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David F. von Hippel & Peter Hayes

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# Regional Cooperation for Nuclear Spent Fuel Management in East Asia: Costs, Benefits and Challenges – Part II

David F. von Hippel<sup>a</sup> and Peter Hayes<sup>b,c</sup>

<sup>a</sup>Nautilus Institute, Eugene, OR, USA; <sup>b</sup>Nautilus Institute, Berkeley, CA, USA; <sup>c</sup>Center for International Security Studies, Sydney University, Sydney, Australia

## ABSTRACT

East Asia is home to some of the most dynamic economies on earth, but also a locus of current and historical national and international conflicts. Some of the largest economies lack domestic energy resources, and nuclear power has been adopted as a perceived key to energy security. Lacking, however, is a concerted strategy for managing nuclear spent fuel at the regional or even, for the most part, national levels. Regional cooperation on spent fuel management offers many benefits, as well as challenges. This two-part paper explores four different “scenarios” of regional spent-fuel management, ranging from a national “go-it-alone” option to regional cooperation on uranium supply, enrichment and “back-end” spent fuel management. Results for physical flows of nuclear materials and other inputs and outputs, and for the relative costs of each scenario, are presented. Results suggest that the costs of scenarios that include reprocessing are higher than those without reprocessing, and costs for increased dry-cask storage (reducing the amount of fuel stored in high-density spent fuel pools) are likely to be a tiny part of overall nuclear fuel cycle costs. As a result, radiological risk and attendant political, social and legal concerns should drive decisions regarding spent fuel management, not costs.

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## Introduction

This two-part paper provides an update of our analysis of scenarios for nuclear fuel cycle cooperation in East Asia within the context of three different nuclear energy paths for the nations of the region. Part I, published in Volume 1, Issue 2, of *Journal for Peace and Nuclear Disarmament*, provides an introduction and background to the energy and, specifically, nuclear energy and nuclear spent fuel issues in the region, describes the methods used to evaluate combined future nuclear fuel cycle “paths” and cooperation scenarios, and summarizes the results of those evaluations with respect to physical flows of nuclear materials and costs. Part II, below, provides a brief description of the energy security analysis methods applied to the path/scenario combinations described in Part I, and the results of those analyses, and also provides a discussion of the implications of

the combined analyses on nuclear fuel cycle policy in the region and potential international cooperation on fuel cycle management.

## Methods and Key Modelling Assumptions and Inputs

The key methods used in assessing the physical flows of nuclear materials and other inputs and outputs for each element of each nuclear expansion path and cooperation scenario, and of assessing the costs of nuclear fuel cycle activities, are described in Part I of this article. Additional online materials that accompany both Parts of this article provide details of key inputs, assumptions and methods.

An additional element of the analysis of paths and scenarios, the assessment of the relative energy security impacts of different ways of configuring the nuclear fuel cycle in the region, begins with the quantitative results generated as described in Part I, and couple them with qualitative energy security considerations as described below to provide a side-by-side comparison of the energy security – broadly defined to include not just energy supply and price security, but technological, economic, environmental, social/cultural and military security aspects as well<sup>1</sup> – attributes of four cooperation scenarios. As such, we used the energy security comparison methodology developed under a series of initiatives starting in 1998 (Suzuki et al. 1998).

## Results

Summaries of the future nuclear capacity and generation paths generated for this analysis are provided in Part I of this paper, along with presentations of results of analyses of regional spent fuel management cooperation scenarios focusing on uranium production and enrichment, spent fuel management, spent fuel production and the relative costs of the different scenarios. The remainder of this section focuses on the comparison of the relative energy security attributes of the different scenarios, as introduced in section 2, above.

### *Energy Security Attributes Comparison of Scenarios*

The broader energy security definition referred to earlier in section 2 (Suzuki et al. 1998) of this paper was used to develop a multiple-attribute method to compare national energy policy scenarios. This method was adapted to compare the energy security attributes of the four regional nuclear fuel cycle scenarios developed and evaluated as described above. It should be emphasized that while many different attributes and measures could be chosen for this analysis, the approach taken here has generally been to focus on attributes that are significantly different between scenarios, in order to provide guidance on the key policy trade-offs involved in choosing one scenario over another. Key results of this comparison are as follows:

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<sup>1</sup>See, for example, von Hippel and Hayes (2010) and von Hippel et al. (2011).

### ***Energy Supply Security***

Arguably, Scenario 1, in which the major current nuclear energy nations of the region own and run their own enrichment and reprocessing facilities, provides greater energy supply security on a purely national level. On a regional level, depending on the strength of the agreements developed to structure regional cooperation on nuclear fuel cycle issues, Scenarios 2 and 3, and possibly 4, may offer better energy supply security. Scenarios 3 and 4 also offer the added security of shared fuel stockpiles.

### ***Economic Security***

Scenarios including reprocessing have significantly higher annual costs, when viewed over the entire fuel cycle, than the scenario without reprocessing. The additional cost is still, however (as noted above), only a relatively small fraction of the cost of nuclear power as a whole. That said, the use of reprocessing and related required waste-management technologies may expose the countries of the region to additional economic risks if the technologies have costs that are unexpectedly high (as has been the case, for example, with Japan's Rokkasho reprocessing plant). In addition, the required additional investment, probably by governments or by companies backed by governments (tens of billions of dollars, at least) in facilities related to fuel reprocessing may divert investment from other activities, within the energy sector and in other sectors of potentially more benefit to the long-term health of the economies of the region. On the other hand, the development of in-country and in-region nuclear facilities will have its own job-creation benefits in the nuclear industry and some related industries.

