

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (Million dollars)	2010	$ 2	$ 2	$ 2	$ 2
	2030	$ 2,891	$ 819	$ 819	$ -
	2050	$ 3,776	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 89,361	$ 14,320	$ 14,320	$ 2,068
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (Million dollars)	2010	$ 2	$ 2	$ 2	$ 2
	2030	$ 4,345	$ 1,274	$ 1,274	$ -
	2050	$ 6,892	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 150,560	$ 25,736	$ 25,736	$ 2,068
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (Million dollars)	2010	$ 2	$ 2	$ 2	$ 2
	2030	$ 1,222	$ -	$ -	$ -
	2050	$ 1,727	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 35,896	$ 2,068	$ 2,068	$ 2,068

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 1,649	$ 1,738	$ -
	2050	$ -	$ 3,005	$ 3,001	$ -
	Cumulative, 2000-2050	$ 1,427	$ 55,529	$ 55,844	$ 1,427

		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 2,413	$ 2,521	$ -
	2050	$ -	$ 5,630	$ 5,620	$ -
	Cumulative, 2000-2050	$ 1,427	$ 93,463	$ 93,740	$ 1,427

		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 1,090	$ 1,285	$ -
	2050	$ -	$ 1,565	$ 1,781	$ -
	Cumulative, 2000-2050	$ 1,427	$ 31,412	$ 35,625	$ 1,427

Parameter	YEAR	BAU Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Use in Domestic Reactors (Million dollars)	2010	$ 2	$ 2	$ 2	$ 2
	2030	$ 2,891	$ 2,468	$ 2,557	$ -
	2050	$ 3,776	$ 3,005	$ 3,001	$ -
	Cumulative, 2000-2050	$ 90,788	$ 69,848	$ 70,164	$ 3,495

Parameter	YEAR	MAX Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Use in Domestic Reactors (Million dollars)	2010	$ 2	$ 2	$ 2	$ 2
	2030	$ 4,345	$ 3,687	$ 3,795	$ -
	2050	$ 6,892	$ 5,630	$ 5,620	$ -
	Cumulative, 2000-2050	$ 151,987	$ 119,199	$ 119,476	$ 3,495

Parameter	YEAR	MIN Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Use in Domestic Reactors (Million dollars)	2010	$ 2	$ 2	$ 2	$ 2
	2030	$ 1,222	$ 1,090	$ 1,285	$ -
	2050	$ 1,727	$ 1,565	$ 1,781	$ -
	Cumulative, 2000-2050	$ 37,322	$ 33,480	$ 37,693	$ 3,495

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of High-level Waste (as vitrified) from Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (cubic meters)	2010	0	0	0	0
	2030	184	28	28	-
	2050	269	-	-	-
	Cumulative, 2000-2050	5,653	484	484	70
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of High-level Waste (as vitrified) from Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (cubic meters)	2010	0	0	0	0
	2030	273	43	43	-
	2050	517	-	-	-
	Cumulative, 2000-2050	9,734	871	871	70
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of High-level Waste (as vitrified) from Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (cubic meters)	2010	0	0	0	0
	2030	117	-	-	-
	2050	165	-	-	-
	Cumulative, 2000-2050	3,312	70	70	70

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of High-level Waste (as vitrified) from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (cubic meters)	2010	-	-	-	-
	2030	-	158	167	-
	2050	-	288	288	-
	Cumulative, 2000-2050	137	5,321	5,352	137

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of High-level Waste (as vitrified) from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (cubic meters)	2010	-	-	-	-
	2030	-	231	242	-
	2050	-	540	539	-
	Cumulative, 2000-2050	137	8,957	8,983	137

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of High-level Waste (as vitrified) from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (cubic meters)	2010	-	-	-	-
	2030	-	104	123	-
	2050	-	150	171	-
	Cumulative, 2000-2050	137	3,010	3,414	137

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of High-level Waste (as vitrified) from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	0	0	0	0
	2030	184	186	194	-
	2050	269	288	288	-
	Cumulative, 2000-2050	5,789	5,806	5,836	207
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of High-level Waste (as vitrified) from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	0	0	0	0
	2030	273	274	285	-
	2050	517	540	539	-
	Cumulative, 2000-2050	9,871	9,827	9,854	207
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of High-level Waste (as vitrified) from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	0	0	0	0
	2030	117	104	123	-
	2050	165	150	171	-
	Cumulative, 2000-2050	3,449	3,080	3,484	207

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of High-level Wastes from Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 240	$ 36	$ 36	$ -
	2050	$ 351	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 7,373	$ 632	$ 632	$ 91

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of High-level Wastes from Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 356	$ 56	$ 56	$ -
	2050	$ 674	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 12,697	$ 1,136	$ 1,136	$ 91

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of High-level Wastes from Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 153	$ -	$ -	$ -
	2050	$ 216	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 4,320	$ 91	$ 91	$ 91

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of High-level Wastes from Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 206	$ 217	$ -
	2050	$ -	$ 376	$ 375	$ -
	Cumulative, 2000-2050	$ 178	$ 6,941	$ 6,980	$ 178

		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of High-level Wastes from Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 302	$ 315	$ -
	2050	$ -	$ 704	$ 702	$ -
	Cumulative, 2000-2050	$ 178	$ 11,683	$ 11,718	$ 178

		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of High-level Wastes from Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 136	$ 161	$ -
	2050	$ -	$ 196	$ 223	$ -
	Cumulative, 2000-2050	$ 178	$ 3,926	$ 4,453	$ 178

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of High-level Wastes from All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Use in Domestic Reactors (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 240	$ 242	$ 253	$ -
	2050	$ 351	$ 376	$ 375	$ -
	Cumulative, 2000-2050	$ 7,551	$ 7,573	$ 7,612	$ 270
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of High-level Wastes from All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Use in Domestic Reactors (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 356	$ 358	$ 371	$ -
	2050	$ 674	$ 704	$ 702	$ -
	Cumulative, 2000-2050	$ 12,875	$ 12,818	$ 12,853	$ 270
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of High-level Wastes from All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Use in Domestic Reactors (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 153	$ 136	$ 161	$ -
	2050	$ 216	$ 196	$ 223	$ -
	Cumulative, 2000-2050	$ 4,498	$ 4,018	$ 4,544	$ 270

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Electricity Use for Treatment of High-level Wastes from Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (GWh)	2010	0.0	0.0	0.0	0.0
	2030	5.5	0.8	0.8	-
	2050	8.1	-	-	-
	Cumulative, 2000-2050	169.6	14.5	14.5	2.1

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Electricity Use for Treatment of High-level Wastes from Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (GWh)	2010	0.0	0.0	0.0	0.0
	2030	8.2	1.3	1.3	-
	2050	15.5	-	-	-
	Cumulative, 2000-2050	292.0	26.1	26.1	2.1

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Electricity Use for Treatment of High-level Wastes from Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (GWh)	2010	0.0	0.0	0.0	0.0
	2030	3.5	-	-	-
	2050	5.0	-	-	-
	Cumulative, 2000-2050	99.4	2.1	2.1	2.1

