Deep Borehole Disposal of Nuclear Spent Fuel and High Level Waste as a Focus of Regional East Asia Nuclear Fuel Cycle Cooperation

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Executive Summary

This study explores a possible technological strategy that would avoid security and sustainability dilemmas associated with the management of the rapidly growing quantities of nuclear spent fuel in the East Asia region. 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) shallow geologic repositories. In contrast, this study examines the disposal of spent fuel directly into very deep boreholes after a once-through cycle (that is, without separating its radioactive components of reprocessing).

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 an assessment been made of the regional cooperation potential from its implementation in lieu of various proposed regional spent fuel storage and reprocessing schemes.

Deep borehole technology is advancing rapidly, and 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, 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. 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 5km in the borehole, which would be capped.

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.

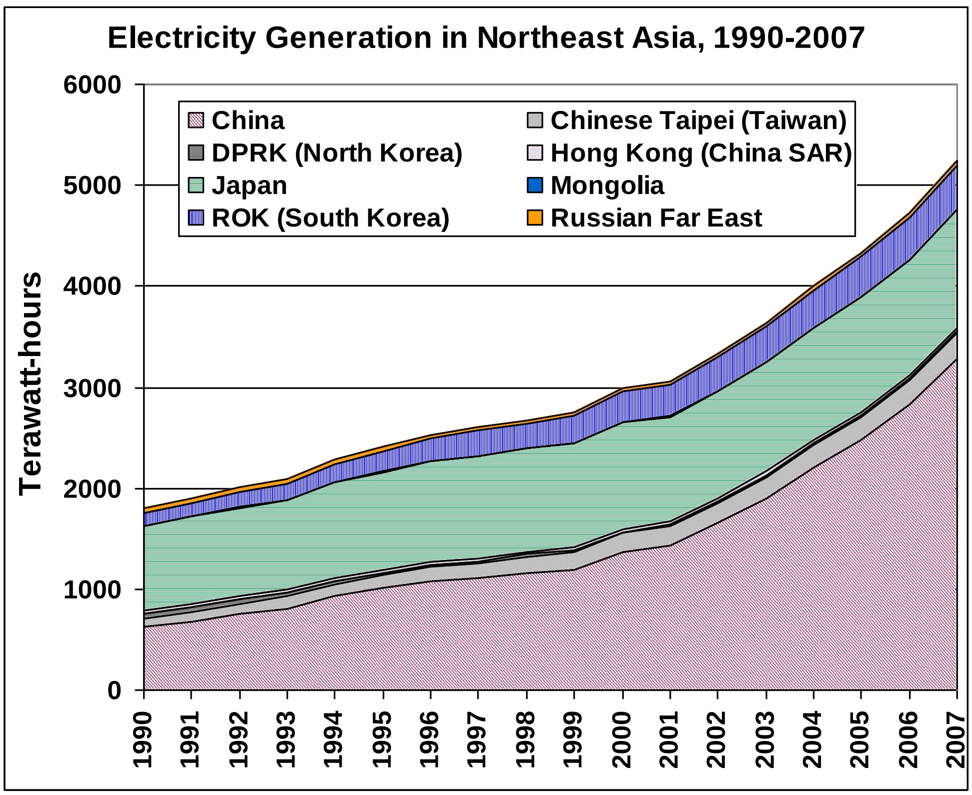
In the study that follows, we describe the nuclear power sector in East Asia, note some of the attributes and questions related to deep borehole disposal of nuclear wastes, explore the barriers and uncertainties that may be involved in applying the concept, review the status of research on or related to deep borehole disposal of nuclear wastes in the countries of East Asia, and present some key research questions that need answering in order to compare different deep borehole disposal concepts with other national and regional proposals for managing spent fuel.

We conclude this study by proposing a multi-disciplinary collaborative program of research designed to systematically and comprehensively evaluate the relative attributes of the technical, cost, security, safeguards, and other benefits of different nuclear fuel cycle management approaches, including deep borehole disposal, with a view to determining which of these approaches best supports a prospective nuclear weapon free zone in East Asia.

1. Introduction

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, and especially, electricity needs. As a recent, eye-opening example of these increased needs, China added more than 100 gigawatts (GWe) of electrical generating capacity—equivalent to 150 percent of the total generation capacity in the ROK as of 2007—in the year 2006 alone, with the vast bulk of that added capacity being coal-fired. This vast increase in generation comes with attendant concerns regarding the global climate impacts of steadily increasing coal consumption. Even more striking than growth in primary energy use—and indeed one of its main drivers—has been the increase in electricity generation (and consumption) in the region. Figure 1 shows the trend in electricity generation in Northeast Asia by country from 1990 through 2007.

Figure 1: Electricity Generation in Northeast Asia, 1990-2007



Sources: Data from BP (2008)[1] for all countries except the DPRK (von Hippel and Hayes, 2007)[2], Mongolia (USDOE/EIA, 2008)[3], and RFE (estimated from Gulidov and Ognev, 2007)[4]. Generation figures shown are for gross generation (that is, including in-plant electricity use), except for Mongolia and the RFE.

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[1] British Petroleum Co. (BP, 2008), BP Statistical Review of World Energy 2008. Downloaded as Excel workbook "statistical_review_full_report_workbook_2008.xls" from

With the lessons of the "energy crises" of the 1970s in mind, several of the countries of East Asia—starting with Japan, and continuing with the ROK, Taiwan, and China—have sought to diversify their energy sources and bolster their energy supply security by developing nuclear power. Several other East Asian nations are currently discussing adopting nuclear power as well. At the same time, global security concerns related to terrorism and to the nuclear weapons activities of North Korea, Pakistan, and India, as well as the (nominally peaceful) uranium enrichment program pursued by Iran (and the recently revealed North Korean enrichment program), have focused international concern on the potential for nuclear proliferation associated with nuclear power.

1.1. Summary of Spent Nuclear Fuel and Related Proliferation Situation in East Asia

East Asia and the Pacific includes three nuclear weapons states—one a recent addition to the list, three major economies that are nearly completely dependent on energy imports and for whom 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 1 provides a summary of the status of major nuclear fuel-cycle activities in each country in Northeast Asia (except Mongolia, which has uranium resources and is contemplating roles in the regional fuel cycle[5]), plus several other potential major "players" in nuclear power in East Asia and the Pacific.

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http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2008/STAGING/local_assets/downloads/spreadsheets/statistical_review_full_report_workbook_2008.xls.

[2] 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, dated June, 2007, and available as http://www.nautilus.org/publications/essays/napsnet/reports/07042DPRKEnergyBalance.pdf/at_download/file.

[3] USDOE Energy Information Administration (USDOE/EIA, 2008a), International Energy Annual 2006. Energy consumption, production, population, carbon dioxide emissions, and consumption per unit GDP data files downloaded from http://www.eia.doe.gov/iea/.

[4] 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://www.nautilus.org/projects/asian-energy-security/2007/Russia%20Energy%20Changes.ppt/view.

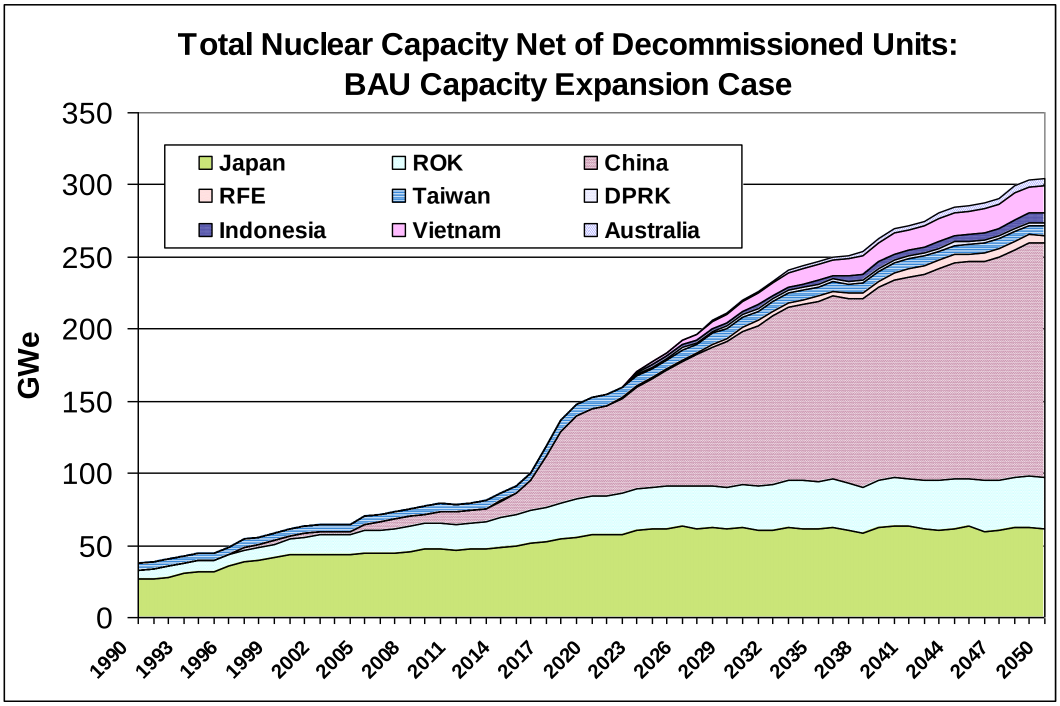
[5] See, for example U. Agvaanluvsan (2009), "The Global Context of Nuclear Industry in Mongolia". Mongolia Today, the Mongolian National News Agency, December 2009, available as http://iis-db.stanford.edu/pubs/22822/AgvaanluvsanMongolia_nuclear_industry.pdf.

Table 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	No significant mining, milling. Some domestic enrichment, but most enrichment services imported	Significant experience with reprocessing, commercial-scale facility now in testing; interim spent-fuel storage facility.
ROK	Mature nuclear industry, ~18 GWe at 4 sites as of 2010	No significant U resources, enrichment services imported, but some domestic fuel fabrication	Very limited tests with reprocessing; at-reactor spent fuel storage thus far
DPRK	Had small (5 MWe equiv.) reactor for heat and Pu production, now partly decommissioned. Policy to acquire LWRs, and recently has begun to build small domestic LWR unit (~25 MWe).	At least modest uranium resources and history of U mining; some production exported; recently revealed enrichment facility estimated at about 2000 centrifuge units.	Reprocessing of Pu for weapons use. Arrangements/plans for spent fuel management unknown
China	Relatively new but rapidly-growing nuclear power industry; ~9 GWe as of 2010	Domestic enrichment and U mining/milling, but not sufficient for large reactor fleet.	Nuclear weapons state. Small reprocessing facility; plans for spent fuel storage facilities.
Russian Far East	One small plant (48 MWe) in far North of RFE (RF has large reactor fleet); plans for larger (1 GWe scale) units for power export	Domestic enrichment and U mining/milling (but not in 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; no enrichment	No back-end facilities
Taiwan	~5 GWe at 3 sites, plant at 4th site under construction	No U resources, no enrichment—imports enrichment services	Current spent-fuel storage at reactor, no reprocessing
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 full-scale reactors planned	Some U resources, but no production; no enrichment	Consideration of back-end facilities in early stages

The historically significant (as a fraction of total generation) use of nuclear power in Japan, the ROK, and Taiwan continues to grow, albeit with capacity added more slowly than in past decades. This growth is far outstripped, however, by in-progress and planned growth in nuclear power use in China. Figure 2 shows a "business as usual" projection for regional nuclear generation capacity, prepared by Nautilus and its colleagues in the region as a part of the MacArthur-funded "East Asia Science and Security" project[6]. In this projection, regional nuclear capacity rises from about 80 GWe in today (2010) to over 300 GWe by 2050, with more than two-thirds of capacity additions being in China.

Figure 2: Nuclear Generation Capacity Projections in East Asia and the Pacific



Despite these robust plans for nuclear capacity additions, old concerns regarding the management of nuclear spent fuel and other wastes remain, at best, only partially addressed. The spent fuel pools at reactor sites that hold used reactor fuel for cooling for at least 5-6 years after discharge from the reactor vessel, and often considerably longer, are reaching capacity at many reactor sites in the ROK, Taiwan, and Japan. None of the countries of the region have an operating permanent disposal facility for spent fuel or high-level nuclear wastes (HLW), and those countries that have the most proximate need for spent fuel disposal—again the ROK, Taiwan, and Japan—have high population densities, geological issues, and other practical considerations that, when coupled with relatively active civil society sectors and democratic political systems, make the domestic siting of any nuclear waste management facilities more than problematic.

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[6] Future Regional Nuclear Fuel Cycle Cooperation in East Asia: Energy Security Costs and Benefits, prepared by David von Hippel, Tatsujiro Suzuki, Tadahiro Katsuta, Jungmin Kang, Alexander Dmitriev, Jim Falk, and Peter Hayes, June, 2010.

1.2. Spent Fuel Management Options—Storage and Disposal

Although spent fuel pools at reactors can be used to store fuel discharged from reactors for longer than the minimum five or six years required for initial cooling, sometimes even for 10-25 years, longer-term storage arrangements or other means of managing spent fuel must ultimately be found. Several different options for long-term management of spent fuel (not including reprocessing, which is discussed below), include:

- **At-reactor storage of spent fuels in "dry casks"**. In this approach, spent fuel assemblies are placed in large, thick steel containers, from which liquids are removed, and an inert gas is added, before the containers are welded shut and placed in an even larger concrete cask. The size of the entire assembly is 2-3 meters in diameter, and 7-10 meters tall, depending on the type. Dry casks are resilient to the elements and most possible types of tampering and attack, and can keep nuclear wastes safely isolated from the environment for many decades, and possibly centuries. Dry cask storage facilities do, however, need to be continuously monitored and guarded, and ultimately, perhaps every 100 years or so, the spent fuel inside must be placed in a new cask. This means that institutions spanning many human lifetimes must operate continuously and successfully. At-reactor dry cask storage facilities also effectively prevent reactor sites from being freed for unlimited use after the reactors themselves are decommissioned. At-reactor storage of spent fuels is inexpensive and relatively easy and quick to set up, but in some countries (notably Japan, but others as well), agreements with communities hosting reactors prohibit at-reactor storage.
- **Centralized storage of spent fuels in dry casks**. In-country "interim" spent fuel storage can also be done at centralized locations, rather than at reactor sites. This approach requires siting one or more interim storage facilities to collect spent fuel from several reactors (or nationwide). The fuel is stored in dry casks as above. This approach requires the transport of spent fuel, either before or after transfer to dry casks, from reactor sites to the storage facility. In addition, siting of a central repository may be more difficult than at-reactor storage, depending on the regulations and agreements with local communities that are in force in a particular country. These facilities can, however, be built relatively quickly, and their operation is only modestly more complex than at-reactor storage. Other requirements are the same as for dry-cask storage.
- **Permanent storage/disposal of spent fuel and HLW**. In this approach, pursued in many nations but thus far completed in none, a tunnel- or cavern-like repository, often designed to be several hundred meters deep, is mined from rock in a geologically stable location, and spent fuel and other radioactive materials are stored in canisters placed in the caverns or tunnels.[7] In concept, when fully occupied, the repository would be sealed, though it could be monitored and guarded for some time thereafter. This option requires transport of spent fuels, either before or after being placed in canisters, from reactors nationwide to the

[7] Japan did investigate deep ocean trench sediment disposal using "waste projectiles" to penetrate and encapsulate high level nuclear waste in the shallow seabed in the 1970s, but this approach proved too risky and politically and legally difficult to implement, and is now ruled out by various international treaties as well as the negative experience with the radioactive waste dumping in the Sea of Japan by the former Soviet Union. C. Hollister, "The Seabed Option," Oceanus, 20: 1, 1977, p. 23; and W. Bishop and C. Hollister, "Seabed Disposal—Where to Look," Nuclear Technology, December 1974, p. 440.

repository facility. Historically, siting and construction of these facilities has proven to be difficult, expensive (many billions of dollars), and time-consuming (sometimes decades, even for facilities not yet complete), involving significant political and social risk.