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Electricity Use for Treatment of High-level Wastes from Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (GWh)	2010	-	-	-	-
	2030	-	4.7	5.0	-
	2050	-	8.6	8.6	-
	Cumulative, 2000-2050	4.1	159.6	160.6	4.1

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Electricity Use for Treatment of High-level Wastes from Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (GWh)	2010	-	-	-	-
	2030	-	6.9	7.2	-
	2050	-	16.2	16.2	-
	Cumulative, 2000-2050	4.1	268.7	269.5	4.1

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Electricity Use for Treatment of High-level Wastes from Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (GWh)	2010	-	-	-	-
	2030	-	3.1	3.7	-
	2050	-	4.5	5.1	-
	Cumulative, 2000-2050	4.1	90.3	102.4	4.1

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Electricity Use for Treatment of High-level Wastes from All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Use in Domestic Reactors (GWh)	2010	0.0	0.0	0.0	0.0
	2030	5.5	5.6	5.8	-
	2050	8.1	8.6	8.6	-
	Cumulative, 2000-2050	173.7	174.2	175.1	6.2
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Electricity Use for Treatment of High-level Wastes from All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Use in Domestic Reactors (GWh)	2010	0.0	0.0	0.0	0.0
	2030	8.2	8.2	8.5	-
	2050	15.5	16.2	16.2	-
	Cumulative, 2000-2050	296.1	294.8	295.6	6.2
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Electricity Use for Treatment of High-level Wastes from All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Use in Domestic Reactors (GWh)	2010	0.0	0.0	0.0	0.0
	2030	3.5	3.1	3.7	-
	2050	5.0	4.5	5.1	-
	Cumulative, 2000-2050	103.5	92.4	104.5	6.2

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Medium-level Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (cubic meters)	2010	0	0	0	0
	2030	321	48	48	-
	2050	468	-	-	-
	Cumulative, 2000-2050	9,831	842	842	122
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Medium-level Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (cubic meters)	2010	0.3	0.3	0.3	0.3
	2030	474.9	75.0	75.0	-
	2050	899.3	-	-	-
	Cumulative, 2000-2050	16,929.3	1,514.0	1,514.0	121.8
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Medium-level Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (cubic meters)	2010	0.3	0.3	0.3	0.3
	2030	203.6	-	-	-
	2050	287.8	-	-	-
	Cumulative, 2000-2050	5,759.7	121.8	121.8	121.8

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Medium-level Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (cubic meters)	2010	-	-	-	-
	2030	-	275	290	-
	2050	-	501	500	-
	Cumulative, 2000-2050	238	9,255	9,307	238
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Medium-level Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (cubic meters)	2010	-	-	-	-
	2030	-	402	420	-
	2050	-	938	937	-
	Cumulative, 2000-2050	238	15,577	15,623	238
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Medium-level Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (cubic meters)	2010	-	-	-	-
	2030	-	182	214	-
	2050	-	261	297	-
	Cumulative, 2000-2050	238	5,235	5,937	238

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Medium-level Waste from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	0	0	0	0
	2030	321	323	338	-
	2050	468	501	500	-
	Cumulative, 2000-2050	10,068	10,097	10,150	360
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Medium-level Waste from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	0	0	0	0
	2030	475	477	495	-
	2050	899	938	937	-
	Cumulative, 2000-2050	17,167	17,091	17,137	360
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Medium-level Waste from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	0	0	0	0
	2030	204	182	214	-
	2050	288	261	297	-
	Cumulative, 2000-2050	5,998	5,357	6,059	360

Parameter	YEAR	BAU Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Low-level Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (cubic meters)	2010	2	2	2	2
	2030	2,244	337	337	-
	2050	3,276	-	-	-
	Cumulative, 2000-2050	68,814	5,897	5,897	853

Parameter	YEAR	MAX Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Low-level Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (cubic meters)	2010	2	2	2	2
	2030	3,324	525	525	-
	2050	6,295	-	-	-
	Cumulative, 2000-2050	118,505	10,598	10,598	853

Parameter	YEAR	MIN Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Low-level Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (cubic meters)	2010	2	2	2	2
	2030	1,425	-	-	-
	2050	2,014	-	-	-
	Cumulative, 2000-2050	40,318	853	853	853

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Low-level Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (cubic meters)	2010	-	-	-	-
	2030	-	1,924	2,027	-
	2050	-	3,506	3,501	-
	Cumulative, 2000-2050	1,665	64,783	65,151	1,665

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Low-level Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (cubic meters)	2010	-	-	-	-
	2030	-	2,815	2,941	-
	2050	-	6,568	6,556	-
	Cumulative, 2000-2050	1,665	109,041	109,364	1,665

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Low-level Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (cubic meters)	2010	-	-	-	-
	2030	-	1,271	1,499	-
	2050	-	1,825	2,078	-
	Cumulative, 2000-2050	1,665	36,647	41,562	1,665

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Low-level Waste from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	2	2	2	2
	2030	2,244	2,261	2,365	-
	2050	3,276	3,506	3,501	-
	Cumulative, 2000-2050	70,479	70,681	71,049	2,517

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Low-level Waste from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	2	2	2	2
	2030	3,324	3,340	3,466	-
	2050	6,295	6,568	6,556	-
	Cumulative, 2000-2050	120,169	119,639	119,962	2,517

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Low-level Waste from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	2	2	2	2
	2030	1,425	1,271	1,499	-
	2050	2,014	1,825	2,078	-
	Cumulative, 2000-2050	41,983	37,500	42,415	2,517

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Solid Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (cubic meters)	2010	0	0	0	0
	2030	240	36	36	-
	2050	351	-	-	-
	Cumulative, 2000-2050	7,373	632	632	91
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Solid Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (cubic meters)	2010	0	0	0	0
	2030	356	56	56	-
	2050	674	-	-	-
	Cumulative, 2000-2050	12,697	1,136	1,136	91
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Solid Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (cubic meters)	2010	0	0	0	0
	2030	153	-	-	-
	2050	216	-	-	-
	Cumulative, 2000-2050	4,320	91	91	91

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Solid Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (cubic meters)	2010	-	-	-	-
	2030	-	206	217	-
	2050	-	376	375	-
	Cumulative, 2000-2050	178	6,941	6,980	178

		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Solid Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (cubic meters)	2010	-	-	-	-
	2030	-	302	315	-
	2050	-	704	702	-
	Cumulative, 2000-2050	178	11,683	11,718	178

		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Solid Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (cubic meters)	2010	-	-	-	-
	2030	-	136	161	-
	2050	-	196	223	-
	Cumulative, 2000-2050	178	3,926	4,453	178

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Solid Waste from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	0	0	0	0
	2030	240	242	253	-
	2050	351	376	375	-
	Cumulative, 2000-2050	7,551	7,573	7,612	270
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Solid Waste from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	0	0	0	0
	2030	356	358	371	-
	2050	674	704	702	-
	Cumulative, 2000-2050	12,875	12,818	12,853	270
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Solid Waste from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	0	0	0	0
	2030	153	136	161	-
	2050	216	196	223	-
	Cumulative, 2000-2050	4,498	4,018	4,544	270