Permanent in-country disposal of nuclear wastes is a topic of discussion in the nuclear policy community, and often the public as well, in all of the countries of East Asia where nuclear power is in extensive use (and a few others who might host such facilities), As yet, however, no final decisions have been made as to siting such facilities in the region, and many political and other hurdles remain to be overcome in finding appropriate places for long-term storage or disposal of nuclear materials.

1.3. Reprocessing/recycling of Spent Fuels

In part to reduce the burden on eventual long-term nuclear wastes storage/disposal facilities, in part to put off the day when such facilities are needed, in part with an eye toward extending the life of uranium resources and extending the benefits obtained from imported nuclear fuels, and in part, as we discuss in Section 3, for political or national security reasons having little to do with the practical advantages of the technology, several countries in the region have adopted or expressed interest in "reprocessing".

Reprocessing refers to the partial or complete separation of the plutonium contained in nuclear spent fuel from other fuel components. The resulting plutonium can then be mixed with uranium and introduced into Light Water Reactors (LWRs) as mixed-oxide fuel (MOx). Reprocessing is currently being pursued in Japan, at the Rokkasho plant. Though currently prohibited from reprocessing by its Nuclear Supplier Agreement with the United States, some nuclear industry groups in the ROK aspire to a form of reprocessing called "pyro-processing". The pyro-processing concept involves the use of partially-separated plutonium as a fuel for liquid-sodium-cooled "fast" reactors designed to eliminate ("burn") the plutonium to fission products. China has started a small reprocessing facility as well.

Reprocessing is touted as a solution (often partial, and not completely accurately) to spent fuel disposal siting problems, but by creating large stocks of plutonium (or, in the case of pyro-processing, mixtures of plutonium and other transuranic compounds that are not particularly more diversion-resistant), raises concerns related to nuclear weapons proliferation. These nuclear weapons considerations are particularly of relevance in Northeast Asia, where the potential (or perceived potential) for Japan or the ROK to possess nuclear weapons affects and is affected by the status and possible solutions (or not) to the problem of possession of nuclear weapons (and weapons-making capability) by the Democratic Peoples' Republic of Korea (DPRK). In addition, these nuclear weapons considerations considerably affect the potential for establishment of a nuclear weapons free zone in Northeast Asia, starting with Japan and Korea, and possibly growing to encompass other states as well.

Given the context outlined above—significant and growing inventories of spent nuclear fuel, difficulties in many countries in siting fuel repositories, and proliferation (and other) concerns with regard to reprocessing, some have argued that the way forward lies with regional cooperation on spent fuel management to reduce risks at both the national and international levels. One cooperation option on the "back end" of the nuclear fuel cycle (spent fuel management) for the countries of the Northeast Asia region is to collaborate on the siting, construction, and operation of a permanent repository for spent fuel and HLW. Here, one option is to collaborate on construction of a mined repository of the type that has been under consideration for many years in a number of countries. The problem with these schemes has been the asymmetry of interest and capacity in the region's nuclear fuel cycles, and historical distrust that blocks cooperation between states on sensitive issues such as nuclear fuel cycle capacities. To date, almost no tangible cooperation has emerged after two decades of conceptual exploration.

Another option, which we dub the "Todai Scheme"[8] due its origins in the nuclear engineering department of the University of Tokyo, is to create a regional nuclear fuel cycle cooperation arrangement based on a degree of enhanced coordination and communication about divergent national spent fuel management strategies. In this scheme, national spent fuel reprocessing technologies may differ—Japan would stick with its PUREX-based path, the ROK would develop pyro-processing to manage spent fuel and to support fast reactors, possibly in close cooperation with the United States, and China would begin commercial reprocessing. The Todai scheme ostensibly would create trust by regional monitoring and verification schemes, thereby creating transparency and building confidence between these states that have very high levels of historical antagonism and current mistrust.[9] However, one key element of this approach—the ROK objective to establish a pyro-processing capacity and strategy—requires US support and legal approval, and is under intense negotiation as part of the dialogue related to the renewal of the US-ROK nuclear cooperation agreement due no later than 2014.[10]

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[8] This concept has had many versions and names, such as "ASIA-ATOM," "PACATOM" etc. We are drawing on the most recent version articulated by analysts at the Center of Global Excellence at University of Tokyo Nuclear Engineering Department. Although now dated, see also K. Kaneko *et al*, Energy and Security in Northeast Asia: Proposals for Nuclear Cooperation, Institute on Global Conflict and Cooperation, February 1, 1998, at: http://escholarship.org/uc/item/0xw8d5c1

[9] In principle, such a regional scheme could include a front-end uranium and enrichment fuel supply consortium, both to exercise purchasing power to reduce cost, and by stockpiling and/or emergency leasing arrangements, insulate nuclear reactors from fuel supply cutoff in the case of disruption of global uranium and enrichment markets. This approach might be modeled after the three leading concepts for such cooperation under discussion at a global level, viz, an IAEA low-enriched uranium (LEU) "bank," a Russian reserve of LEU for IAEA member states, and the German Multilateral Enrichment Sanctuary Project. See T. Rauf, "New Approaches to the Nuclear Fuel Cycle," in C. McCombie and T. Isaacs, Multinational Approaches to the Nuclear Fuel Cycle, American Academy of Arts and Sciences, 2010, p. 24 at: http://iis-db.stanford.edu/pubs/22926/isaacsInside.pdf. It might also foster nuclear power as a mitigative and adaptive response to dangerous climate change, which would entail sharing reactor and other technology, as well as creating financing schemes for utilities to switch from fossil to nuclear power stations. However, to date, its proponents have not made these arguments as a basis for a regional fuel cycle management scheme. Nautilus has commissioned work on the climate-nuclear dimension by Zhou Yun, Climate Change and Nuclear Power: Issues of Interaction, draft paper, 2010.

[10] Yonhap, "U.S., S. Korea Set For Talks on Nuclear Pact: Sources," July 30, 2010, at: http://english.yonhapnews.co.kr/news/2010/07/30/55/0200000000AEN20100730003500315F.HTML and S.W. Park *et al*, "The Domestic and International Politics of Spent Nuclear Fuel in South Korea: Are We Approaching Meltdown?" Korea Economic Institute Academic Paper Series," March 2010, Volume 5, Number 3, at: http://www.keia.org/Publications/AcademicPaperSeries/2010/APS-ParkPomperScheinman.pdf

A variant of these national and regional spent fuel management options that has been less studied but may have advantages over conventional mined repositories built with an eye to retrieval and reprocessing, may be regional collaborations on deep borehole disposal of spent nuclear fuel and/or other nuclear materials.

This study provides a preliminary examination of a deep borehole disposal strategy for management of spent fuel and other radioactive wastes from the nuclear power sector. The goal of the study is to begin to establish a counterpoint concept for comparison with alternative regional nuclear fuel cycle cooperation (and non-cooperation) schemes, including those aimed at reprocessing and plutonium retrieval and/or recycling, with respect to the relative political, economic, military, and proliferation risks and benefits associated with these alternative strategies.

1.4. Deep Borehole Disposal of Nuclear Spent Fuel and High Level Waste as an Opportunity for Regional Cooperation

In deep borehole disposal (DBD) of nuclear materials, a borehole less than a meter in diameter is drilled into stable geologic strata using standard (or advanced) drilling techniques derived from the petroleum and mining industries. The hole is drilled to a depth of 3 to 5 km below ground level. In concept, radioactive materials, potentially including spent fuel (cooled as needed), HLW, and/or plutonium (pure or in mixtures) are placed in suitable canisters, and lowered into a "disposal zone" in the bottom 1 to 2 km of the borehole. The borehole is then filled with inert materials such as rock and clay, and sealed, sometimes at several depths as well as at the surface, with plugs of concrete. The placement of the materials to be disposed of in deep, "basement" rock that does not exchange water with near-surface aquifers is intended to essentially permanently isolate the wastes from the biosphere. In addition, retrieval (or clandestine removal) of radioactive materials from the borehole would be very difficult, if not impossible, with current technology, meaning that a borehole disposal facility might need no significant ongoing on-site monitoring.

There are several general possibilities for DBD application in East Asia. These possibilities are presented here in brief, together with notes regarding their main attributes and drawbacks.

- **National independent DBD facilities**. Each nation with a nuclear power program could develop its own DBD facility. This application of DBD minimizes the need to transport spent nuclear fuel and other radioactive materials for disposal, though some in-country land-based, and probably, in the case of at least the ROK and Japan, coastal shipping transport would be needed. Establishment of national DBD facilities gives each country control of its nuclear materials throughout the back end of the fuel cycle, but misses opportunities for confidence-building oversight and safeguard measures that would help to foster trust between the nations of the region. National facilities would also arguably be less open to taking wastes from new nuclear power nations with waste generation too modest to develop their own facilities. Although it is not clear yet what economies of scale might exist for DBD technologies, a national approach would likely miss any cost reduction benefits that might accrue from building larger facilities. The burial of wastes in many different locations under the national facilities approach may be a benefit, in that it spreads the risk of having a large amount of waste in one location, or a drawback, in that it means that a number of different disposal locations must be remembered and monitored by future generations.

- **National coordinated DBD facilities**. DBD facilities could alternatively be located in each nuclear user country, but handling and disposal could be done under the supervision and oversight of an international authority such as the International Atomic Energy Agency, and with the participation of representatives of other countries in the region. This oversight and participation would provide for safeguards assuring all parties that nuclear materials are being properly disposed of and not diverted for weapons purposes. Coordination activities would make in-country DBD facilities slightly more difficult and expensive to implement, as doing so would require consultations with other parties. The other benefits and drawbacks of this approach are largely as above.
- **International DBD facilities in nuclear weapons nations**. Another alternative is to site one or more DBD facilities in nuclear weapons nations who are members of the UN Security Council, presumably in the region, though siting of such a facility in the United States is a theoretical possibility (but likely not a practical one, for a host of reasons[11]). This probably means siting of a facility in China or the Russian Far East, both of which have sparsely-settled areas that may be geologically suitable (though particularly in China, nuclear materials would need to be transported through areas with relatively large populations). Advantages here include economies of scale, and the avoidance of having to site long-term disposal facilities in each nation, the ability to place wastes in a centralized location that can be easily monitored, and the assurance that the materials will not contribute to proliferation (at least at the national scale). Drawbacks could include reluctance on the part of other states to place their nuclear materials with nuclear weapons states, and social and political difficulties associated with the nuclear weapons states accepting materials from other nations.
- **International DBD facilities in non-nuclear weapons nations**. Finally, one or more international DBD facilities in the region could be hosted by non-nuclear weapons nations. These could be nations with substantial existing nuclear power programs, although in most cases, the high population densities and limited options for siting extensive DBD facilities in nations like Japan, the ROK, or Taiwan, together with social and political considerations, may limit the ability of those nations to host multi-national facilities. Alternatively, nations without current nuclear power programs, but with low populations densities and suitable geology, could host such facilities. Possibilities in East Asia and the Pacific include Mongolia and Australia, though these two nations present very different choices (and siting of facilities in each case would present different obstacles). The advantages of DBD facilities in non-nuclear weapons states, and particularly in those nations without current nuclear power programs, include the ability to have the facility be more truly international in nature, rather than dominated by a nuclear weapons state host, economies of scale, and the avoidance of having to site long-term disposal facilities in each nation, and some of the other advantages of a centralized facility noted above. Disadvantages include providing nuclear

[11] These reasons include the need for long-distance shipping of nuclear materials from Asia, the unlikelihood of obtaining local acceptance of a facility that would dispose of wastes from other nations, and a likely reluctance on the part of some Asian nations, particularly, perhaps, Russia and China, to send nuclear materials to the U.S. On the other hand, accepting wastes for disposal in the United States may be consistent with some of the "take-back" nuclear supplier proposals offered in recent years.

materials for disposal, however permanent, in another country. In the case of a centralized repository in a major current nuclear user state, social and political difficulties are likely to attend the siting of an international facility, and other nuclear power nations may have concerns about sending nuclear materials to another nuclear power country. In the case where a non-nuclear power state accepts the wastes, in addition to social and political concerns in the host country regarding siting, countries shipping wastes to the repository may have concerns about contributing to proliferation in that country (which means that a robust safeguards and oversight regime must be developed before the facility becomes operational).

1.5. Goals and Structure of this Study

The overall goals and structure of the remainder of this study are as follows:

- **Section 2** summarizes the current concept of DBD disposal of nuclear wastes, presenting brief summaries of the different elements of the DBD concept as currently conceived. Section 2 provides an overview of the application of drilling and related technologies developed in other fields to the disposal of nuclear materials, and of the expected costs of DBD technologies, as well as short- and long-term environmental concerns related to DBD of nuclear materials.
- **Section 3** describe key unknowns and uncertainties about DBD-related technologies as they apply to nuclear spent fuel disposal, including technological and legal uncertainties associated with DBD application, and political and institutional barriers that groups seeking to develop DBD of nuclear wastes might face.
- **Section 4** describes our understanding to date of the status of DBD research both internationally and in the countries of the region, identifying key organizations and individuals involved in DBD research and development.
- **Section 5** identifies next steps in the exploration of the applicability of the DBD concept to cooperative nuclear waste management solutions in East Asia, focusing on cooperation strategies that would also serve to address proliferation and other security concerns.

It should be noted that this study is not intended to be a comprehensive review of the potential application of DBD technologies to the management of spent fuels in East Asia. Rather, it is intended to be a “scoping study” to review some of the information resources available for assessing the applicability to the technologies to East Asia, and to identify some of the questions to be answered (and the means for asking those questions) in a more detailed technology and policy assessment of the costs and benefits of DBD of nuclear materials in East Asia, relative to other nuclear materials management options.

2. Use of Deep Boreholes to Dispose of Nuclear Wastes

Deep borehole disposal (DBD) of nuclear materials—including high level wastes, spent fuel from nuclear reactors, possibly plutonium and other transuranics, and other concentrated very radioactive or otherwise dangerous materials, has not been tried on a commercial scale. DBD of nuclear materials has, however, been a topic of research for many years, with the earliest mentions of the concept of borehole disposal (though not necessarily deep disposal) of nuclear materials dating to the 1950s, and study of deep borehole disposal dating to at least the 1990s[12]. Interest in DBD of nuclear materials has increased in recent years, as evidenced in the publication of a number of new studies and reviews on the topic. This additional attention is likely the result of a combination of a perceived "renaissance" in nuclear power development, the ongoing struggles of most nations to site long-term repositories for nuclear materials, and the improvements in deep drilling technologies. Below we provide a brief summary of the general concept of deep borehole disposal of nuclear materials, summarize some of the key research on the topic to date, then identify some of the key steps in, parameters of, and concerns about DBD of nuclear materials. As noted above, the summaries provided in this section are not intended to be fully comprehensive, rather to explore some of the major issues that would need to be addressed by a comparative study of DBD disposal versus other alternatives for managing "back-end" nuclear materials in East Asia.

2.1. General DBD Concept

A number of different concepts for disposal of nuclear materials in boreholes hundreds or thousands of meters deep have been offered over the years. In the 1950s, the United States and the Soviet Union (USSR) disposed of uncontained liquid radioactive wastes in boreholes. Borehole disposal variants suggested have included[13]:

- "Deep underground melting", either for uncontained wastes or wastes in containers, where the heat generated by radioactive decay in the materials disposed of melts the rock in the disposal zone to form a barrier to migration of the wastes;
- "Deep self burial", in which the heat from wastes packaged in a heavy container melts the rock below its initial placement in a borehole such that the package buries itself at an indeterminate depth;
- Disposal of nuclear materials in boreholes previously used to access hydrocarbon deposits; and
- Disposal of encapsulated nuclear materials in deep boreholes at high temperature, where heat from the wastes melts surrounding rock and seals the waste in place, low temperature, where encapsulated wastes are held in place by plugs made of various materials, or in a hybrid approach where capsules of high-temperature wastes are used at various intervals to help seal capsules of low-temperature materials into the borehole.

In this study we focus primarily on encapsulated waste disposal in deep (3-5 km) boreholes. In this DBD concept, appropriately prepared nuclear materials, possibly including vitrified HLW, spent reactor fuel, or appropriately diluted plutonium (or other fissile material) are placed in metal canisters and lowered into boreholes drilled in basement rock below geologically stable strata. The disposal zone, where canisters are placed in the borehole, uses the bottom 1-2 km of the borehole. Canisters would be fixed into place in the borehole with a combination of filler and sealing materials, potentially including rubble or crushed rock, grout,

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[12] See, for example, N. Chapman and F. Gibb (2003), "A Truly Final Waste Management Solution: Is Very Deep Borehole Disposal a Manageable Solution for High-Level Wastes or Fissile Materials?". Radwaste Solutions, July/August 2003, pages 26-37

[13] For more detailed summaries of these borehole disposal variants, see Chapman and Gibbs, 2003 (ibid).

bentonite clay, or cement. Different filler materials may be used at different depth and in different positions in the borehole. Deep borehole disposal of nuclear materials takes advantage of findings from studies of hydrology in test boreholes that indicate that deep, saline groundwater does not mix with water in aquifers closer to the surface. This means that, in theory, wastes placed at depths of 3-5 km can be effectively isolated indefinitely from the biosphere.

2.2. Key Research to Date

In the past two decades, several groups have worked to evaluate the application of deep borehole disposal to disposal of nuclear material. This work includes (but is by no means limited to):

- A group at Sandia National Laboratory in the United States examined placement of high-level wastes, potentially including spent nuclear fuel assemblies, in deep boreholes drilled using "off-the-shelf" drilling technologies from the oil and geothermal exploration and production fields[14]. In studies of the mobility of radionuclides from wastes placed in deep boreholes, the Sandia group found that "Thermal, hydrologic, and geochemical calculations suggest that radionuclides in spent fuel emplaced in deep boreholes will experience little physical reason to leave the borehole/near borehole domain." The Sandia group further found that most of the mobility of radioactivity would take place in the first 600 or so years after waste emplacement, when heat produced by the wastes drive thermal movement in groundwater, and that total vertical movement of radioactive materials would be limited to about 100 meters, and concluded using a "[s]implified and conservative performance assessment" that the dose of radiation to an individual on the surface via a groundwater pathway, at a date some 8000 years in the future, would be ten orders of magnitude (one ten-billionth) of what is currently considered an acceptable dose.

- The Swedish group MKG (Swedish NGO Office of Nuclear Waste Review (or Miljöorganisationernas kärnavfallsgranskning in Swedish) reviewed previous research on the borehole concept in Sweden and in other nations[15]. MKG concluded its review by noting that:

  > "Very deep borehole disposal might offer important advantage compared to the relatively more shallow KBS [mined repository] approach that is presently planned to be used by the Swedish nuclear industry in Sweden, in that it has the potential of being more robust. The reason for this is that very deep borehole disposal appears to permit emplacement of the waste at depths where the entire repository zone would be surrounded by stable,

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[14] See, for example, Patrick V. Brady, Bill W. Arnold, Geoff A. Freeze, Peter N. Swift, Stephen J. Bauer, Joseph L. Kanney, Robert P. Rechard, Joshua S. Stein (2009), Deep Borehole Disposal of High-Level Radioactive Waste, Sandia National Laboratory Report SAND2009-4401, available as brc.gov/e-mails/August10/Borehole_SAND2009-4401.pdf.

[15] Karl-Inge Åhäll (MKG, 2006), Final Deposition of High-level Nuclear Waste in Very Deep Boreholes: An evaluation based on recent research of bedrock conditions at great depths. MKG Report 1, October 2006. Swedish NGO Office of Nuclear Waste Review (MKG). Available as http://www.nuclearliaison.com/pdfs/MKG_Final_Deposition_of_High_Level_Nuclear_Waste_in_Very_Deep_Boreholes_December_2006.pdf.

density-stratified groundwater having no contact with the surface, whereas a KBS-3 repository would be surrounded by upwardly mobile groundwater."

"This hydro-geological difference is a major safety factor, which is particularly apparent in all scenarios that envisage leakage of radioactive substances. Another advantage of a repository at a depth of 3 to 5 km is that it is less vulnerable to impacts from expected events (e.g., changes in groundwater conditions during future ice ages) as well as undesired events (e.g. such as terrorist actions, technical malfunction and major local earthquakes)."

MKG notes, however, that "[d]ecisive for the feasibility of a repository based on the very deep borehole concept is, however, the ability to emplace the waste without failures. In order to achieve this further research and technological development is required.[on] borehole disposal" The research reviewed by MKG included work done in the UK (see below), in Germany, and in Sweden by SKB (Svensk kärnbränslehantering AB, or the Swedish Nuclear Fuel and Waste Management Company).

- The Deep Borehole Disposal Research Group of the Immobilization Science Research Laboratory at the University of Sheffield, United Kingdom (UK) has undertaken a variety of different type of research on deep borehole disposal of nuclear materials, including the geological and other aspects of disposal of both low temperature (for example, cooled spent fuels and high-level wastes) and high temperature (for example, "young" spent nuclear fuel) nuclear materials. A recent review by Fergus Gibb, a leader of the University of Sheffield group, concludes "A number of DBD concepts for vitrified HLW, spent fuel and fissile materials have passed the scientific proof-of-concept stage. A performance assessment has confirmed the strength of the generic safety case for DBD, although more detailed quantifications of individual concepts still need to be made. Technologies exist for drilling the boreholes, deploying and recovering waste packages, creating the near-field engineered barriers and sealing the boreholes. All that is needed are practical demonstrations that they can be successfully employed at the depths required. The potential returns for the management of high-level wastes are out of all proportion to the relatively modest investment required to start such a programme."[16] Additional recent UK-based summaries of DBD application to nuclear materials include reports prepared by Safety Assessment Management Ltd. For the NIREX corporation, and by John Beswick for the Nuclear Decommissioning Authority of the UK[17].
- Researchers at the Department of Nuclear Science and Engineering of the Massachusetts Institute of Technology (MIT), including as a part of the 2003 review, The Future of Nuclear

[16] F. Gibb (2010), "Radwaste Management Deep boreholes: Looking down the bore". Nuclear Engineering International, 25 March 2010. Available as http://www.neimagazine.com/story.asp?storyCode=2055863. See also the earlier review, N. Chapman and F. Gibb (2003), "A Truly Final Waste management solution: Is Very Deep Borehole Disposal a Realistic Option for High-level Wastes or Fissile Materials?". Radwaste Solutions July/August 2003, p.26-37.

[17] NIREX, Inc. (2004), A Review of the Deep Borehole Disposal Concept for Radioactive Waste. NIREX Report # N/108. J. Beswick (2007), Status of Technology for Deep Borehole Disposal, prepared for the UK Nuclear Decommissioning Authority, June 2007.

Power[18], have studied and reviewed various aspects of the DBD concept, including investigations of the flow of heat in boreholes, cost evaluations, the design of canisters for disposal, and issues associated with the siting and licensing of national and regional facilities, among other topics[19]. In a recent review, Michael Driscoll of MIT offered the following summary of the MIT group's findings on the topic over the past 20 years[20]:

"--Confirmative of work by others

--Prospects are good for very effective sequestration

--The main escape threat is by transport in water

--Most challenging radionuclide is I-129

--Weakest link may be borehole plug

--The approach appears to be cost--effective: <100 $/kg HM for ready--to--use hole (1 mill/kW[h] fee is equivalent to ~400 $/kgHM)

--The thermal loading is quite tolerable – local max. rock temperature increase can be kept to 20° to 30°C"

and

"--Deep boreholes are worth reconsideration – especially as an alternative to transmutation

--Should exploit synergism with enhanced/engineered geothermal systems (EGS)".

Other groups, including Europe-based ARIUS (the Association for Regional and International Underground Storage[21]) also have or are beginning research projects to investigate the prospects for DBD of nuclear materials.

2.3. Siting of Borehole Facilities

Some of the key criteria for siting of DBD facilities for disposal of nuclear materials include the presence of crystalline rock at the surface or within 1 km of the surface in locations that are tectonically stable and located at a distance from population centers, and not near international borders (for example, greater than 200 km from borders)[22]. Other key considerations as described by various authors include "relatively easy to drill, yet stable

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[18] MIT (2003), The Future of Nuclear Power: An Interdisciplinary MIT Study. Available from http://web.mit.edu/nuclearpower/. Deep borehole disposal is discussed briefly in Chapter 7 of this report ("Alternative disposal technologies: The deep borehole approach", page 56).

[19] One example of the MIT group's research on the DBD topic is C. Hoag (2005), Canister Design for Deep Borehole Disposal of Nuclear Waste, Available as www.dtic.mil/cgi-in/GetTRDoc?Location=U2&doc=GetTRDoc.

[20] M. Driscoll (2010), "A Case for Disposal of Nuclear Waste in Deep Boreholes", prepared for Deep Borehole Disposal of Nuclear Waste: Sandia-MIT Workshop, March 15, 2010, Washington, DC, and available as http://www.mkg.se/uploads/Presentation_-_Michael_Driscoll_-_A_Case_for_Disposal_of_Nuclear_Waste_in_Deep_Boreholes_100315.pdf.

[21] Charles McCombie and Neil Chapman, personal communication. See http://www.arius-world.org

[22] Heiken, G, Woldegabriel, G, Morley, R, Plannerer, H and Rowley, J. Disposition of excess weapons plutonium in deep boreholes – Site selection handbook. Report of the Los Alamos National Laboratory, Report LA-13168-MS. 1996.

sedimentary cover over a medium to course grained crystalline basement [that is, basement rocks of low permeability to flow of water] in a relatively unstressed rock mass with a near saline water regime at depth"[23], and "stable crystalline basement rocks in regions with average geothermal heat flow"[24]. The granitic or other crystalline basement rock should ideally be less than 2 km deep to provide for a long disposal zone in the borehole, and geochemically reducing conditions at the disposal depth to limit the mobility of elements in the wastes[25]. It has been suggested that potential locations for borehole disposal, in additional to (preferably remote) continental locations, could include undersea locations, accessed from manmade islands or by directional drilling from coastal locations, or remote islands over stable basement rocks[26].

Conversely, sites that would not be well-suited for deep borehole disposal of nuclear materials would include sites in or near areas of active volcanism (due to the risk of emplaced materials being melted and brought to the surface with magma), sites at or near where the earth's crustal plates collide or are drawing apart (which are often volcanic, and in any case again offer the possibility of mixing and vertical transport of wastes with rock), sites with soft or heavily fractured basement rocks (due to the greater potential for deep groundwater bearing radioactivity to make its way to the biosphere), and areas that are near substantial human populations (due to enhanced—though likely still small—risk of interaction of humans with wastes in the short term, and possibly in the longer term as well).

2.4. Preparation of Boreholes

Deep borehole disposal would be done in boreholes drilled with equipment designed for petroleum or other geological prospecting or exploration, or, ultimately, with advanced equipment purpose-built for the task. To date, most studies have considered final (disposal zone) borehole diameters of about 0.45 meters, though work done in Sweden in the early 2000s considered boreholes of up to 0.8 meters in diameter. The diameter of boreholes is an important issue, as the larger the diameter, in theory, the larger the waste canister that can be accommodated, and the greater the quantity of waste that can be disposed of in a single

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[23] J. Beswick (2007), Status of Technology for Deep Borehole Disposal, prepared for the UK Nuclear Decommissioning Authority, June 2007.

[24] N. Chapman and F. Gibb (2003), "A Truly Final Waste management solution: Is Very Deep Borehole Disposal a Realistic Option for High-level Wastes or Fissile Materials?". Radwaste Solutions July/August 2003, p.26-37

[25] W. W Arnold, B. N. Swift, and P. V. Brady (2010), "Deep Borehole Disposal—Performance Assessment and Criteria for Site Selection", prepared for Deep Borehole Disposal of Nuclear Waste: Sandia-MIT Workshop, March 15, 2010, Washington, DC.

[26] Remote islands offer particular advantages for deep borehole disposal, including making drilling or tunneling into the disposal error much more difficult (given existing technologies, at least) due to the "moat" effect of the island location, and that (assuming adequate port facilities), nuclear materials could travel by sea to the disposal sites, thus avoiding at least some land transit that might go through populated areas (and the related risk of terrorist attack). In addition, some sea islands are already controlled by the military of nuclear weapons states, for example, in the Russian Far East region. Islands chosen to host deep borehole disposal sites, however, would have to offer the same stable basement geology as good sites on continents, that is, would have to be non-volcanic, not be in areas where crustal plates collide or separate, and offer crystalline rocks and hydrology isolated from the biosphere at disposal (3 – 5 km) depths.

borehole[27]. In its evaluation of the DBD technology, Sandia National Laboratory envisioned a series of holes of decreasing diameters constituting a borehole for disposal of nuclear materials, starting with a 1.2 m diameter hole at the surface (to 15 m), then a 0.9 m hole to 150 m, and a 0.66 m hole to 1500 meters, with a 0.45 m hole extending to 5.2 km and including the disposal zone for nuclear materials.

Different lining strategies are used for the different hole diameters, as shown in Figure 3[28]. Liners made of metal and cement are used to seal segments of the borehole to prevent migration of materials from the borehole to the surrounding rock, to facilitate the placement of waste materials, and to limit the flow of groundwater through the borehole, particularly at shallower depths. In some concepts, however, boreholes are left unlined, particularly when high-temperature disposal (where the heat from radioactive decay of the nuclear materials in the disposal package melts the surrounding rock, which ultimately cools to provide a "sarcophagus" of rock around the package) is the goal. Figure 4 provides a schematic of the emplacement of canisters of nuclear material in the borehole, and Figure 5 shows an overview of a borehole installation within its surrounding geology[29]. Though most deep borehole disposal studies have focused on borehole diameters of less than 1 meter (often less than 0.5 m), which are consistent with most experience in geological exploration and expected to be most cost-effective, larger diameter holes are certainly possible. Boreholes up to 5 meters in diameter and 2 km in depth (but not both) have been used in the past for nuclear explosives testing and deep mine access[30]. Future improvements in mining and geological exploration technologies may make larger-diameter boreholes more feasible and economical.