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from Cooled Spent LWR Fuel (UOx only) Reprocessed in Domestic Plants, Less Plutonium Used to make MOx Fuel (metric tonnes heavy metal)	2010	(0.06)	(0.06)	(0.06)	(0.06)
	2030	6.35	2.65	0.57	-
	2050	(12.25)	-	(5.08)	-
	Cumulative, 2000-2050	(19.76)	45.32	(39.13)	6.56

		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from Cooled Spent LWR Fuel (UOx only) Reprocessed in Domestic Plants, Less Plutonium Used to make MOx Fuel (metric tonnes heavy metal)	2010	(0)	(0)	(0)	(0)
	2030	7	4	1	-
	2050	(20)	-	(6)	-
	Cumulative, 2000-2050	(33)	81	(28)	7

		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from Cooled Spent LWR Fuel (UOx only) Reprocessed in Domestic Plants, Less Plutonium Used to make MOx Fuel (metric tonnes heavy metal)	2010	(0)	(0)	(0)	(0)
	2030	5	-	(1)	-
	2050	(8)	-	(4)	-
	Cumulative, 2000-2050	(23)	6	(56)	7

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally, Less Plutonium Used to make MOx Fuel (metric tonnes heavy metal)	2010	(0.37)	(0.37)	(0.37)	(0.37)
	2030	(0.00)	3.83	6.65	-
	2050	(0.00)	(10.44)	(6.30)	-
	Cumulative, 2000-2050	12.01	(51.45)	24.56	12.59

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally, Less Plutonium Used to make MOx Fuel (metric tonnes heavy metal)	2010	(0)	(0)	(0)	(0)
	2030	0	3	7	-
	2050	-	(18)	(15)	-
	Cumulative, 2000-2050	12	(107)	(22)	13

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally, Less Plutonium Used to make MOx Fuel (metric tonnes heavy metal)	2010	(0)	(0)	(0)	(0)
	2030	0	3	7	-
	2050	(0)	(10)	(3)	-
	Cumulative, 2000-2050	12	(51)	49	13

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from All Cooled Spent LWR Fuel (UOx only) Reprocessed, Less Plutonium Used to make MOx Fuel (metric tonnes heavy metal)	2010	(0.43)	(0.43)	(0.43)	(0.43)
	2030	6.35	6.48	7.22	-
	2050	(12.25)	(10.44)	(11.37)	-
	Cumulative, 2000-2050	(7.75)	(6.13)	(14.57)	19.15

		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from All Cooled Spent LWR Fuel (UOx only) Reprocessed, Less Plutonium Used to make MOx Fuel (metric tonnes heavy metal)	2010	(0)	(0)	(0)	(0)
	2030	7	7	8	-
	2050	(20)	(18)	(21)	-
	Cumulative, 2000-2050	(21)	(25)	(50)	19

		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from All Cooled Spent LWR Fuel (UOx only) Reprocessed, Less Plutonium Used to make MOx Fuel (metric tonnes heavy metal)	2010	(0)	(0)	(0)	(0)
	2030	5	3	5	-
	2050	(8)	(10)	(8)	-
	Cumulative, 2000-2050	(10)	(46)	(7)	19

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from Cooled Spent LWR Fuel (UOx only) Reprocessed in Domestic Plants (metric tonnes heavy metal)	2010	0.01	0.01	0.01	0.01
	2030	17.63	2.65	2.65	-
	2050	25.74	-	-	-
	Cumulative, 2000-2050	540.68	46.34	46.34	6.70
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from Cooled Spent LWR Fuel (UOx only) Reprocessed in Domestic Plants (metric tonnes heavy metal)	2010	0.01	0.01	0.01	0.01
	2030	26.12	4.12	4.12	-
	2050	49.46	-	-	-
	Cumulative, 2000-2050	931.11	83.27	83.27	6.70
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from Cooled Spent LWR Fuel (UOx only) Reprocessed in Domestic Plants (metric tonnes heavy metal)	2010	0.01	0.01	0.01	0.01
	2030	11.20	-	-	-
	2050	15.83	-	-	-
	Cumulative, 2000-2050	316.78	6.70	6.70	6.70

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally (metric tonnes heavy metal)	2010	-	-	-	-
	2030	-	15.11	15.93	-
	2050	-	27.55	27.51	-
	Cumulative, 2000-2050	13.08	509.01	511.90	13.08
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally (metric tonnes heavy metal)	2010	-	-	-	-
	2030	-	22	23	-
	2050	-	52	52	-
	Cumulative, 2000-2050	13	857	859	13
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally (metric tonnes heavy metal)	2010	-	-	-	-
	2030	-	10	12	-
	2050	-	14	16	-
	Cumulative, 2000-2050	13	288	327	13

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from All Cooled Spent LWR Fuel (UOx only) Reprocessed (metric tonnes heavy metal)	2010	0.01	0.01	0.01	0.01
	2030	17.63	17.76	18.58	-
	2050	25.74	27.55	27.51	-
	Cumulative, 2000-2050	553.76	555.35	558.24	19.78
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from All Cooled Spent LWR Fuel (UOx only) Reprocessed (metric tonnes heavy metal)	2010	0	0	0	0
	2030	26	26	27	-
	2050	49	52	52	-
	Cumulative, 2000-2050	944	940	943	20
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from All Cooled Spent LWR Fuel (UOx only) Reprocessed (metric tonnes heavy metal)	2010	0	0	0	0
	2030	11	10	12	-
	2050	16	14	16	-
	Cumulative, 2000-2050	330	295	333	20

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost/Benefit of Storage/ safeguarding/ disposal of Plutonium from Reprocessing Operations (fraction not used as MOx) (Million dollars)	2010	$ 160	$ 160	$ 160	$ 160
	2030	$ 263	$ 239	$ 241	$ 159
	2050	$ 79	$ 84	$ 58	$ 159
	Cumulative, 2000-2050	$ 10,371	$ 9,772	$ 9,660	$ 7,949
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost/Benefit of Storage/ safeguarding/ disposal of Plutonium from Reprocessing Operations (fraction not used as MOx) (Million dollars)	2010	$ 160	$ 160	$ 160	$ 160
	2030	$ 286	$ 263	$ 264	$ 159
	2050	$ 38	$ 26	$ (48)	$ 159
	Cumulative, 2000-2050	$ 11,679	$ 10,832	$ 10,356	$ 7,949
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost/Benefit of Storage/ safeguarding/ disposal of Plutonium from Reprocessing Operations (fraction not used as MOx) (Million dollars)	2010	$ 160	$ 160	$ 160	$ 160
	2030	$ 161	$ 126	$ 139	$ 159
	2050	$ 71	$ (35)	$ 81	$ 159
	Cumulative, 2000-2050	$ 8,146	$ 6,643	$ 7,986	$ 7,949

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost of Disposal of High-level Wastes from Reprocessing Operations (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 240	$ 242	$ 253	$ -
	2050	$ 351	$ 376	$ 375	$ -
	Cumulative, 2000-2050	$ 8,015	$ 8,037	$ 8,076	$ 733
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost of Disposal of High-level Wastes from Reprocessing Operations (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 356	$ 358	$ 371	$ -
	2050	$ 674	$ 704	$ 702	$ -
	Cumulative, 2000-2050	$ 13,339	$ 13,282	$ 13,317	$ 733
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost of Disposal of High-level Wastes from Reprocessing Operations (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 153	$ 136	$ 161	$ -
	2050	$ 216	$ 196	$ 223	$ -
	Cumulative, 2000-2050	$ 4,962	$ 4,481	$ 5,008	$ 733

(Note: Includes in 2000 value costs for HLW stocks accumulated by Japan by 2000, mostly from fuel reprocessed internationally)

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Implied Mass of Uranium Separated during Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Domestically for Domestic Reactors (metric tonnes)	2010	1	1	1	1
	2030	1,507	226	226	-
	2050	2,200	-	-	-
	Cumulative, 2000-2050	46,204	3,960	3,960	573

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Implied Mass of Uranium Separated during Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Domestically for Domestic Reactors (metric tonnes)	2010	1	1	1	1
	2030	2,232	352	352	-
	2050	4,227	-	-	-
	Cumulative, 2000-2050	79,567	7,116	7,116	573

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Implied Mass of Uranium Separated during Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Domestically for Domestic Reactors (metric tonnes)	2010	1	1	1	1
	2030	957	-	-	-
	2050	1,353	-	-	-
	Cumulative, 2000-2050	27,071	573	573	573

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Implied Mass of Uranium Separated during Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Domestic Reactors (metric tonnes)	2010	-	-	-	-
	2030	-	1,292	1,361	-
	2050	-	2,354	2,351	-
	Cumulative, 2000-2050	1,118	43,497	43,744	1,118

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Implied Mass of Uranium Separated during Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Domestic Reactors (metric tonnes)	2010	-	-	-	-
	2030	-	1,890.0	1,974.7	-
	2050	-	4,410.0	4,402.1	-
	Cumulative, 2000-2050	1,117.7	73,213.0	73,429.8	1,117.7

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Implied Mass of Uranium Separated during Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Domestic Reactors (metric tonnes)	2010	-	-	-	-
	2030	-	853	1,006	-
	2050	-	1,226	1,395	-
	Cumulative, 2000-2050	1,118	24,606	27,906	1,118

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Implied Mass of Uranium Separated during All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Domestic Reactors (metric tonnes)	2010	1	1	1	1
	2030	1,507	1,518	1,588	-
	2050	2,200	2,354	2,351	-
	Cumulative, 2000-2050	47,322	47,457	47,704	1,690

		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Implied Mass of Uranium Separated during All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Domestic Reactors (metric tonnes)	2010	1	1	1	1
	2030	2,232	2,242	2,327	-
	2050	4,227	4,410	4,402	-
	Cumulative, 2000-2050	80,685	80,329	80,546	1,690

		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Implied Mass of Uranium Separated during All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Domestic Reactors (metric tonnes)	2010	1	1	1	1
	2030	957	853	1,006	-
	2050	1,353	1,226	1,395	-
	Cumulative, 2000-2050	28,188	25,178	28,479	1,690

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Number of Casks Required for Dry Cask Storage of Cooled Spent LWR Fuel (UOx only) for Storage/Disposal, Net of Reprocessing (units)	2010	28	107	107	107
	2030	56	75	68	238
	2050	130	162	162	441
	Cumulative, 2000-2050	2,571	5,463	5,431	10,642

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Number of Casks Required for Dry Cask Storage of Cooled Spent LWR Fuel (UOx only) for Storage/Disposal, Net of Reprocessing (units)	2010	28	107	107	107
	2030	56	48	39	290
	2050	148	179	179	696
	Cumulative, 2000-2050	1,955	5,108	5,073	13,988

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Number of Casks Required for Dry Cask Storage of Cooled Spent LWR Fuel (UOx only) for Storage/Disposal, Net of Reprocessing (units)	2010	28	107	107	107
	2030	57	112	95	204
	2050	75	138	120	285
	Cumulative, 2000-2050	3,051	5,718	5,367	8,404

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Number of Casks Required for Dry Cask Storage of Cooled Spent LWR MOx Fuel for Storage/Disposal (units)	2010	-	-	-	-
	2030	2	2	2	-
	2050	29	29	29	-
	Cumulative, 2000-2050	311	311	317	1
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Number of Casks Required for Dry Cask Storage of Cooled Spent LWR MOx Fuel for Storage/Disposal (units)	2010	-	-	-	-
	2030	3.9	3.9	3.9	-
	2050	47.8	47.8	49.2	-
	Cumulative, 2000-2050	514.8	514.8	526.2	0.7
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Number of Casks Required for Dry Cask Storage of Cooled Spent LWR MOx Fuel for Storage/Disposal (units)	2010	-	-	-	-
	2030	1	1	1	-
	2050	16	16	16	-
	Cumulative, 2000-2050	188	188	188	1

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Number of Casks Required for Cooled Spent LWR Fuel, UOx and MOx, for Domestic Reactors (units)	2010	28	107	107	107
	2030	57	77	69	238
	2050	159	191	191	441
	Cumulative, 2000-2050	2,882	5,774	5,748	10,643
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Number of Casks Required for Cooled Spent LWR Fuel, UOx and MOx, for Domestic Reactors (units)	2010	28	107	107	107
	2030	59	52	43	290
	2050	196	227	228	696
	Cumulative, 2000-2050	2,470	5,622	5,599	13,988
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Number of Casks Required for Cooled Spent LWR Fuel, UOx and MOx, for Domestic Reactors (units)	2010	28	107	107	107
	2030	58	113	97	204
	2050	92	155	137	285
	Cumulative, 2000-2050	3,239	5,906	5,555	8,404

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost of Casks Required for Dry Cask Storage of Cooled Spent LWR Fuel (UOx only) for Storage/Disposal, Not Including Spent Fuel Reprocessed Domestically or Internationally (Million dollars)	2010	$ 23	$ 86	$ 86	$ 86
	2030	$ 44	$ 60	$ 54	$ 191
	2050	$ 104	$ 130	$ 129	$ 353
	Cumulative, 2000-2050	$ 2,057	$ 4,370	$ 4,345	$ 8,514
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost of Casks Required for Dry Cask Storage of Cooled Spent LWR Fuel (UOx only) for Storage/Disposal, Not Including Spent Fuel Reprocessed Domestically or Internationally (Million dollars)	2010	$ 23	$ 86	$ 86	$ 86
	2030	$ 44	$ 38	$ 31	$ 232
	2050	$ 118	$ 144	$ 143	$ 557
	Cumulative, 2000-2050	$ 1,564	$ 4,086	$ 4,059	$ 11,190
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost of Casks Required for Dry Cask Storage of Cooled Spent LWR Fuel (UOx only) for Storage/Disposal, Not Including Spent Fuel Reprocessed Domestically or Internationally (Million dollars)	2010	$ 23	$ 86	$ 86	$ 86
	2030	$ 45	$ 89	$ 76	$ 163
	2050	$ 60	$ 111	$ 96	$ 228
	Cumulative, 2000-2050	$ 2,441	$ 4,574	$ 4,293	$ 6,723