[27] As indicated in a companion paper prepared for Nautilus by Jungmin Kang ("An Initial Exploration of the Potential for Deep Borehole Disposal of Nuclear Wastes in South Korea", December, 2010), this issue may be of special significance in nations that use heavy water reactors (CANDU-type), which use unenriched uranium fuel, and as a consequence produce a much larger volume of spent fuel to be managed per unit of electricity output than light water reactors.

[28] Figures 3 and 4 are taken from Patrick V. Brady, Bill W. Arnold, Geoff A. Freeze, Peter N. Swift, Stephen J. Bauer, Joseph L. Kanney, Robert P. Rechard, Joshua S. Stein (2009), Deep Borehole Disposal of High-Level Radioactive Waste, Sandia National Laboratory Report SAND2009-4401, available as brc.gov/e-mails/August10/Borehole_SAND2009-4401.pdf.

[29] Figure 5 is taken from Figure 1 in N. Chapman and F. Gibb (2003), "A Truly Final Waste management solution: Is Very Deep Borehole Disposal a Realistic Option for High-level Wastes or Fissile Materials?". Radwaste Solutions July/August 2003, p.26-37

[30] J. Beswick (2007), Status of Technology for Deep Borehole Disposal, prepared for the UK Nuclear Decommissioning Authority, June 2007.

Figure 3: Schematic of Borehole Disposal Concept Showing Proposed Drill Diameters and Liners

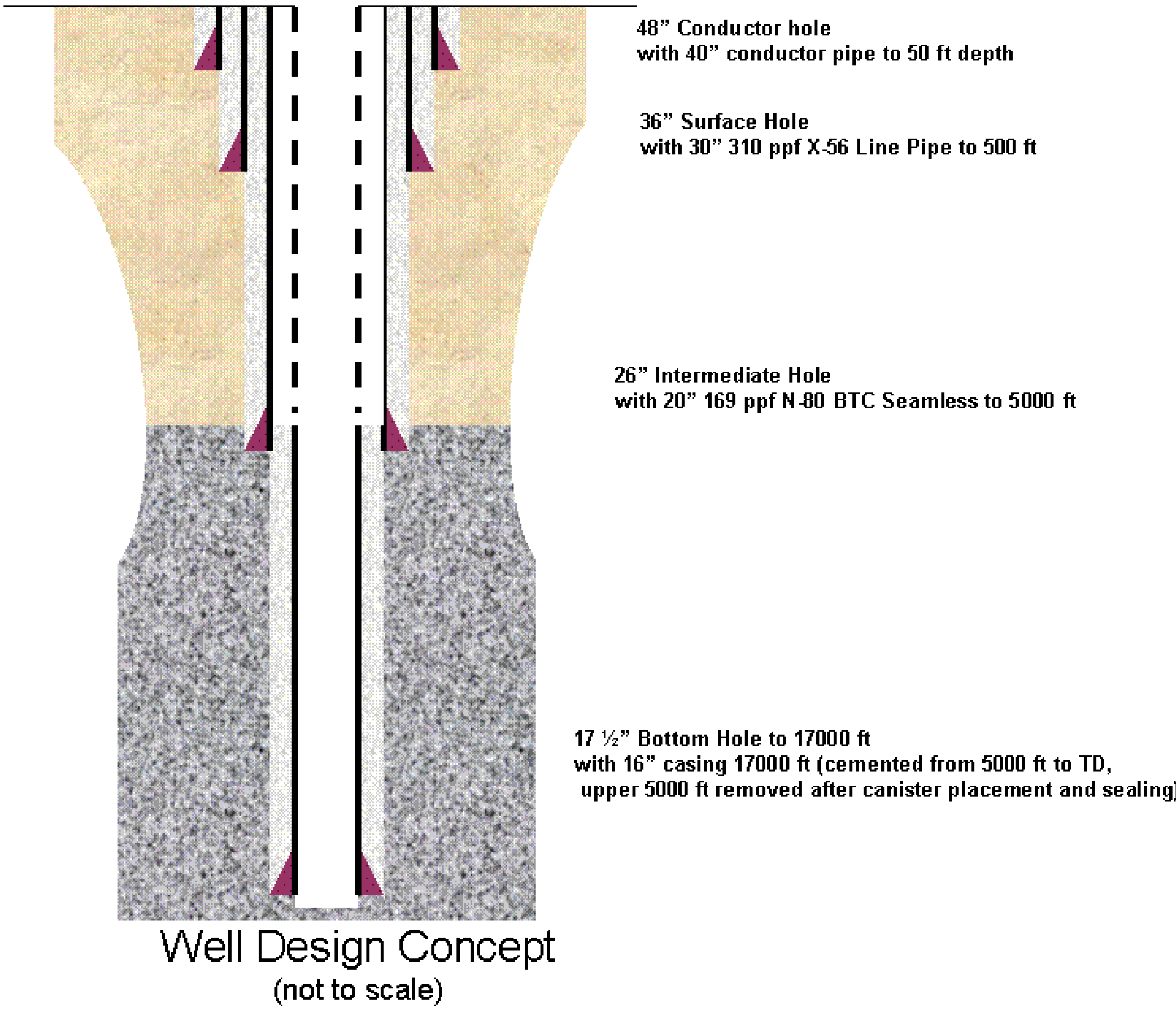


Figure 4: Schematic of Borehole Disposal Concept Showing Placement of Nuclear Materials within Borehole

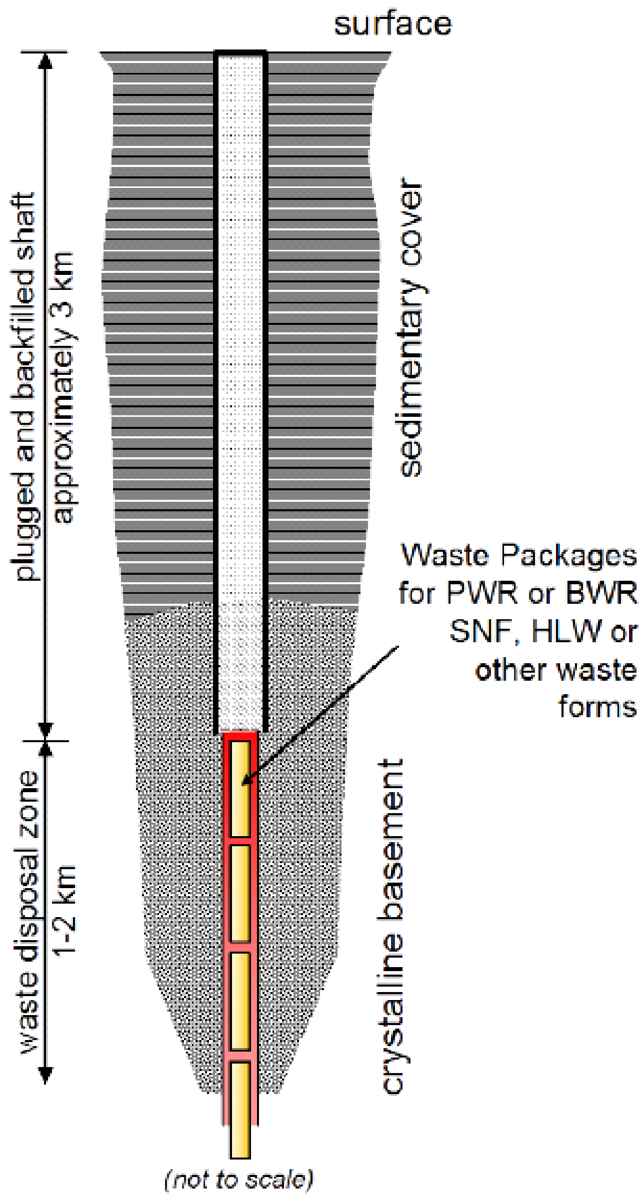
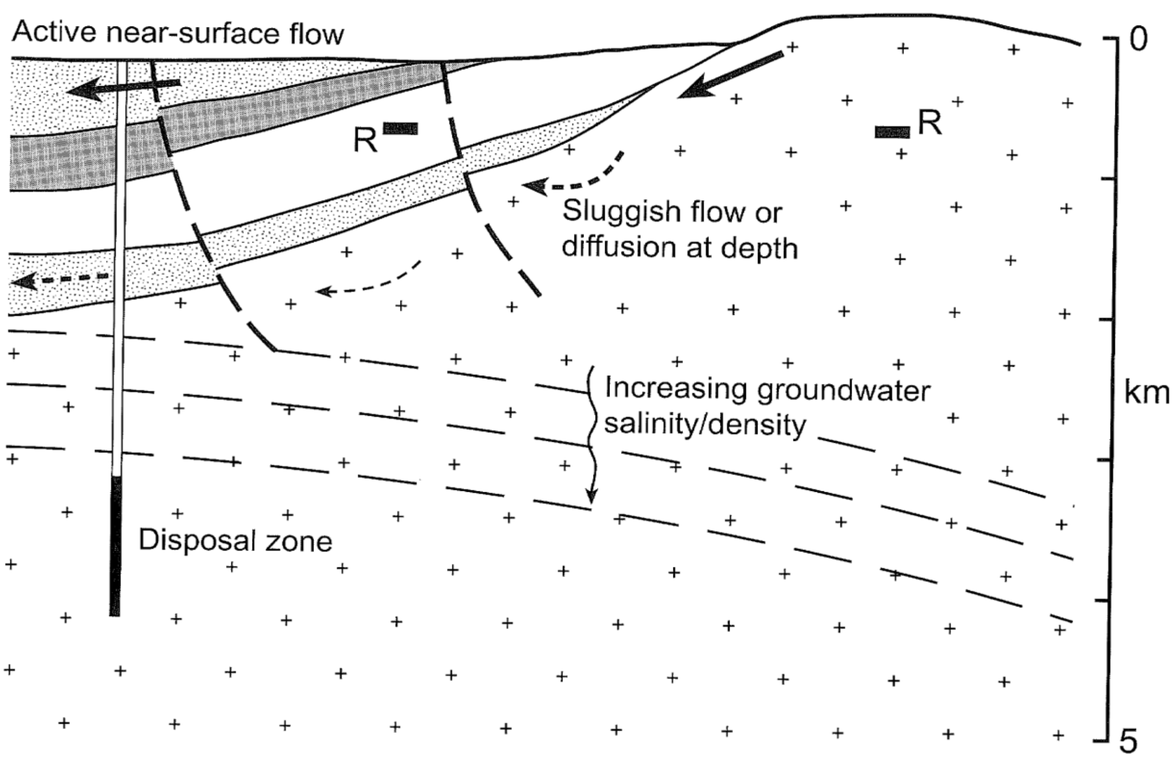


Figure 5: Example of Borehole Disposal Concept Showing Placement of Borehole within Surrounding Geology



2.5. Preparation of Wastes for Disposal

Nuclear materials to be disposed of in deep boreholes must be prepared for disposal. In some cases, this is as simple as placing the materials, with little preparation, in a metal canister made of steel, copper, or other materials. In some cases more complex types of preparation are required. Three major types of nuclear materials are typically considered for DBD:

- **Spent fuels from nuclear power plants**, in particular, today and in the near future, from light-water reactors and heavy water reactors. Fuel assemblies for the most common PWR (pressurized water reactor) and BWR (boiling water reactor) power plants measure from about 0.14 to 0.2 meters square and 4.0 to 4.5 meters long, and in the simplest disposal protocol, would be placed cylindrical metal canisters on the order of 0.25 to 0.35 m in diameter for borehole disposal. A simple type of canister for disposal of spent fuels could be made from well casing of the appropriate diameter, with end-caps welded on, and filled with powdered clay (bentonite) to stabilize assemblies during emplacement. The disposal canisters need to be strong enough to prevent releases of radioactivity and exposure through the process of waste emplacement phase, factoring in the possible need for strength during recovery operations in case canisters are stuck or damaged during emplacement[31]. Otherwise, the canisters need not have any intrinsic containment characteristics of their own, though some studies (and historical/geological evidence) indicates that copper has attractive properties as a canister material due to its long-term stability in reducing environments underground. Spent nuclear fuel destined for low-temperature DBD would be cooled in a combination of spent fuel pools and, perhaps, additional intermediate storage for on the order of 30 years before they are placed in a container for disposal. This cooling time allows short-lived radioactivity (especially from the fission products Strontium-90 and Cesium-137) to decay substantially, reducing the overall thermal burden of the wastes substantially. In the high-temperature DBD variant, fuels would be emplaced much earlier after removal from the reactor. We presume that the latter option of necessity requires a number of modifications in procedures for fuel handling due to the additional radioactivity and thermal flux of the uncooled spent fuel[32], and probably considerable additional expense, but we have not researched such requirements in detail. As research on the DBD concept continues, it may become useful to research methods of packaging fuel elements more densely than their original assembly in order to be able to place more elements per unit length/depth of borehole. The key criterion here would be to keep fuel elements sufficiently separated that the risk of a self-sustained nuclear chain reaction event (critical event or "criticality") is acceptably low. Up to the point where criticality is a concern, however, and assuming thermal limits for disposal are not exceeded, any addition to the density of spent fuel packing for disposal increases the amount of material that can be placed per borehole, reducing the number of boreholes that must be drilled, but at the cost (and potential security risk, and associated safeguards requirements) of additional handling of nuclear materials.

- For **high level wastes, for example, from reprocessing operations**, originally liquid wastes are typically concentrated, then mixed with borosilicate glass in a process called "vitrification" into glass logs. These logs are poured (or placed) into canisters, which could be placed in deep borehole disposal. Because the volumes of these wastes are typically small relative to the volume of spent fuel, and thus occupy relatively little space per unit of nuclear electricity produced, HLW are expected by many researchers to be good candidates for borehole disposal. In Japan, the source of most of the vitrified HLW currently produced from reprocessing of spent fuel in the East Asia region, HLW is contained in canisters 1.34 m in height and 0.43 m in diameter[33]. These canisters would be a tight fit for a 0.45 m borehole, but are of approximately the right size for borehole disposal.
- For disposal of **plutonium**, a number of options exist. Plutonium can be disposed of in the form of mixed oxide fuel (presumably, either fresh fuel or spent fuel), mixed with HLW, as a metal, as an oxide, mixed with other actinides, or immobilized with other substances (for

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[31] Patrick V. Brady, Bill W. Arnold, Geoff A. Freeze, Peter N. Swift, Stephen J. Bauer, Joseph L. Kanney, Robert P. Rechard, Joshua S. Stein (2009), Deep Borehole Disposal of High-Level Radioactive Waste, Sandia National Laboratory Report SAND2009-4401, available as brc.gov/e-mails/August10/Borehole_SAND2009-4401.pdf.

[32] For example, spent fuel that has been removed from a reactor for one year has approximately ten times the thermal flux of spent fuel that has cooled for 30 years. C. Hoag (2005), Canister Design for Deep Borehole Disposal of Nuclear Waste, Available as www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.