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost of Casks Required for Dry Cask Storage of Cooled Spent LWR MOx Fuel for Storage/Disposal (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 1.33	$ 1.33	$ 1.33	$ -
	2050	$ 23.09	$ 23.09	$ 23.58	$ -
	Cumulative, 2000-2050	$ 248.88	$ 248.85	$ 253.20	$ 0.53
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost of Casks Required for Dry Cask Storage of Cooled Spent LWR MOx Fuel for Storage/Disposal (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 3.13	$ 3.13	$ 3.13	$ -
	2050	$ 38.22	$ 38.22	$ 39.34	$ -
	Cumulative, 2000-2050	$ 411.87	$ 411.82	$ 420.98	$ 0.53
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost of Casks Required for Dry Cask Storage of Cooled Spent LWR MOx Fuel for Storage/Disposal (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 1.16	$ 1.16	$ 1.16	$ -
	2050	$ 13.18	$ 13.18	$ 13.18	$ -
	Cumulative, 2000-2050	$ 150.32	$ 150.32	$ 150.32	$ 0.53

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost of Casks Required for Dry Cask Storage of Cooled Spent LWR UOx and MOx Fuel for Storage/Disposal (Million dollars)	2010	$ 23	$ 86	$ 86	$ 86
	2030	$ 46	$ 61	$ 55	$ 191
	2050	$ 127	$ 153	$ 153	$ 353
	Cumulative, 2000-2050	$ 2,306	$ 4,619	$ 4,598	$ 8,514
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost of Casks Required for Dry Cask Storage of Cooled Spent LWR UOx and MOx Fuel for Storage/Disposal (Million dollars)	2010	23	86	86	86
	2030	48	41	34	232
	2050	157	182	182	557
	Cumulative, 2000-2050	1,976	4,498	4,480	11,191
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost of Casks Required for Dry Cask Storage of Cooled Spent LWR UOx and MOx Fuel for Storage/Disposal (Million dollars)	2010	23	86	86	86
	2030	47	91	77	163
	2050	73	124	110	228
	Cumulative, 2000-2050	2,591	4,725	4,444	6,724

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Operating and Maintenance Cost for Casks Required for Dry Cask Storage of Cooled Spent LWR Fuel (UOx only) for Storage/Disposal Beyond Spent Fuel Pool Capacity, Not Including Spent Fuel Reprocessed Domestically or Internationally (Million dollars)	2010	$ 1	$ 9	$ 9	$ 9
	2030	$ 13	$ 28	$ 28	$ 35
	2050	$ 32	$ 55	$ 54	$ 106
	Cumulative, 2000-2050	$ 579	$ 1,250	$ 1,244	$ 1,851

		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Operating and Maintenance Cost for Casks Required for Dry Cask Storage of Cooled Spent LWR Fuel (UOx only) for Storage/Disposal Beyond Spent Fuel Pool Capacity, Not Including Spent Fuel Reprocessed Domestically or Internationally (Million	2010	$ 1	$ 9	$ 9	$ 9
	2030	$ 13	$ 24	$ 24	$ 36
	2050	$ 26	$ 51	$ 51	$ 140
	Cumulative, 2000-2050	$ 516	$ 1,137	$ 1,131	$ 2,152

		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Operating and Maintenance Cost for Casks Required for Dry Cask Storage of Cooled Spent LWR Fuel (UOx only) for Storage/Disposal Beyond Spent Fuel Pool Capacity, Not Including Spent Fuel Reprocessed Domestically or Internationally (Million	2010	$ 1	$ 9	$ 9	$ 9
	2030	$ 20	$ 32	$ 31	$ 34
	2050	$ 51	$ 57	$ 54	$ 84
	Cumulative, 2000-2050	$ 908	$ 1,351	$ 1,310	$ 1,643

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Total Annual Operating and Maintenance Cost for Casks Required for Dry Cask Storage of Cooled Spent LWR MOx Fuel for Storage/Disposal (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 0.06	$ 0.06	$ 0.06	$ 0.01
	2050	$ 3.11	$ 3.11	$ 3.17	$ 0.01
	Cumulative, 2000-2050	$ 23.87	$ 23.86	$ 24.19	$ 0.21

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		MAX Capacity Expansion Paths			
Total Annual Operating and Maintenance Cost for Casks Required for Dry Cask Storage of Cooled Spent LWR MOx Fuel for Storage/Disposal (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 0.11	$ 0.11	$ 0.11	$ 0.01
	2050	$ 5.15	$ 5.15	$ 5.26	$ 0.01
	Cumulative, 2000-2050	$ 40.63	$ 40.62	$ 41.26	$ 0.21

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		MIN Capacity Expansion Paths			
Total Annual Operating and Maintenance Cost for Casks Required for Dry Cask Storage of Cooled Spent LWR MOx Fuel for Storage/Disposal (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 0.06	$ 0.06	$ 0.06	$ 0.01
	2050	$ 1.88	$ 1.88	$ 1.88	$ 0.01
	Cumulative, 2000-2050	$ 14.79	$ 14.79	$ 14.79	$ 0.21

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Operating and Maintenance Cost for Casks Required for Dry Cask Storage of All Cooled Spent LWR Fuel for Storage/Disposal (Million dollars)	2010	$ 1	$ 9	$ 9	$ 9
	2030	$ 13	$ 28	$ 28	$ 35
	2050	$ 36	$ 58	$ 57	$ 106
	Cumulative, 2000-2050	$ 602	$ 1,274	$ 1,268	$ 1,852

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Operating and Maintenance Cost for Casks Required for Dry Cask Storage of All Cooled Spent LWR Fuel for Storage/Disposal (Million dollars)	2010	$ 1	$ 9	$ 9	$ 9
	2030	$ 13	$ 24	$ 24	$ 36
	2050	$ 31	$ 56	$ 56	$ 140
	Cumulative, 2000-2050	$ 556	$ 1,177	$ 1,172	$ 2,152

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Operating and Maintenance Cost for Casks Required for Dry Cask Storage of All Cooled Spent LWR Fuel for Storage/Disposal (Million dollars)	2010	$ 1	$ 9	$ 9	$ 9
	2030	$ 20	$ 32	$ 31	$ 34
	2050	$ 53	$ 59	$ 56	$ 84
	Cumulative, 2000-2050	$ 923	$ 1,366	$ 1,325	$ 1,644

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Storage/Disposal of Cooled Spent LWR Fuel (UOx only), Not Including Spent Fuel Reprocessed Domestically or Internationally (Million dollars)	2010	$ 102	$ 385	$ 385	$ 284
	2030	$ 153	$ 270	$ 244	$ 290
	2050	$ 372	$ 583	$ 582	$ 625
	Cumulative, 2000-2050	$ 7,572	$ 19,666	$ 19,552	$ 16,455
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Storage/Disposal of Cooled Spent LWR Fuel (UOx only), Not Including Spent Fuel Reprocessed Domestically or Internationally (Million dollars)	2010	$ 24	$ 385	$ 385	$ 284
	2030	$ 58	$ 173	$ 140	$ 381
	2050	$ 334	$ 646	$ 644	$ 932
	Cumulative, 2000-2050	$ 2,978	$ 18,388	$ 18,263	$ 21,068
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Storage/Disposal of Cooled Spent LWR Fuel (UOx only), Not Including Spent Fuel Reprocessed Domestically or Internationally (Million dollars)	2010	$ 102	$ 385	$ 385	$ 284
	2030	$ 126	$ 402	$ 343	$ 252
	2050	$ 264	$ 498	$ 433	$ 353
	Cumulative, 2000-2050	$ 7,266	$ 20,584	$ 19,320	$ 12,988

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Storage/Disposal of Cooled Spent MOx Fuel (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 1	$ 6	$ 6	$ -
	2050	$ 87	$ 104	$ 106	$ -
	Cumulative, 2000-2050	$ 784	$ 1,120	$ 1,139	$ 2
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Storage/Disposal of Cooled Spent MOx Fuel (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 3	$ 14	$ 14	$ -
	2050	$ 122	$ 172	$ 177	$ -
	Cumulative, 2000-2050	$ 1,057	$ 1,853	$ 1,894	$ 2
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Storage/Disposal of Cooled Spent MOx Fuel (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 1	$ 5	$ 5	$ -
	2050	$ 58	$ 59	$ 59	$ -
	Cumulative, 2000-2050	$ 547	$ 676	$ 676	$ 2

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Storage/Disposal of All Cooled Spent Fuel (Million dollars)	2010	$ 102	$ 385	$ 385	$ 284
	2030	$ 154	$ 276	$ 250	$ 290
	2050	$ 459	$ 687	$ 688	$ 625
	Cumulative, 2000-2050	$ 8,356	$ 20,786	$ 20,692	$ 16,458
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Storage/Disposal of All Cooled Spent Fuel (Million dollars)	2010	$ 24	$ 385	$ 385	$ 284
	2030	$ 61	$ 187	$ 154	$ 381
	2050	$ 456	$ 818	$ 821	$ 932
	Cumulative, 2000-2050	$ 4,035	$ 20,241	$ 20,158	$ 21,070
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Storage/Disposal of All Cooled Spent Fuel (Million dollars)	2010	$ 102	$ 385	$ 385	$ 284
	2030	$ 128	$ 407	$ 349	$ 252
	2050	$ 323	$ 558	$ 493	$ 353
	Cumulative, 2000-2050	$ 7,813	$ 21,261	$ 19,997	$ 12,990

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Total Annual Implied Operating and Maintenance Costs of Storing Cooled Spent LWR Fuel (UOx only) Remaining in Spent Fuel Pools (Million dollars)	2010	$ 91	$ 74	$ 74	$ 74
	2030	$ 215	$ 74	$ 74	$ 74
	2050	$ 335	$ 74	$ 74	$ 74
	Cumulative, 2000-2050	$ 9,561	$ 3,790	$ 3,790	$ 3,790
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Implied Operating and Maintenance Costs of Storing Cooled Spent LWR Fuel (UOx only) Remaining in Spent Fuel Pools (Million dollars)	2010	$ 91	$ 74	$ 74	$ 74
	2030	$ 170	$ 74	$ 74	$ 74
	2050	$ 396	$ 74	$ 74	$ 74
	Cumulative, 2000-2050	$ 9,412	$ 3,790	$ 3,790	$ 3,790
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Implied Operating and Maintenance Costs of Storing Cooled Spent LWR Fuel (UOx only) Remaining in Spent Fuel Pools (Million dollars)	2010	$ 91	$ 74	$ 74	$ 74
	2030	$ 226	$ 74	$ 74	$ 74
	2050	$ 270	$ 74	$ 74	$ 74
	Cumulative, 2000-2050	$ 9,044	$ 3,790	$ 3,790	$ 3,790

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Total Annual Implied Operating and Maintenance Costs of Storing Cooled Spent LWR Fuel (MOx only) Remaining in Spent Fuel Pools (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 1	$ 1	$ 1	$ 0
	2050	$ 73	$ 73	$ 74	$ 0
	Cumulative, 2000-2050	$ 559	$ 559	$ 566	$ 5
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Implied Operating and Maintenance Costs of Storing Cooled Spent LWR Fuel (MOx only) Remaining in Spent Fuel Pools (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 3	$ 3	$ 3	$ 0
	2050	$ 121	$ 121	$ 123	$ 0
	Cumulative, 2000-2050	$ 951	$ 951	$ 966	$ 5
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Implied Operating and Maintenance Costs of Storing Cooled Spent LWR Fuel (MOx only) Remaining in Spent Fuel Pools (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 1	$ 1	$ 1	$ 0
	2050	$ 44	$ 44	$ 44	$ 0
	Cumulative, 2000-2050	$ 346	$ 346	$ 346	$ 5

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Operating and Maintenance Cost of Spent Fuel Pool Storage of All Cooled Fuel after Other Storage/Disposal Implemented (Million dollars)	2010	$ 91	$ 74	$ 74	$ 74
	2030	$ 217	$ 76	$ 76	$ 74
	2050	$ 408	$ 147	$ 148	$ 74
	Cumulative, 2000-2050	$ 10,120	$ 4,348	$ 4,356	$ 3,795

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Operating and Maintenance Cost of Spent Fuel Pool Storage of All Cooled Fuel after Other Storage/Disposal Implemented (Million dollars)	2010	$ 91	$ 74	$ 74	$ 74
	2030	$ 173	$ 77	$ 77	$ 74
	2050	$ 517	$ 195	$ 198	$ 74
	Cumulative, 2000-2050	$ 10,363	$ 4,741	$ 4,756	$ 3,795

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Operating and Maintenance Cost of Spent Fuel Pool Storage of All Cooled Fuel after Other Storage/Disposal Implemented (Million dollars)	2010	$ 91	$ 74	$ 74	$ 74
	2030	$ 228	$ 76	$ 76	$ 74
	2050	$ 314	$ 118	$ 118	$ 74
	Cumulative, 2000-2050	$ 9,391	$ 4,136	$ 4,136	$ 3,795