[33] Federation of Electric Power Companies of Japan (FEPC, 2002), Japan's Vitrified Waste Program". Available as http://www.japannuclear.com/nuclearpower/waste.

example, in a rock or glass matrix) including with other radioactive materials. NIREX[34], based on earlier US DOE studies, suggests that plutonium could be immobilized in synthetic rock-like titanate ceramic pellets with thin Pu-free coating at a 1% Pu loading, mixed with an equal volume of Pu-free ceramic pellets and kaolinite (clay-based) grout, and emplaced directly in boreholes without any canisters Halsey[35] lists the key characteristics that can affect disposal of HLW in general as radionuclide inventory, chemical and mechanical attributes, criticality control, thermal output, release rates (aqueous and gaseous), and diversion resistance, and each of these is a consideration in developing appropriate packaging for disposal of plutonium in deep boreholes.

2.6. Emplacement and Entombment of Wastes

Emplacement of nuclear materials in boreholes entails a combination of moving nuclear materials to the borehole site (either before or after placing the materials in canisters for disposal), handling the materials on site—which may require special equipment depending on the radioactivity of the materials, lowering the disposal canisters into place, and entombing the canisters.

Moving materials to the site will likely use the types of road vehicles, rail cars, and ships now used for moving nuclear materials around the world. These vehicles range from highly specialized (for example, for nuclear spent fuel) to quite standard, depending on the form of the nuclear materials and the mass of its container.

Processing of materials for disposal could take place on-site at the borehole or at facilities nearer to the origin of the wastes. Deciding on which of these approaches makes more sense will depend on the types of materials to be handled and the processing required, as well as the transport route and mode for moving the materials, but also on non-technical issues such as nuclear materials handling policies in the country or countries involved, local jobs issues, and international safeguards considerations.

Handling canisters at the borehole site may require special shielding and remote handling equipment if the materials to be disposed of are sufficiently radioactive as to be dangerous for humans to be near the canisters.

Lowering canisters into place will likely be done using a system of cables, perhaps aided, especially in lined boreholes, by a custom-built carriage to guide the canister on its way down. The carriage may be retrievable or may be left in place in the borehole once the canister reaches the disposal position. One can imagine canisters being guided and supervised on its way down by a combination of cameras and lights allowing operators to observe progress, and possibly remote-controlled and/or "smart" robotic equipment allowing operators to guide canisters

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[34] NIREX, Inc. (2004), A Review of the Deep Borehole Disposal Concept for Radioactive Waste. NIREX Report # N/108

[35] W. G. Halsey (1996), "Repository and Deep Borehole Disposition of Plutonium". Paper was prepared for submittal to the American Nuclear Society 1995 Annual Meeting Philadelphia, PA, June 26,1995, dated February, 1996; Lawrence Livermore National Laboratory # UCRGJC-123436 PREPRINT. Available as www.osti.gov/bridge/servlets/purl/241548-bT41lr/webviewable/. See also K. L. Ferguson, Excess Plutonium Disposition: The Deep Borehole Option, Report # W S RC -TR-94-0266, dated August 9, 1994, and available as http://www.osti.gov/bridge/servlets/purl/10187048-6FP5W8/webviewable/10187048.pdf.

through difficult areas, free canisters when stuck, and/or "ream" out bore holes to allow passage of the canisters. These types of equipment may in part be available already,, but some will doubtless have to be developed for the purpose, as experience operating at the extreme depths contemplated for DBD is currently lacking.

A number of different alternatives exist for entombment of wastes placed in deep boreholes, varying in part with whether "cold" or "hot" waste placement is envisioned. Many concepts of DBD include filling in spaces between waste canisters vertically in the borehole, and between the borehole wall and the canisters, with materials such as grout, cement, or bentonite (mostly for cold wastes emplacement). Concepts for hot waste emplacement call for a substantial plug of concrete to be poured at the base of the hole, then for hot waste canisters to be inserted in the hole, melting the surrounding rock and sealing in the nuclear materials. A variant of this approach for cooled materials disposal uses electrical heating elements inserted into the borehole to melt the surrounding rock at intervals to seal in the canisters below. Another proposal uses a high-density support matrix (HDSM) material above and around low-temperature canisters. The composition of the HDSM is such that it is melted by the heat from the canisters, then slowly cools as the canisters cool, "effectively soldering the canisters in place"[36]. Examples of HDSM are fine metal shot (tiny spheres) made, for example, of lead and lead alloys[37].

Several of these approaches are shown schematically in Figure 6. Once the disposal zone in the borehole is filled by one of the methods above, the remainder of the borehole is filled with a combination of crushed rock, cement, and other materials. Considerations in filling the top portion (top 2-3 km) of the borehole include isolating the bottom part of the borehole from the hydrology of the upper geological layers, in part by using materials that allow normal groundwater flow through the upper part of the borehole and removing the upper hole casing, though this approach is not used in all concepts. Near the top of the hole, most concepts include a thick cement plug, then the top of the borehole is obliterated, and the site restored (but cataloged) to make finding the borehole difficult for intruders.

Directional drilling, which is becoming much more common in the oil and gas industry, may allow a single borehole access shaft to be used to drill multiple emplacement boreholes at slight (a few degrees) angles to the main shaft, thus reducing drilling costs and the footprint of a major disposal facility. Figure 7 (from MKG[38], after Chapman and Gibb, 2003) shows a schematic of how directional drilling might work (though the angles of deviation from the central

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[36] F. Gibb (2010), "Deep Borehole Disposal as an Alternative to Mined Repositories for Spent Fuel and Other HLW", Presentation dated September 28, 2010. This presentation is the source for Figure 4. A similar presentation by the same author was provided at the Deep Borehole Disposal of Nuclear Waste Sandia-MIT Workshop, March 15, 2010.

[37] F.G.F. Gibb, N.A. McTaggart, K.P. Travis, D. Burley and K.W. Hesketh (2007), "High-density support matrices: Key to the deep borehole disposal of spent nuclear fuel". Journal of Nuclear Materials, Volume 374, Issue 3, 15 March 2008, Pages 370-377.

[38] Karl-Inge Åhäll (MKG, 2006), Final Deposition of High-level Nuclear Waste in Very Deep Boreholes: An evaluation based on recent research of bedrock conditions at great depths. MKG Report 1, October 2006. Swedish NGO Office of Nuclear Waste Review (MKG). Available as http://www.nuclearliaison.com/pdfs/MKG_Final_Deposition_of_High_Level_Nuclear_Waste_in_Very_Deep_Boreholes_December_2006.pdf.

hole are much greater in the schematic than they would likely be in a real installation). Directional drilling of multiple disposal zones from the same central borehole would, however, somewhat complicate the emplacement of wastes, as the disposal zones are no longer all directly below the access hole, and as it would be necessary to guide canisters into different disposal hole openings. Development of new remote technologies to aid the waste emplacement process and keep track of where canisters have been placed may be required.

Figure 6: Examples of Wastes Emplacement in Boreholes with Different Sealing Approaches (LTVDD = "Low Temperature Very Deep Disposal" and HTVDD = = "High Temperature Very Deep Disposal")

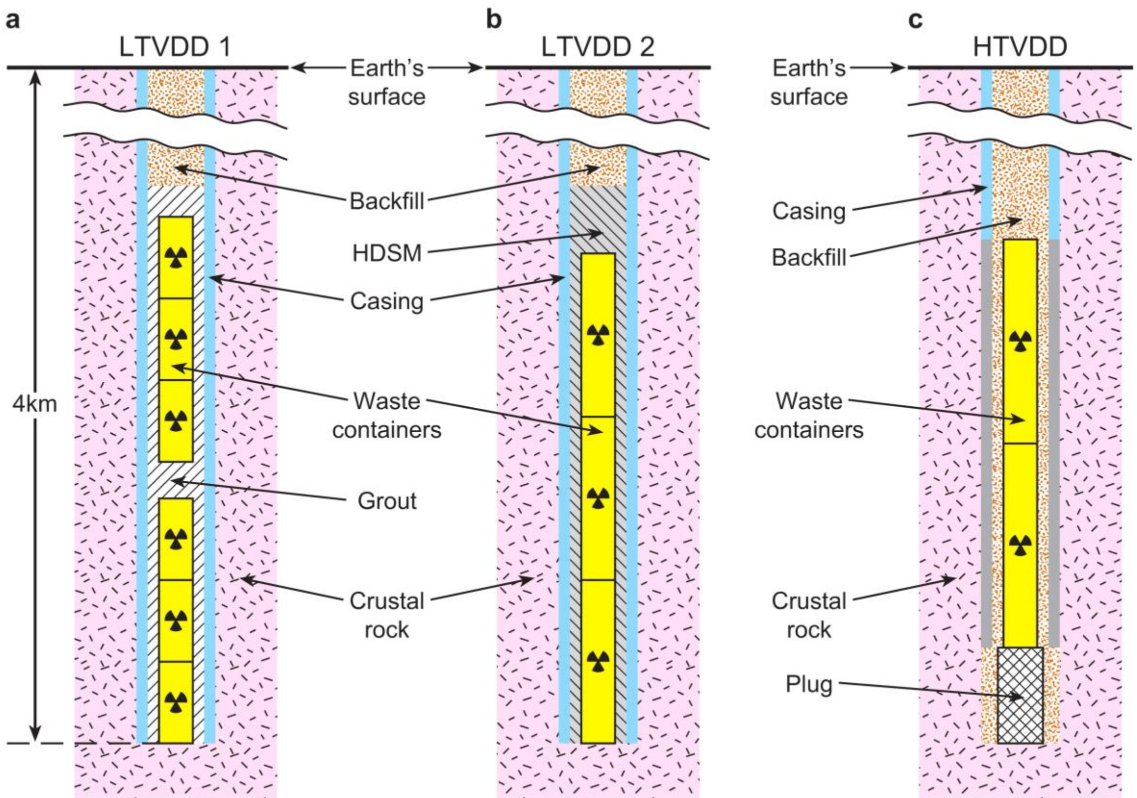
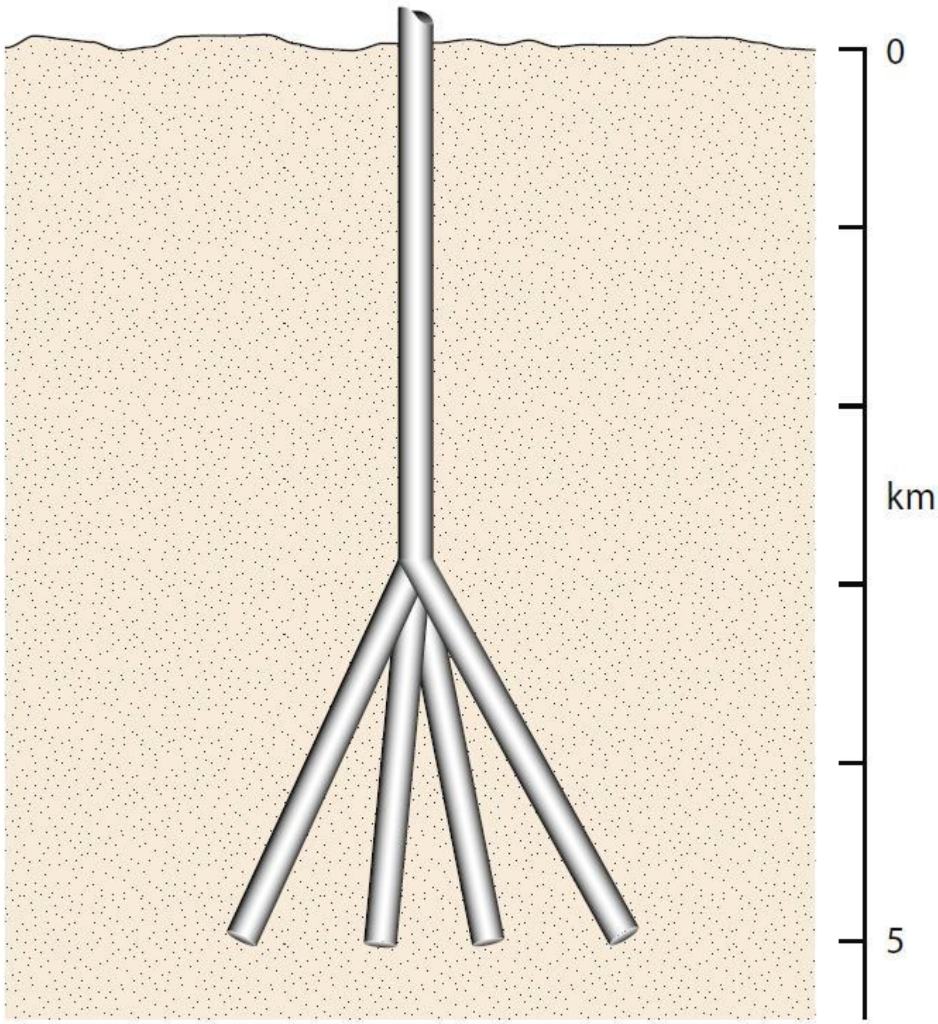


Figure 7: Example of "Fanned Array" Drilling to Increase Efficiency of Wastes Emplacement in Boreholes



2.7. Site Security

Nuclear materials-related security concerns related to DBD sites can be divided into those related to the handling of nuclear materials at the site during emplacement operations, and those of concern after emplacement is complete.

During emplacement operations, the types of security needed at the site will depend on the types of materials handled and the types of processes carried out on site. A DBD site that simply receives nuclear materials in sealed canisters for disposal will require less complex arrangements for securing nuclear materials than a site that takes in nuclear wastes in other forms (for example, spent fuel rods, and in the extreme case, plutonium metal), processes them in some way, and places them in containers for DBD insertion. In each case, however, particularly in facilities shared by several countries, stringent safeguards, materials accounting, and oversight procedures will be necessary to assure DPB project participants that all nuclear material fuels entering the DBD facility are properly handled and ultimately placed permanently in boreholes.

In the longer term, a key advantage of deep borehole disposal is that the depth of burial of nuclear materials is such as to impose a formidable physical barrier to state and non-state actors who might try to access the emplaced materials. Sealing the borehole as described above essentially means that it will be no easier (perhaps more difficult) to access the disposed materials via the remains of the borehole shaft itself then via a new borehole drilled nearby. Drilling several kilometers into the earth in search of buried nuclear wastes is today a time-consuming task, and one that seems unlikely, even with current remote surveillance technologies, to go undetected. In the future, drilling technologies (or other technologies for digging holes as yet undeveloped) will doubtless improve such that creating a hole in the earth will be cheaper and faster, but technologies for detecting such activities will likely develop apace. In any case, it is possible that sensors buried within the borehole could be left with the emplaced nuclear materials to both provide feedback on the status of the materials and to indicate the presence of disturbances—such as seismic activity or nearby drilling—that could affect the security of the materials in the borehole. Developing power sources that would power such sensors for hundreds or thousands of years, either within the borehole or by wire from the surface, may be daunting. Building and maintaining the social organization required to keep track of such sensors and their outputs over such a time period, however, is at likely to be at least as daunting. It may even be that the best approach, in the long term, to securing deep borehole disposal of nuclear wastes is ultimately to restore the site as much as possible to its original condition, and trust on the depth of burial to provide security, even without significant ongoing monitoring. Deciding on a long-term security approach is a matter for significant policy discussion, necessitated by the long-term nature of the commitments that we as humans have made (fully wittingly or not) when we decided to harness nuclear power.