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Transport to Storage/Disposal for LWR Fuel (UOx only), Not Including Spent Fuel Reprocessed Domestically or Internationally (Million dollars)	2010	$ 6	$ 127	$ 127	$ 14
	2030	$ 7	$ 112	$ 103	$ 7
	2050	$ 64	$ 195	$ 192	$ 23
	Cumulative, 2000-2050	$ 912	$ 6,865	$ 6,790	$ 595
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Transport to Storage/Disposal for LWR Fuel (UOx only), Not Including Spent Fuel Reprocessed Domestically or Internationally (Million dollars)	2010	$ 0	$ 127	$ 127	$ 14
	2030	$ -	$ 93	$ 81	$ 12
	2050	$ 56	$ 218	$ 212	$ 37
	Cumulative, 2000-2050	$ 285	$ 6,805	$ 6,690	$ 836
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Transport to Storage/Disposal for LWR Fuel (UOx only), Not Including Spent Fuel Reprocessed Domestically or Internationally (Million dollars)	2010	$ 6	$ 127	$ 127	$ 14
	2030	$ 5	$ 133	$ 113	$ 6
	2050	$ 40	$ 164	$ 143	$ 6
	Cumulative, 2000-2050	$ 757	$ 6,787	$ 6,360	$ 401

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Transport to Storage/Disposal for Cooled Spent MOx Fuel (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 2.0	$ 2.0	$ -
	2050	$ 13.9	$ 34.2	$ 34.9	$ -
	Cumulative, 2000-2050	$ 113.1	$ 368.6	$ 375.1	$ 0.1
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Transport to Storage/Disposal for Cooled Spent MOx Fuel (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 4.6	$ 4.6	$ -
	2050	$ 22.8	$ 56.6	$ 58.3	$ -
	Cumulative, 2000-2050	$ 174.1	$ 610.0	$ 623.6	$ 0.1
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Transport to Storage/Disposal for Cooled Spent MOx Fuel (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 1.7	$ 1.7	$ -
	2050	$ 10.3	$ 19.5	$ 19.5	$ -
	Cumulative, 2000-2050	$ 86.0	$ 222.7	$ 222.7	$ 0.1

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Transport to Storage/Disposal for All Cooled Spent Fuel (Million dollars)	2010	$ 6	$ 127	$ 127	$ 14
	2030	$ 7	$ 114	$ 105	$ 7
	2050	$ 78	$ 229	$ 227	$ 23
	Cumulative, 2000-2050	$ 1,026	$ 7,234	$ 7,165	$ 595
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Transport to Storage/Disposal for All Cooled Spent Fuel (Million dollars)	2010	$ 0	$ 127	$ 127	$ 14
	2030	$ -	$ 98	$ 86	$ 12
	2050	$ 79	$ 275	$ 270	$ 37
	Cumulative, 2000-2050	$ 459	$ 7,415	$ 7,313	$ 836
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Transport to Storage/Disposal for All Cooled Spent Fuel (Million dollars)	2010	$ 6	$ 127	$ 127	$ 14
	2030	$ 5	$ 135	$ 115	$ 6
	2050	$ 51	$ 184	$ 162	$ 6
	Cumulative, 2000-2050	$ 843	$ 7,010	$ 6,582	$ 401

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Medium-level Wastes from Reprocessing In-country (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 100	$ 15	$ 15	$ -
	2050	$ 145	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 3,056	$ 262	$ 262	$ 38

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Medium-level Wastes from Reprocessing In-country (Million dollars)	2010	0	0	0	0
	2030	148	23	23	-
	2050	280	-	-	-
	Cumulative, 2000-2050	5,263	471	471	38

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Medium-level Wastes from Reprocessing In-country (Million dollars)	2010	0	0	0	0
	2030	63	-	-	-
	2050	89	-	-	-
	Cumulative, 2000-2050	1,791	38	38	38

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Medium-level Wastes from Reprocessing Out-of--country (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 85	$ 90	$ -
	2050	$ -	$ 156	$ 155	$ -
	Cumulative, 2000-2050	$ 74	$ 2,877	$ 2,894	$ 74

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Medium-level Wastes from Reprocessing Out-of--country (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 125	$ 131	$ -
	2050	$ -	$ 292	$ 291	$ -
	Cumulative, 2000-2050	$ 74	$ 4,843	$ 4,857	$ 74

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Medium-level Wastes from Reprocessing Out-of--country (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 56	$ 67	$ -
	2050	$ -	$ 81	$ 92	$ -
	Cumulative, 2000-2050	$ 74	$ 1,628	$ 1,846	$ 74

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Medium-level Wastes from All Reprocessing (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 100	$ 100	$ 105	$ -
	2050	$ 145	$ 156	$ 155	$ -
	Cumulative, 2000-2050	$ 3,130	$ 3,139	$ 3,156	$ 112
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Medium-level Wastes from All Reprocessing (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 148	$ 148	$ 154	$ -
	2050	$ 280	$ 292	$ 291	$ -
	Cumulative, 2000-2050	$ 5,337	$ 5,314	$ 5,328	$ 112
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Medium-level Wastes from All Reprocessing (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 63	$ 56	$ 67	$ -
	2050	$ 89	$ 81	$ 92	$ -
	Cumulative, 2000-2050	$ 1,865	$ 1,665	$ 1,884	$ 112

Parameter	YEAR	BAU Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Low-level Wastes from Reprocessing In-country for Use in Domestic Reactors (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 42	$ 6	$ 6	$ -
	2050	$ 62	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 1,303	$ 112	$ 112	$ 16
Parameter	**YEAR**	**MAX Capacity Expansion Paths Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Implied Costs for Treatment and Disposal/Storage of Low-level Wastes from Reprocessing In-country for Use in Domestic Reactors (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 63	$ 10	$ 10	$ -
	2050	$ 119	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 2,243	$ 201	$ 201	$ 16
Parameter	**YEAR**	**MIN Capacity Expansion Paths Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Implied Costs for Treatment and Disposal/Storage of Low-level Wastes from Reprocessing In-country for Use in Domestic Reactors (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 27	$ -	$ -	$ -
	2050	$ 38	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 763	$ 16	$ 16	$ 16

Parameter	YEAR	BAU Capacity Expansion Paths Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Low-level Wastes from Reprocessing Out-of-country (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 36	$ 38	$ -
	2050	$ -	$ 66	$ 66	$ -
	Cumulative, 2000-2050	$ 32	$ 1,226	$ 1,233	$ 32
Parameter	**YEAR**	**MAX Capacity Expansion Paths Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Implied Costs for Treatment and Disposal/Storage of Low-level Wastes from Reprocessing Out-of-country (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 53	$ 56	$ -
	2050	$ -	$ 124	$ 124	$ -
	Cumulative, 2000-2050	$ 32	$ 2,064	$ 2,070	$ 32
Parameter	**YEAR**	**MIN Capacity Expansion Paths Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Implied Costs for Treatment and Disposal/Storage of Low-level Wastes from Reprocessing Out-of-country (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 24	$ 28	$ -
	2050	$ -	$ 35	$ 39	$ -
	Cumulative, 2000-2050	$ 32	$ 694	$ 787	$ 32

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Low-level Wastes from All Reprocessing (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 42	$ 43	$ 45	$ -
	2050	$ 62	$ 66	$ 66	$ -
	Cumulative, 2000-2050	$ 1,334	$ 1,338	$ 1,345	$ 48
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Low-level Wastes from All Reprocessing (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 63	$ 63	$ 66	$ -
	2050	$ 119	$ 124	$ 124	$ -
	Cumulative, 2000-2050	$ 2,275	$ 2,265	$ 2,271	$ 48
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Low-level Wastes from All Reprocessing (Million dollars)	2010	$ 0	$ 0	$ 0	$ 0
	2030	$ 27	$ 24	$ 28	$ -
	2050	$ 38	$ 35	$ 39	$ -
	Cumulative, 2000-2050	$ 795	$ 710	$ 803	$ 48

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Solid Wastes from Reprocessing In-country (Million dollars)	2010	$ 0.0	$ 0.0	$ 0.0	$ 0.0
	2030	$ 0.2	$ 0.0	$ 0.0	$ -
	2050	$ 0.3	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 7.1	$ 0.6	$ 0.6	$ 0.1

		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Solid Wastes from Reprocessing In-country (Million dollars)	2010	$ 0.0	$ 0.0	$ 0.0	$ 0.0
	2030	$ 0.3	$ 0.1	$ 0.1	$ -
	2050	$ 0.6	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 12.2	$ 1.1	$ 1.1	$ 0.1

		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Solid Wastes from Reprocessing In-country (Million dollars)	2010	$ 0.0	$ 0.0	$ 0.0	$ 0.0
	2030	$ 0.1	$ -	$ -	$ -
	2050	$ 0.2	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 4.2	$ 0.1	$ 0.1	$ 0.1

		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Solid Wastes from Reprocessing Out-of-country (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 0.2	$ 0.2	$ -
	2050	$ -	$ 0.4	$ 0.4	$ -
	Cumulative, 2000-2050	$ 0.2	$ 6.7	$ 6.7	$ 0.2

		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Solid Wastes from Reprocessing Out-of-country (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 0.3	$ 0.3	$ -
	2050	$ -	$ 0.7	$ 0.7	$ -
	Cumulative, 2000-2050	$ 0.2	$ 11.2	$ 11.3	$ 0.2

		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Solid Wastes from Reprocessing Out-of-country (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ -	$ 0.1	$ 0.2	$ -
	2050	$ -	$ 0.2	$ 0.2	$ -
	Cumulative, 2000-2050	$ 0.2	$ 3.8	$ 4.3	$ 0.2

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Solid Wastes from All Reprocessing (Million dollars)	2010	$ 0.0	$ 0.0	$ 0.0	$ 0.0
	2030	$ 0.2	$ 0.2	$ 0.2	$ -
	2050	$ 0.3	$ 0.4	$ 0.4	$ -
	Cumulative, 2000-2050	$ 7.3	$ 7.3	$ 7.3	$ 0.3
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Solid Wastes from All Reprocessing (Million dollars)	2010	$ 0.0	$ 0.0	$ 0.0	$ 0.0
	2030	$ 0.3	$ 0.3	$ 0.4	$ -
	2050	$ 0.6	$ 0.7	$ 0.7	$ -
	Cumulative, 2000-2050	$ 12.4	$ 12.3	$ 12.4	$ 0.3
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Solid Wastes from All Reprocessing (Million dollars)	2010	$ 0.0	$ 0.0	$ 0.0	$ 0.0
	2030	$ 0.1	$ 0.1	$ 0.2	$ -
	2050	$ 0.2	$ 0.2	$ 0.2	$ -
	Cumulative, 2000-2050	$ 4.3	$ 3.9	$ 4.4	$ 0.3

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Uranium Separated During from Reprocessing In-country (Million dollars)	2010	$ 0.0	$ 0.0	$ 0.0	$ 0.0
	2030	$ 12.0	$ 1.9	$ 1.8	$ -
	2050	$ 15.8	$ -	$ (0.4)	$ -
	Cumulative, 2000-2050	$ 350.3	$ 33.9	$ 27.0	$ 4.9

	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Uranium Separated During from Reprocessing In-country (Million dollars)	2010	0.0	0.0	0.0	0.0
	2030	17.6	3.0	2.8	-
	2050	30.5	-	(0.5)	-
	Cumulative, 2000-2050	603.3	60.9	51.9	4.9

	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Uranium Separated During from Reprocessing In-country (Million dollars)	2010	0.0	0.0	0.0	0.0
	2030	7.7	-	(0.1)	-
	2050	9.6	-	(0.3)	-
	Cumulative, 2000-2050	204.3	4.8	(0.2)	4.9

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		BAU Capacity Expansion Paths			
Implied Costs for Treatment and Disposal/Storage of Uranium Separated During from Reprocessing Out-of-country (Million dollars)	2010	$ (0.0)	$ (0.0)	$ (0.0)	$ (0.0)
	2030	$ (0.0)	$ 10.1	$ 10.9	$ -
	2050	$ (0.0)	$ 17.1	$ 17.4	$ -
	Cumulative, 2000-2050	$ 9.5	$ 327.1	$ 335.2	$ 9.5
		MAX Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Uranium Separated During from Reprocessing Out-of-country (Million dollars)	2010	$ (0.0)	$ (0.0)	$ (0.0)	$ (0.0)
	2030	$ 0.0	$ 14.7	$ 15.6	$ -
	2050	$ -	$ 32.1	$ 32.3	$ -
	Cumulative, 2000-2050	$ 9.5	$ 548.9	$ 557.5	$ 9.5
		MIN Capacity Expansion Paths			
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Uranium Separated During from Reprocessing Out-of-country (Million dollars)	2010	$ (0.0)	$ (0.0)	$ (0.0)	$ (0.0)
	2030	$ 0.0	$ 6.8	$ 8.2	$ -
	2050	$ (0.0)	$ 8.5	$ 10.3	$ -
	Cumulative, 2000-2050	$ 9.5	$ 183.2	$ 216.5	$ 9.5

	BAU Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Uranium Separated During from All Reprocessing (Million dollars)	2010	$ (0.0)	$ (0.0)	$ (0.0)	$ (0.0)
	2030	$ 12.0	$ 12.1	$ 12.7	$ -
	2050	$ 15.8	$ 17.1	$ 17.0	$ -
	Cumulative, 2000-2050	$ 359.8	$ 360.9	$ 362.1	$ 14.4
	MAX Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Uranium Separated During from All Reprocessing (Million dollars)	2010	$ (0.0)	$ (0.0)	$ (0.0)	$ (0.0)
	2030	$ 17.6	$ 17.7	$ 18.4	$ -
	2050	$ 30.5	$ 32.1	$ 31.9	$ -
	Cumulative, 2000-2050	$ 612.8	$ 609.7	$ 609.4	$ 14.4
	MIN Capacity Expansion Paths				
Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Uranium Separated During from All Reprocessing (Million dollars)	2010	$ (0.0)	$ (0.0)	$ (0.0)	$ (0.0)
	2030	$ 7.7	$ 6.8	$ 8.1	$ -
	2050	$ 9.6	$ 8.5	$ 10.0	$ -
	Cumulative, 2000-2050	$ 213.8	$ 188.0	$ 216.3	$ 14.4