The IAEA has published a guide entitled <u>Borehole Disposal Facilities for Radioactive Wastes, Specific Safety Guide</u>[39]. Although this guide focuses on near-surface (30 m or less) or intermediate (down to a few hundred meters) borehole disposal, it may provide a starting point for development of international regulations for deep borehole disposal of radioactive materials.

2.8. Costs

The major cost associated with deep borehole disposal, and the major time requirement, is for drilling the borehole itself. The studies we have reviewed offer a range of different costs estimates, which is not wholly surprising given that exploration of the DBD concept is in an early phase. Several trends are clear, however. First, drilling costs increase substantially with the diameter of the borehole. Current drilling technologies developed for the petroleum extraction and mining fields can drill holes of 0.5 m or less fairly readily, but drills to make larger-diameter boreholes, though they do exist, are much less common (and even rigs to drill 0.5 m holes are not currently in large supply—see below). Second, and relatedly, the speed at which

[39] IAEA, 2009, Report # SSG-1. Available as www-pub.iaea.org/MTCD/publications/PDF/Pub1418_web.pdf.

a hole can be drilled decreases substantially as hole size increases. Beswick[40] cites a decrease in drill penetration rate of 33% for an increase in hole diameter from 50 cm to 75 cm, with a further 60% decrease in drilling speed in moving up to a 1 meter diameter drill. Third, the deeper the hole, the more slowly drilling is likely to proceed. Beswick suggests that 5 km boreholes will take 30 to 50 percent longer to drill than 4 km boreholes. Finally, the geological conditions encountered in any given hole, and just plain luck—breakage of bit, crumbling of borehole walls, and other events—can dramatically influence the time required to drill a borehole, and, indeed, whether a borehole is ultimately usable for disposal. In a 2009 presentation[41], Beswick estimates the cost of drilling 5 km deep, 0.5 m diameter boreholes at £35 - £40 million for the first boreholes (about $57 to 65 million), with subsequent boreholes costing somewhat less, at £25 - £30 million ($41 to 49 million) each.

Sandia researchers estimate a cost of about $20 million per borehole for a 5 km deep borehole of a design similar to that shown in Figure 3 (~0.45 m diameter at the bottom of the hole), using a drilling approach adapted from geothermal well drilling. The average time to complete a borehole of this depth is estimated by Sandia at 110 days, with a similar time required to place nuclear materials in the borehole and fill it. For a similar-sized borehole (0.5 m), Beswick implies a significantly longer 240 to 270 days would be required for drilling. Estimates from MKG (based on earlier work in Sweden) imply a cost range of about $11 to $29 million per borehole for holes of diameters of 0.6-0.8 m[42]. Chapman and Gibb list costs for 4 km boreholes of 0.8 m diameter that would be on the order of $10 million per hole in today's currency[43].

2.9. Technological Development in Related Industries

Drilling technologies designed for petroleum exploration and production and for geothermal energy extraction are applicable to DBD. Beswick notes that "[d]rilling rigs for oilfield purposes are built up to 4,000 HP size with lifting capacities up to 900 metric tonnes (2,000,000 or 1,000 short ton). These rigs, suitably adapted for this application would probably be suitable for drilling boreholes with finished diameters of 500 mm to 4 km or 5 km. However, there are only two or three rigs of this capacity in the world today."

Technologies in the petroleum and geothermal fields continue to advance in a number of areas, including the composition and efficiency of drill bits, casing technologies, improved bearings, and accumulating experience with drilling deep wells. Directional drilling technologies, such as those needed to drill multiple emplacement zones using the same access

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[40] J. Beswick (2007), Status of Technology for Deep Borehole Disposal, prepared for the UK Nuclear Decommissioning Authority, June 2007.

[41] J. Beswick (2009), "An Alternative to a Deep Mined Repository: Disposal in Large Diameter Boreholes", presented at "Radioactive Waste Immobilization Network Meeting #11", University of Sheffield, UK, 23rd April 2009, and available as http://www.rwin.org.uk/presentations/RWINXI/5-JohnBeswickRWINXI090423.ppt.

[42] Karl-Inge Åhäll (MKG, 2006), Final Deposition of High-level Nuclear Waste in Very Deep Boreholes: An evaluation based on recent research of bedrock conditions at great depths. MKG Report 1, October 2006. Swedish NGO Office of Nuclear Waste Review (MKG). Available as http://www.nuclearliaison.com/pdfs/MKG_Final_Deposition_of_High_Level_Nuclear_Waste_in_Very_Deep_Boreholes_December_2006.pdf.

[43] N. Chapman and F. Gibb (2003), "A Truly Final Waste management solution: Is Very Deep Borehole Disposal a Realistic Option for High-level Wastes or Fissile Materials?". Radwaste Solutions July/August 2003, p.26-37

hole (see Figure 5), are also advancing rapidly. Further advances are likely. In the context of technologies for drilling geothermal wells, a MIT report prepared for the US Department of Energy[44] summarizes some of the potential technologies that might reduce well costs as follows:

> "Such techniques include projectile drilling, spallation drilling, laser drilling, and chemical drilling. Projectile drilling consists of projecting steel balls at high velocity using pressurized water to fracture and remove the rock surface. The projectiles are separated and recovered from the drilling mud and rock chips…. Spallation drilling uses high temperature flames to rapidly heat the rock surface, causing it to fracture or "spall." Such a system could also be used to melt non-spallable rock…. Laser drilling uses the same mechanism to remove rock, but relies on pulses of laser to heat the rock surface. Chemical drilling involves the use of strong acids to break down the rock, and has the potential to be used in conjunction with conventional drilling techniques….. These drilling techniques are in various stages of development but are not yet commercially available. However, successful development of any of these technologies could cause a major change in drilling practices, dramatically lower drilling costs – and, even more important, allow deeper drilling capabilities to be realized."

It is natural to look to the petroleum industry for guidance on whether drilling costs for DBD can be expected to decrease over time. Unfortunately costs trends in the oil and gas industry are complicated by supply and demand factors affecting oil rig availability under different crude oil price regimes. Correcting for some of these factors, as well as for inflation, Augustine et al[45] conclude that with the exception of shallower wells, costs for drilling generally declined between 1981 and 2003. The complex shape of the historical relationship between drilling cost and time, however, makes it currently difficult (it seems to us) to sensibly extrapolate those data to project future DBD borehole costs, particularly as oil and gas (and geothermal) wells typically use significantly smaller-bore holes than would be needed for most types of DBD.

2.10. Key Environmental Safety Concerns

Environmental safety concerns related to DBD include short-term concerns related to borehole drilling and nuclear materials handling and emplacement, and much longer-term concerns associated with the degree to which DBD effectively isolates radioactive materials from the biosphere.

Short-term environmental concerns include:

- Exposure of humans and other living things to radiation during the routine handling of nuclear materials destined for deep borehole disposal. Steps where radioactive exposure could occur include handling of nuclear materials to ready them for transport, transportation

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[44] Massachusetts Institute of Technology (2006), The Future of Geothermal Energy in the 21[st]: Century Impact of Enhanced Geothermal Systems (EGS) on the United States. Chapter 6, "Drilling Technology and Costs", available as www1.eere.energy.gov/geothermal/pdfs/egs_chapter_6.pdf. Full report available from http://www1.eere.energy.gov/geothermal/egs_technology.html.

[45] C. Augustine, J. W. Tester, and B. Anderson (2006), "A Comparison of Geothermal with Oil and Gas Well Drilling Costs", in PROCEEDINGS, Thirty-First Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 30-February 1, 2006. Report #SGP-TR-179, available as www2.cemr.wvu.edu/~anderson/papers/SGP-TR-179.pdf.

to the borehole site, handling at the borehole site (or elsewhere) to place the materials in canisters for disposal, and, ultimately decommissioning of nuclear waste handling facilities associated with DBD.

- Acute exposure to radioactivity and/or long-term contamination could occur at any of the above steps as a result of accidents, including industrial accidents in handling nuclear materials, and road, rail, or shipping accidents—though containers for transport are normally so robust as to rule out most scenarios of such exposure—and radiation release as a result of natural disasters (freak weather events or earthquakes, for example), acts of war, or acts of terrorism or sabotage affecting facilities where nuclear materials are being handled outside of containing vessels. Both these types of exposure and radiation releases due to routine handling of nuclear materials are generic to any nuclear waste management option that involves handling and/or moving of nuclear materials from one place to another.
- Accidental radiation leakage to near-surface groundwater as a result of the failure of emplacement containers before they are lowered through the borehole zones where such groundwater is present, or failure of canisters in place before the borehole is sealed to prevent water flow from the disposal zone of the borehole toward the top of the borehole. These releases could be the result of damage to waste canisters and their contents either as a result of "getting stuck" part way to their emplacement depth, or as result of failed attempts to free "stuck" canisters. Radiologically-contaminated drilling or canister handling equipment, or contaminated drilling fluids, could provide additional pathways for radiation to enter the biosphere.
- Non-radiological environmental impacts of deep borehole drilling and waste emplacement operations could occur as a result of power generation at remote sites (local air pollution) the building and operation of roads to remote borehole sites through delicate environmental areas, and the operation of heavy equipment at borehole sites. These types of impacts are common to any large industrial facility or construction site, but may be exacerbated by the remoteness of DBD facilities.

Long-term environmental concerns associated with deep borehole disposal, as with any type of disposal of radioactive (or, for that matter, highly toxic) materials, are associated with the risk that even if waste placement proceeds entirely as planned, radioactive material in the wastes will ultimately reach the biosphere. Modeling by Sandia National Laboratory and others (see section 2.2) suggests that the probability of significant amounts of radiation reaching the biosphere from materials properly placed in deep boreholes is extremely low—on the order of 10^{-10} times a significant human dose only after the approximately 8000 years needed for the most mobile isotope, Iodine129, to potentially reach surface waters. Other paths of non-routine exposure, such as the disruption of borehole burial sites by volcanic or earthquake activity, by glacial action in ice ages[46], or by human intrusion or some kind[47], should be significantly less

[46] Though ice ages do not seem imminent at present, given increasing human contributions to greenhouse gases in the atmosphere.

[47] It is impossible to predict what types of facilities humans may have for prospecting or even moving around at great depths within the earth's crust thousands, tens of thousands, or hundreds of thousands of years from now, but it seems reasonable to assume, barring some sort of cataclysm, that human abilities to access the earth's deep places

likely for deep borehole disposal than for other types of nearer-surface or at-surface nuclear materials repositories, but, given the long time scales needed for the radiation in nuclear wastes to decay to negligible levels, cannot be totally discounted. These risks can, however be mitigated through careful site selection, DBD design and execution, and consistent communications with future generations about monitoring of DBD emplacements.

3. Key Unknowns, Uncertainties, Regarding DBD of Nuclear Wastes, and Potential Barriers to Application

Despite the significant amount of research the deep borehole nuclear materials disposal concept has received to date (though probably several orders of magnitude less, in monetary terms, than has been spent on mined repository research and development) key uncertainties and barriers to DBD implementation remain in a number of areas. Technological uncertainties, legal uncertainties, and perhaps most significantly, political and institutional barriers must be overcome before deep borehole disposal of nuclear materials can come to fruition, particularly at a regional scale. These uncertainties and barriers are discussed briefly below. In most cases, however, we are focusing on identifying these issues as topics for further collaborative study with colleagues within and outside of East Asia.

3.1. Technological Uncertainties

Technological uncertainties associated with DBD include (but are hardly limited to) issues such as:

- **The extent to which existing drilling technologies are applicable to DBD.** Most experience with drilling deep boreholes is in the oil and gas and mining industries, and most of that experience does not involve boreholes of sufficient diameter to be broadly useful for DBD of nuclear materials.
- Better understanding is needed of **technical issues such as borehole stability** under increased heat and radiation loadings, and under the extreme pressures encountered in deep boreholes. For example, will the walls of boreholes at great depth remain as drilled? Ferguson[48] notes that the "[d]iameter of hole and depth are key parameters. Stress/strain impacts on [the] surrounding geosphere will be more critical than in previous drilling. Some evidence suggests that changes in the dimensions of boreholes over time at depths of 4-5 km may be significant enough to affect the emplacement of canisters.

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will be better than they are today. As such, the potential for future humans to encounter DBD-emplaced wastes cannot be utterly discounted.

[48] K. L. Ferguson (1994), Excess Plutonium Disposition: The Deep Borehole Option. Prepared for the U.S> Department of Energy; Report number W S RC -TR-94-0266, dated August 9, 1994. This reference includes the passage "The borehole testing program planned by the Germans includes handling and emplacement demonstration as a key focus. There has recently been emphasis on an assessment of long-term dimensional changes ('convergence') of boreholes. This type of behavior can have significant emplacement and/or retrieval consequences. Recent measurements at temperatures well below expected extremes of the depths of deep borehole emplacement indicate a reduction in borehole diameter of one meter holes in the range of several millimeters after 1 year and further converging at a similar rate for the following year or two. At the more extreme pressures of the depths of the deep borehole concept the rates may be at an accelerated pace."

- **How to monitor boreholes**. What types of monitoring systems will be needed (if any?) in order to ensure that borehole disposal performs as expected? What types of technologies can be deployed to assure that monitoring can be carried out over the long term?
- Research is needed to **better understand the movement of groundwater** at very great depths, and the impacts that boreholes themselves can have on groundwater movement at the disposal depths What happens if packages are stuck on the way down
- **The degree to which progress in drilling technologies can meet the needs of DBD implementation in a timely manner** is a key uncertainty. Progress in drilling technologies for continues, but the impact of that progress on the types of boreholes needed for DBD of nuclear materials is hard to estimate. What impact will progress in drilling technologies have on the costs of deep borehole disposal?
- The need to line boreholes with metal or other casings. It is unclear what fraction of a borehole accommodating nuclear materials must be lined or should be lined. For boreholes not lined, systems will be needed for recovering casings, as well as for obliterating the upper portions of boreholes when holes are completed. How will sealing systems work (and what sealing systems should be used) over the great distances involved in DBD of nuclear materials? Research on the hydrology at depth and the dimensional stability or large-diameter, deep boreholes, along with convergence on the types of nuclear wastes to be emplaced, will help to identify the needs to line disposal boreholes.
- Technologies for shaft disposal (lowering canisters into place), handling of packages at depth, recovering from borehole jams[49].

3.2. Legal Uncertainties

In addition to the technical issues above, a number of national and international legal uncertainties will need to be addressed and resolved before DBD facilities for nuclear spent fuels can be implemented. These uncertainties include (but again, are by no means limited to):

- **International jurisdiction over deep strata, especially when under seabeds**. Which legal entities have jurisdiction over the geological strata that DBD would use? And in instances where such boreholes extend out from national boundaries (or are in international waters), what existing laws, if any, pertain to DBD?

  One possibility for DBD noted above is to use directional drilling, or man-made islands to place nuclear materials in deep boreholes drilled under the seabed. Sub-seabed disposal is apparently prohibited under the UN Convention on Law of the Sea and the associated London Convention and Protocol[50], but we have not yet seen information indicating whether

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[49] These and other technical/engineering uncertainties and research needs are identified by N. Chapman and F. Gibb (2003), "A Truly Final Waste management solution: Is Very Deep Borehole Disposal a Realistic Option for High-level Wastes or Fissile Materials?", Radwaste Solutions July/August 2003, p.26-37, as well as in P. V. Brady and M. 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, and available as .

[50] C. Whipple (2010), "Disposal of Spent Nuclear Fuel and High-level Radioactive Waste". Prepared as "follow-up to a presentation made to the Disposal Subcommittee of the Blue Ribbon Commission on America's Nuclear Future on July 7, 2010 ", and dated September 10, 2010.

these regulations pertain to placement at the depths contemplated for DBD, or whether this portion of the Law of the Sea is relevant to portions of the seabed not in international waters (that is, in the territorial waters of specific nations).

- In addition, **existing national laws allowing (or not allowing) the burial of spent fuel** will have to be evaluated, and modified, if needed, to make DBD possible. In some nations, laws on the books may make domestic burial of spent fuels difficult.
- **National laws allowing (or not) import of spent fuels from other nations for disposal** will affect the prospects for international collaboration on DBD facilities, as will **national laws regulating the export of nuclear materials**. In both cases, research will need to be done to assess how existing laws would international DBD concepts, and, if needed, laws might need to be modified if the regional community decides to proceed with a shared DBD facility.
- **Licensing regulations for DBD facilities** will be needed to allow DBD plants to be operated legally in their host country, and to be used by other nations. Existing regulations for mined repositories in some nations (and perhaps IAEA guidelines for same) may serve as a starting point, but DBD facilities will have special attributes that require particular licensing regulations—involving, perhaps, standards for the integrity of a borehole before waste is emplaced, the need for groundwater flow testing in boreholes, security arrangements on site, and doubtless many other requirements. Developing, negotiating, and bringing into force these regulations in participating nations will be non-trivial and time-consuming.
- **Compensation arrangements** for DBD facilities hosts will need to be worked out on several spatial levels, including for the local communities within a country that host a facility, for the country hosting the facility, and, potentially, for the countries and communities through which nuclear materials must travel to reach a DBD facility. Deciding on a reasonable level of compensation will be a political, as well as legal, issue.
- **National and international laws and protocols related to** safeguards will be needed to secure fuel shipment and handling in each of the countries participating in DBD consortia prior to disposal. Such laws exist in some of the countries in East Asia that might participate in a regional DBD facility, but not in all, though international models for such laws are available as models.

3.3. Political and Institutional Barriers

At least as important as technical and legal considerations to the future of the DBD concept, and perhaps, arguably, more important, are existing and likely political and institutional barriers to DBD in the countries of the region, and among the international community in general. Understanding these barriers, and how to address them, will be key to the successful implementation of DBD, assuming that further research continues to indicate that DBD is technically promising.

A (non-exhaustive) sampling of some of the potential political barriers to DBD implementation includes the following:

- On the local and sub-national level, the siting of DBD facilities may require political struggles, with local opposition to DBD facilities on the basis of their perceived environmental impacts and radiological risks likely in many nations, and perhaps among environmental groups operating in those nations. Opposition to nuclear materials transport by communities along transport groups, and by non-governmental organizations (local, national, and international), is not unlikely. Companies operating nuclear reactors will also have a political stake in DBD facilities development, including to the extent that adopting a DBD approach affects how they must manage nuclear materials, and as a consequence affects their relationships with communities that host nuclear power plants.

- On the national level, political opposition to the non-retrievable disposal of spent fuels will be an issue, particularly in countries where decisionmakers and/or the public have been conditioned to think of spent fuel as a recyclable product. In those countries, permanent disposal of spent fuel may be interpreted as wasting a national resource, and shipping spent fuel permanently to another nation (particularly one with which the nation shipping the materials has had conflicts in the past) may be seen as unwise (or worse). In addition, if a nation is a candidate to host a national or international DBD facility for nuclear materials, a national debate over the location for such a facility is likely. For a nation hosting an international DBD facility, political opposition to accepting dangerous materials from outside the nation, and being perceived as an "international dump", is likely.
- On the international level, the international politics of non-proliferation and control of the nuclear fuel cycle will need to be taken into account in designing and implementing DBD facilities. Shipping nuclear materials containing fissile material for disposal in countries without nuclear weapons (or even nuclear power) may cause policymakers in nuclear weapons/nuclear power countries to question whether non-proliferation ethics are being violated. Nuclear supplier nations will likely want to have a say in how nuclear materials from the reactors they supply will be managed. At a different level, companies whose business is dependent on building support for reprocessing of spent fuel may put pressure on politicians to oppose DBD of spent fuel and plutonium, if not of other nuclear materials (such as reprocessing HLW).

Institutional barriers also will need to be overcome in building support for, and ultimately building, DBD facilities for disposal of nuclear materials. Some of the barriers likely to be encountered in East Asia include:

- Vested interests by key government or other research groups in other, potentially competing, technologies for spent fuel management, including mined repositories, spent fuel reprocessing (in its various forms), and use of recycled plutonium in mixed-oxide fueled-reactors and/or in fast reactors[51].
- The veiled desire on the part of some military and other groups within governments (other than the longstanding nuclear weapons states) to maintain the capability to develop nuclear weapons based on materials from the nuclear fuel cycle. Maintaining inventories of plutonium separated (or partially separated) from spent nuclear reactor fuel is one way to maintain such a capability, particularly for technologically advanced nations. This

[51] Fast reactors use "fast" (high-energy) neutrons from fission of an atom, that is, neutrons not reduced to "thermal" energies by interaction a moderator such as water (present in LWRs and other reactor designs), to sustain the fission chain reaction. Fast reactors are cooled with liquid metals such as sodium, which do not act as moderators. Fast reactors can be used to fission ("burn") many of the radioactive heavy elements in LWR spent fuels (actinides), and as such can to some extent be considered a competing technology for spent fuel management.

institutional issue is, of course, related to overall perceptions of the nuclear weapons situation in the region, in particular, the North Korean nuclear weapons program.

- Reluctance on the part of nuclear industry regulators, both within nations and at the international level, to consider new approaches to nuclear materials disposal.
- Reluctance on the part of policymakers to address existing political and legal barriers to DBD disposal of nuclear materials.

Political and institutional barriers, as noted above, may ultimately prove the most formidable hurdles to implementation of the DBD concert. Information campaigns targeted at the public and at decisionmakers will be needed to address a number of different concerns. As a consequence, engagement efforts are needed to make sure that these barriers, as they exist in the countries of East Asia as well as in the international community more generally, are as well-understood as possible so that effective approaches to promoting DBD can (if warranted) be designed.

4. Work on DBD Concept in East Asia and the Pacific to Date

To date, though some work has gone into research and design (if not construction) of mined repositories for nuclear materials in the countries of East Asia, relatively little work has gone into evaluation of deep borehole disposal of nuclear materials. Below we present a brief, general survey of status of some of the research related to the DBD topic that has taken place in the countries of East Asia (and the Pacific). This survey is not intended to be fully exhaustive, and points up opportunities for follow-on research with colleagues from the region.

4.1. Work on DBD Concept and Related Work in Japan

Based on communications with a high-ranking colleague in the Japanese nuclear regulatory establishment, there have been no official Japanese programs investigating DBD concepts to date. A 2004 report by the Nuclear Waste Management Organization of Japan (NUMO)[52] focuses on design principles, site issues, and safety requirements associated with development of a mined repository for nuclear materials in Japan, as well as reviewing research and development needs for development of such a repository. The NUMO report did, as a part of an appendix on possible repository components, touch briefly on deep borehole disposal as one of several repository concepts. A note related to inclusion of DBD in the comparison reads "This option [very deep borehole disposal] involves some fundamental changes in the basic safety philosophy, but is included for the sake of completeness" (page A1-16). Geological repositories have been a significant topic of research by NUMO, concentrating on disposal of high-level wastes and trans-uranic wastes (TRU) generated during reprocessing and mixed-oxide fuel fabrication[53].

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[52] Nuclear Waste Management Organization of Japan (NUMO, 2004), Development of Repository Concepts for Volunteer Siting Environments. Report # NUMO-TR-04-03, available as http://www.numo.or.jp/en/publications/pdf/RC_040901_FNL.pdf.

[53] See the brochures NUMO (2008), Geological Disposal of Radioactive Wastes in Japan, and Geological Disposal of TRU Wastes, dated July and September, 2008, and available as

4.2. Work on DBD Concept and Related Work in ROK

An initial, informal assessment of work to date on the DBD concept in the Republic of Korea has indicated that no official investigations on the concept had been undertaken on the part of the ROK nuclear research agencies, though at least one individual from the nuclear community has done some unofficial research on the topic[54]. Some background work relevant to DBD has, however, been done by researchers at the Korea Atomic Energy Research Institute in the context of evaluating the suitability of the geology of the ROK for a mined nuclear materials repository[55], as well as design work for mined repositories[56].

4.3. Work on DBD Concept and Related Work in the Democratic Peoples' Republic of Korea (DPRK)

We have no specific knowledge of work on the deep borehole concept for nuclear materials disposal in the DPRK, though we suspect that some work on design of mined repositories has been done there. In the late 1990s, the DPRK had apparently arranged with the Taiwanese electric utility Taipower to accept a load of low-level nuclear waste for the disposal in the DPRK[57]. This suggests that DPRK authorities have given at least some thought to the disposal of nuclear materials in North Korea. From a purely geologic viewpoint, the DPRK might be a suitable site for intra-Korean disposal of spent fuel. Though at present the political and security issues related to such an activity are more than formidable, to say the least, looking to the medium or long term, with a united Korea or an essentially economically integrated North and South Korea, the somewhere in the extensive granitic structures in the Northern part of the Peninsula might ultimately prove a suitable host for a DBD facility.

4.4. Work on DBD Concept and Related Work in China

China has an active program of work on development of mined repositories for nuclear materials, with a focus on disposal of HLW and other materials from reprocessing of spent fuel[58], and plans to open a repository in 2050. We have not yet seen evidence that Chinese

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http://www.numo.or.jp/en/publications/pdf/HLW_200808.pdf and http://www.numo.or.jp/en/publications/pdf/TRU_200809.pdf, respectively.

[54] Jungmin Kang, personal communication, 2010.

[55] C.S. Kim, D.S. Bae, K.S. Kim, Y.S. Koh (1999), "Lithological Suitability for HLW Repository in Korea". Poster presented at the Symposium on "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. Available as http://www-pub.iaea.org/MTCD/publications/PDF/csp_006c/PDF-Files/paper-67.pdf.

[56] J. Lee, D. Cho, H. Choi, and J. Choi (2007), "Concept of a Korean Reference Disposal System for Spent Fuels," Journal of Nuclear Science and Technology, vol. 44, page 1565. Available as http://www.jstage.jst.go.jp/article/jnst/44/12/1565/_pdf.

[57] See, for example, American University School of International Service (1997), "Trade and Environment Case Studies: Case number 403, Taiwan Nuclear Waste Exports (NKORNUKE)", available as http://www1.american.edu/TED/NKORNUKE.htm, dated May, 1997. See also P. Hayes, "Debating the DPRK-Taiwan Nuclear Waste Deal", NAPSNet Policy Forum Online #3, dated March 21, 1997, and available as http://www.nautilus.org/publications/essays/napsnet/forum/security/3a_nukewastedeal.html/.

[58] See, for example, Ju Wang (2010), "High-level radioactive waste disposal in China: update 2010", Journal of Rock Mechanics and Geotechnical Engineering, volume 2 (1), pages: 1–11, available as

researchers have evaluated the DBD concept in any detail, but suspect that some, at least preliminary, evaluation of the deep borehole disposal of nuclear materials has likely been done, if (as in Japan) on an informal and unofficial basis. We are polling colleagues in the Chinese nuclear research community to try and learn more.

4.5. Work on DBD Concept and Related Work in Australia

Australia, though it has not yet implemented commercial nuclear power, is a major supplier of uranium, and has vast, very lightly populated areas potentially geologically suitable for DBD. Although we have not yet located specific studies related to DBD application in Australia, there is a history of proposals for Australia-based international geologic repositories for spent fuel and other nuclear materials going back to the 1980s. A 1984 report by the Australian Science and Technology Council entitled "Australia's Role in the Nuclear Fuel Cycle" concluded, in part, that there was a need for international collaboration in developing HLW waste management programs, and that it was desirable to enabling access (presumably, of the international community) to the highest quality geological sites for disposal of those wastes (presumably, including those in Australia[59].

In the 1990s, a UK-based group called Pangea developed a concept for a large commercial international nuclear waste repository. Although Pangea considered other sites, its primary proposed location for the repository was "extensive contiguous sedimentary basins extending from central Western Australia into northern South Australia". More recently, an organization called the Nuclear Fuel Leasing Group proposed an "Australian Nuclear Fuel Leasing" (ANFL) company that would contract for uranium from Australian mines (only), buy conversion services, presumably on the international market or in Australia, and contract for enrichment, fuel fabrication, and fresh fuel transport services from international suppliers on behalf of nuclear power plant clients around the world. After the ANFL-supplied fuel has been used for generation, the spent fuel would be cooled at the reactor site for 9 to 20 months, then transported to final reprocessing or storage and disposal facilities. Fuel headed to storage or disposal would be stored for about 30 years in Australia, then be transferred to a nearby spent fuel geological disposal facility handling only Australian-origin spent fuel[60].

A mention of the possibility of DBD disposal for high-level wastes from an international reactor fleet in Australia in a presentation by Richard Hurwick[61] suggests that deep borehole disposal has at least been a topic of discussion among the nuclear community in Australia. Recent political trends in Australia have not favored the development of a domestic nuclear power industry, or the expansion of Australia's role in the nuclear fuel cycle beyond its current role as a uranium supplier. Nonetheless, political circumstances are liable to change, and

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http://202.127.156.15/qikan/public/tjdjl_en.asp?wenjianming=2010-01-01&houzhui=.pdf&id=2455l; and Jianchen Wang (2008), "Prospects for Spent Fuel Management of China in the Future", presentation dated 2008-10-20.

[59] World Nuclear Association (2010), "International Nuclear Waste Disposal Concepts", dated November, 2010, and available as http://www.world-nuclear.org/info/inf21.html.

[60] J. Green (2006), "Multilateral nuclear fuel cycle proposals". energyscience.org.au Fact Sheet 13, dated November, 2006, and available as www.energyscience.org.au/FS13%20Nuclear%20Fuel%20Cycles.pdf.

[61] R. Hurwick, "Nuclear power Friend or Foe? The Salon goes Nuclear". Presentation at the Salon in Surry Hills July 28th, 2005; available as http://www.hunwickconsultants.com.au/papers/download/nuclear_power_salon.pdf.

Australia will probably again be considered as a host for international nuclear waste management facilities.

4.6. Work on DBD Concept and Related Work in Russia

According to a brief mention[62] in the World Nuclear Association web page "Storage and Disposal Options, Radioactive Waste Management Appendix 2", some investigations of the deep borehole concept have been undertaken in Russia, but we have no details on this work as yet. A variant of deep borehole disposal called "self sinking capsules", in which the heat of encapsulated nuclear wastes melts the surrounding rock, after which the capsule slowly sinks to an ultimate "super deep" disposal depth, has apparently also been investigated in Russia (as well as the UK)[63]. Considerable research has been done in Russia and the former Soviet Union on deep drilling, including completion of the world's deepest borehole at Kola in 1989 (drilling started in 1970, and was halted in 1994). Beswick reports "[a] number of very deep, superdeep and ultradeep boreholes…[5 to over 10 km]… were drilled between 1970 and 1994, several in the former USSR. The deepest well, Kola drilled in the Murmansk peninsula in the former USSR (Russia) into the Baltic Shield eventually achieved a depth of 12.22 km with a 215 mm (8.50 in) final diameter". Given this background, additional research to learn more about Russian experience with deep borehole drilling in general, and of Russian concepts of deep borehole disposal of nuclear wastes in particular, should be useful. In addition, Russian participation in an East Asian deep borehole repository would seem to be beneficial on the grounds of Russian experience with the technologies involved, as well as for other reasons.

4.7. Work on DBD Concept and Related Work Elsewhere in East Asia

We are as yet not aware of any additional work explicitly on the DBD concept in East Asia, but at least one other proposal for international nuclear fuel cycle cooperation, involving Mongolia, has been floated[64]. An article by Undraa Agvaanluvsan, now of the Institute of Strategic Studies at the National Security Council of Mongolia, stops short of explicitly suggesting that Mongolia host an international facility for nuclear materials storage or disposal, but does suggest that Mongolia's large uranium reserves, democratic government, growing economy, neutral status, and commitment to being nuclear weapons-free mean that it is well placed to "explore the concept of multilateral initiatives with key nuclear partners that can result in a new and markedly improved framework for the future of nuclear power in Northeast Asia and world-wide. Multinational and international participation will be designed to serve the energy supply, security, and nonproliferation needs of the region. Mongolia seeks to offer its resources in an unprecedented way that maximizes transparency and long term stability." Mongolia does, indeed, have geological resources that might be suitable for nuclear materials repositories, as well as resources for the front end of the nuclear fuel cycle. Mongolia's participation in other proposed energy-related multinational initiatives, including the "Gobitec"

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[62] World Nuclear Association, 2010, "Storage and Disposal Options, Radioactive Waste Management Appendix 2". Available as http://www.world-nuclear.org/info/inf04ap2.html#Boreholes.

[63] See http://www.atomic-energy.ru/en/articles/2010/08/26/13144.

[64] U. Agvaanluvsan (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

renewable energy supply interconnection concept[65], which would provide solar and wind power from Gobi Desert regions in Mongolia and adjacent areas of China to Northeast Asian energy consumers, might help to facilitate a role for Mongolia in the back end of the regional nuclear fuel cycle.

5. Possible Regional Deep Borehole Regional Collaboration Concepts

A key "next step" in the exploration of the application of deep borehole disposal of nuclear materials in the East Asia region is to compare national distributed (for example, national) deep borehole disposal with scenarios for regional East Asian cooperation to develop one or a few DBD facilities used by multiple countries. The evaluation and comparison of distributed versus centralized borehole facility alternatives would include the dimensions described below, ranging from geological suitability to institutional design and proliferation considerations. What follows is a list of attributes, posed as questions to be addressed, against which different distributed or centralized DBD concepts for the region might be measured. Considerable learning on the suitability in general of DBD to nuclear materials disposal in East Asia is expected to accompany this research.

5.1. Geological Suitability and Feasible Locations

A first step is to assess the geological suitability of each country in the region for deep borehole disposal of nuclear materials. For example, can each country provide a map and analysis of suitable geological formations for DBD in its territory, both on land, in the near-shore seabeds, and on its islands. Are there any countries in the region that are without suitable geology for DBD disposal? To address these questions, it will be necessary to convene a multi-disciplinary and multi-sectoral working group of geologists from the with nuclear waste and borehole specialists, possibly including drilling specialists from the geological science and petroleum exploration communities. Among the topics that such a working group might address are:

- What is known about the geology of each candidate area for DBD, including deep-strata hydrology? What types of research programs are underway that might help to assess the suitability of the local geology to DBD?
- What types of site access are necessary in order to bring in and use equipment of sufficient size to drill large-bore holes suitable for disposal of nuclear materials?
- The likelihood of sea level rise due to climate change suggests that low-lying coastal areas may be bad sites over time to serve as drilling sites, both due to possible submersion, but also due to increased frequency and intensity of storms. On the other hand, sites that will be inundated, but centuries or longer well after drilling, emplacement, borehole sealing, and site restoration is complete, might provide some favorable aspects in terms of long-term security

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[65] See, for example, B. Seliger and G. Kim, "Promoting an Asian version of 'Desertec': 'Gobitech project' aims to tackle climate change, increase energy security and move forward Northeast Asian integration ", Korea Herald, September 24, 2009, page 4, Analysis and Feature. Available as http://www.koreaherald.com/specialreport/Detail.jsp?newsMLId=20090924000007.

(that is, they would be covered by the sea), in addition to the near-term convenience of site access for ships. How do such considerations apply to candidate sites in each country?

- Is sub-seabed deep borehole disposal of nuclear materials, either by fanning out from coastal land or by drilling at sea through the seabed, permitted by the London Dumping Convention and other legal regimes? Initial indications, based on an assessment of the legality of storing carbon dioxide from power plants on land in sub-seabed strata[66], are that DBD of nuclear materials under the seabed would be prohibited under the London Convention as it is currently written,

5.2. Design and Technological Choices

Counties could work together or separately on issues of DBD facility design and technologies used There may be key technologies that all countries will need that might be developed jointly, for example, by a regional deep borehole consortium with investment from each country and using scientists from each country, The issues to be addressed in this topic area might include:

- What drilling technologies are available and appropriate, and what new drilling technologies will have to be developed? What is the best way to develop those technologies?
- What types of research are necessary for determining the suitability of geologic formations for DBD?
- What types of packaging for spent fuel and other nuclear materials needs to be developed or adapted for deep borehole disposal?

5.3. Hazards and Standards

Questions and issues to be addressed relating to hazards and standards in developing disposal facilities for nuclear materials, whether on a national and regional level include:

- The need to create global and regional standards for deep borehole disposal of nuclear materials, perhaps starting with existing standards for mined repositories.
- Will there be a need to reach regional agreement on national strategies for DBD facility development; or will it be more straightforward to create a regional DBD site or sites that meets global standard? These same questions apply to interim storage of spent fuel, for example, in dry casks.
- Who will develop standards for transport of nuclear materials to DBD facilities? How should nations collaborating on DBD facilities decide on who will transport nuclear materials, and under what operating standards?
- Is there a reduced hazard that arises, in scenarios where DBD is used for spent fuel disposal rather than using reprocessing, from the removal of vulnerability to terrorist or state attack

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[66] C. Wall, C. Bernstone, and M-L. Olvstam (2004). "International and European Legal Aspects on Underground Geological Storage of CO_2". Available as http://www.vattenfall.com/en/ccs/file/International_and_European_le_8469909.pdf.

(especially from missiles or bombs) of surface reprocessing plants from the fuel cycle? Such hazards are already a concern in areas that are technically at war, such as the two Koreas.

5.4. Public Education and Community Acceptance

Though nuclear waste management facilities have historically been extremely difficult to site from a community acceptance perspective. There is the possibility, however, that properly managed public information campaigns and consultation approaches could help deep borehole disposal concepts to obtain community acceptance. Doing so would likely require that potential host communities, and indeed the general public in host nations, be involved from outset; and provided with proper education as to the relative risks and benefits of different waste management approaches. Distributed national versus regional centralized deep borehole facilities may present different profiles of community acceptance, given that separate publics may be informed and affected by the different concepts if implemented. Understanding these issues, and how they would likely play out in each country, will help in making an assessment of the relative benefits of national versus regional DBD (or, for that matter, other) nuclear materials disposal options.

5.5. Economics of Scale

Siting a number of facilities in different countries, rather than one or a few central facilities shared by the region, may or may not be more costly. Does the deep borehole disposal option offer any economies of scale that arise from developing centralized-national or centralized regional approaches to permanent disposal of nuclear materials. That is, is it significantly less expensive to develop a site with concentrated sets of deep boreholes, rather than dispersed sites? And how do any economies of scale compare with other costs or benefits related to transport, security risk, or environmental risk, for example? A number of authors suggest that economies of scale for DBD are not likely to be too strong, though being able to re-site drill rigs without moving them far, and having a large spent-fuel packaging facilities (into canisters for disposal) near centralized borehole facilities, thus reducing transport costs, may allow marginal cost reductions. A key area of research will be to evaluate, to the extent that current unit cost estimates and projections allow, the relative costs of centralized and decentralized deep borehole nuclear materials disposal facilities, as well as regional spent fuel management scenarios that use other approaches (including reprocessing.

In his rough estimate of costs to dispose of LWR and CANDU spent fuel in the ROK using deep boreholes, Jungmin Kang[67] estimated cumulative costs on the order of $4 to $10 billion over 30 years (2020 to 2050) to dispose of the spent fuel produced by reactors in the ROK from the start of the ROK's nuclear energy production in the late 1970s through 2020. Scaling up to a regional (East Asia) level suggests cumulative costs of about $9 to $18 billion over the same time period, with a surprising half of the costs being for disposal of CANDU fuel, mostly from the ROK. Initial costs (assuming that borehole disposal facilities could be started in 2030 or so) to dispose of all of the spent fuel 30 years old and older accumulated by that time would be on the order of a few billion dollars. These rough estimates convert to a cost per kWh of electricity produced using the fuel destined for disposal of about $1 per MWh, or one tenth of one US cent

[67] Jungmin Kang (2010), "An Initial Exploration of the Potential for Deep Borehole Disposal of Nuclear Wastes in South Korea", prepared for Nautilus Institute, December, 2010.

(1 “mill”) per kWh. More detailed estimates of these costs would be compared with the capital and operating costs associated with spent fuel management in other national and regional nuclear fuel cycle scenarios, including, for example, those using reprocessing and/or advanced reactors.

5.6. Institutional Design

Institutional design for deep borehole facility construction and operation will be a key area of investigation for an interdisciplinary, multi-sector working group investigating different approaches to deep borehole disposal and other methods of nuclear materials management. Here a first task might be to look for precedents—national or regional organizations designed to address similar goals in other fields. At present, at least the bulk of borehole drilling activity for petroleum exploration, geothermal exploration, or geoscience is carried out by (or on behalf of) multinational oil companies, parastatal (state-owned) companies, or state organizations (such as Ministries of Petroleum or Mining) themselves. Arguably, in the case of DBD of nuclear wastes, the security sensitivity of the materials suggests that parastatals or governments be used to implement national deep borehole concepts; whereas a centralized regional repository probably needs to take the form of an intergovernmental agency/consortium that leases land from a state or states that control the territory hosting the deep borehole facility. Organizing such a consortium, or adding function to an existing intergovernmental agency, to accomplish the DBD implementation function will require addressing a host of questions, including:

- Which countries will or should (two different questions, actually) lead the process, and which countries should follow in developing a consortium?
- Which legal regime/treaty framework is most suitable for governance of a consortium to guide regional DBD facility development?
- What political process is most suited to exploring and negotiating such a framework, given, for example, the difficulties observed with Six Party Talks approach to addressing a difficult problem in the region?
- Could a regional deep borehole approach for nuclear materials fit well in a regional nuclear weapons free zone treaty?
- Is it conceivable that the DPRK could participate in such a scheme, and if so, under what conditions?
- What indemnity issues arise that are unique to this approach, and how would/could they be handled?

5.7. Safeguards Implications of Alternative Designs

Regional as opposed to national approaches to DBD of nuclear materials, as with other regional versus national approaches to managing the nuclear fuel cycle, have different implications for safeguards on nuclear materials flows and access. A first step in addressing safeguards implications is to prepare forward-looking estimates of the cumulative stocks of spent fuels arising (and other nuclear materials to be managed) from nuclear energy activities, in order to assess the magnitude of facilities and safeguards needed in a given approach to DBD.

In addition, there will be a need to assess parameters such as the types and sizes of interim storage facilities, needed to support deep borehole disposal, including the types and amount of transport facilities required, the diversion risks associated with regional or distributed national interim storage, relative to those posed by a centralized regional repository for more than one country, and the differential monitoring and verification requirements posed by different deep borehole disposal concepts.

To supports DBD safeguards regimes, new and unique surveillance technologies will likely be required to monitor long-term (millennial) non-diffusion of the emplaced radioactive materials in deep geological formations, and/or in groundwater near disposal sites. Such technologies, however, will provide only a piece of the safeguards puzzle. Also required will be human institutions to review, manage, interpret, and if needed, act on the results of monitoring data. These institutions will need to have lifetimes longer than any existing human social construct, lifetimes tens or hundreds of times longer than the oldest religions. How can/should such institutions be organized so as to maintain vigilance over near-geological time scales? Can it even be done? Or can DBD facilities be developed that are intrinsically sufficiently robust against environmental or safeguards risks that the failure, over the long term, of either or both of the technical or institutional elements of a DBD facility monitoring network? Addressing these questions will require a truly interdisciplinary, collaborative approach, with many points of view considered.

5.8. Relative Proliferation Resistance of Deep Borehole versus Competing Regional Schemes

A key element of the evaluation of the DBD concept for nuclear materials disposal will be to evaluate the critical differences between the two variants—national or regional facilities—of deep borehole disposal with the Todai (see Section 1.3 of this study) and similar schemes for nuclear fuel cycle management. In the Todai and similar approaches plutonium and enriched uranium are either left in spent fuels in retrievable interim surface or subsurface storage, or are separated from spent fuels, thus creating many new flows of potentially weapons-usable materials that must be monitored and verified for risk of diversion. Deep borehole disposal appears, based on research thus far, to offer sufficient relative benefits in terms of both costs and reduced proliferation risks, relative to other options, to warrant further investigation. Such investigations must, however, offer systematic, inclusive, and evenhanded assessments of nuclear fuel cycle options, including DBD and other options at the national and regional scales.

5.9. Research Implications

The technical, economic, legal, institutional, security, social, and indeed ethical considerations flagged in above in this "Collaboration Concepts" section, and in the earlier sections of this study, provide just a sample of the often difficult issues that should be addressed in considering nuclear wastes disposal strategies. In research to address these issues, the following steps are proposed:

1. Convene/commission national overviews of the status of nuclear fuel cycle management, and of consideration of deep borehole and other nuclear materials processing/disposal options in particular, in key countries of the region (Japan, the ROK, and China, and possibly others).
2. Convene national expert teams to review the national overviews, and to discuss nuclear fuel cycle issues that pertain to establishment of a nuclear weapons free zone and other issues.

3. Convene a multi-disciplinary, multi sectoral regional discussion group, probably bringing together members of national teams with other experts from within and outside East Asia, for discussions of issues related to nuclear materials management and nuclear weapons free zones. These discussions would include not just technical matters associated with the nuclear fuel cycle and deep borehole disposal strategies, but also foreign affairs, proliferation considerations, economic attributes, approaches for community consultation, the role of civil society organizations, and other issues.
4. With the input and cooperation of discussion group and national expert team members, summarize the results of the discussions above, undertake a systematic quantitative and qualitative analysis of different nuclear fuel cycle management strategies in East Asia (with a Northeast Asia focus), summarize the results of that analysis, and extract the key findings of the analysis for application in support of a nuclear weapons free zone.
5. Work with the members of the discussion groups and national experts to inform policymakers and others of the implications of the findings of the analysis, and help policymakers to develop implementation strategies for moving forward with attractive policy options.