### ***Technological Security***

Scenario 4, which depends on proven dry-cask storage, relies the least on the performance of complex technologies, but implicitly also depends on future generations to manage wastes generated today. Since all of the other scenarios, however, depend on interim storage of spent fuels, plutonium and high-level wastes from reprocessing, and thus imply dependence on a future means of safe disposal, the scenarios are not so different in this long-term outlook.

### ***Environmental Security***

Scenarios 1 through 3 as evaluated offer somewhat (on the order of several to 10%) less uranium mining and processing, with its attendant impacts and waste streams, relative to Scenario 4. This reduction in mining is offset by the additional environmental burden of the need to dispose of a range of solid, liquid and radioactive wastes from reprocessing, MOx fuel fabrication and other practices related to the use of plutonium in nuclear reactor fuels, though the impacts of the two waste streams are not strictly comparable. Differences between the scenarios with regard to the generation of greenhouse gases and more conventional air and water pollutants are likely to be relatively small, and are inconsequential when compared with overall emissions of such pollutants from the full electricity sectors and entire economies of the region.

### ***Social-Cultural Security***

To the extent that some of the countries of the region have growing civil-society movements with concerns regarding nuclear power in general, reprocessing in

particular, and local siting of nuclear fuel-cycle facilities, Scenario 4 arguably offers the highest level of social-cultural security. This advantage has likely been exacerbated by the social/political fallout from the Fukushima accident, although the different countries of the region are finding and will find that the Fukushima accident has impacts of different types and magnitudes on social and cultural issues related to nuclear power. In some cases current laws – in Japan, for example – would have to be changed to allow the long-term at-reactor dry-cask storage included in Scenario 4, and changing those laws has its own risks.

### ***Military Security***

From a national perspective, safeguarding in-country enrichment and reprocessing facilities in Scenario 1, including stocks of enriched uranium and (especially) plutonium, puts the largest strain on military (and/or police) resources. Those responsibilities are shifted largely to the regional level in Scenario 2, and to the international level in Scenario 3, with less stress on national resources, but more reliance on the strength of regional and international agreements. The level of military security (guards and safeguard protocols) required of Scenario 4 is arguably considerably less than in the other scenarios.

## **Discussion**

Below we summarize some of the potential benefits and challenges of nuclear fuel cycle cooperation in East Asia, offer some thoughts on the special case of including the DPRK in nuclear fuel cycle cooperation, explore some of the cost-benefit implications of cooperation scenarios, and describe how the conclusions regarding spent fuel cycle cooperation might interact with other issues related to nuclear power, including some thoughts on what types of projects might be undertaken to build on the work presented here.

### ***Potential Benefits and Challenges of Cooperation***

Some of the benefits of cooperation on nuclear fuel cycle issues could include:

- Scientific, educational and technical exchanges on nuclear fuel cycle issues help to assure that countries have a common understanding and knowledge base with regard to fuel cycle issues.
- Sharing nuclear facilities, whether enrichment, reprocessing, or spent-fuel facilities, provides a viable alternative for countries that may, due to political, social, geological, or other concerns, have few positive prospects for domestic siting of such facilities.
- Achieving economies-of-scale for enrichment facilities, reprocessing centers, or geologic repositories, though economies of scale likely are stronger for some types of facilities – such as enrichment plants or mined geologic repositories – than for others, such as spent-fuel storage based on dry-cask technologies (Bunn et al. 2001).
- Creating a new revenue source for a host country.

- Sharing nuclear facilities may help to assure that all countries maintain consistent practices and quality control standards in working with nuclear materials, as well as consistent levels of safeguards, monitoring and verification in nuclear fuel cycle activities, helping to build confidence between nations.
- Sharing of spent-fuel and reprocessing facilities can help to reduce proliferation risks by avoiding unnecessary accumulation of separated plutonium.

Implementing regional or international facilities, including those for spent fuel/radioactive waste storage/disposal, also will likely involve overcoming obstacles such as:

- Ethical issues in the region. There is some public perception that countries that have the benefits of nuclear power generation should bear the burden of storing and disposing of their radioactive wastes. This argument raises ethical and fairness issues that would oppose the concept of a regional/international repository. To obtain public and political support, an arrangement for the regional/international repository should be based on a fair and equitable sharing of benefits between a repository host and other participating countries.
- Complicating national policies in the management of spent fuel and high-level waste (HLW). A regional/international repository could distract national spent fuel and radioactive waste management programs with hopes for an international facility.
- Perceptions of attempts at coercion by nuclear supplier states felt by states that would potentially participate in fuel cycle cooperation – essentially, perceptions by the nuclear fuel cycle “have nots” that nuclear supplier states (“haves”) are attempting to limit the activities of those that do not have enrichment and/or reprocessing in the guise of non-proliferation.<sup>2</sup>
- A tendency toward decision-making in the nuclear sectors that focuses on the requirements and concerns of a single group of nuclear actors, rather than taking a more holistic approach. For example, groups responsible for the security and profitability of nuclear reactors will likely reach different conclusions as to optimal policy paths than groups focusing on national security/non-proliferation or on nuclear waste management (see, for example, Squassoni 2016).
- Increasing transportation requirements in the region. The regional/international repository will involve frequent transportation of spent fuel/radioactive waste from participating countries to a host country, and increasing concern over nuclear accidents during the transportation that may lead radioactive release to the environment. Proliferation risks due to the diversion of materials during transport are also a concern.

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<sup>2</sup>Yudin (2011) expresses this perception of coercion as follows:

A legacy of exclusiveness and coerciveness may make the future of multilateral approaches to the nuclear fuel cycle rather dim. Many non-supplier states have expressed concerns that suppliers may try to broaden the NPT division between nuclear-weapon states and non-nuclear-weapon states under the guise of non-proliferation. This suspicion can be traced, at least in part, to some early proposals for multilateral approaches—the 2004 Bush proposal, the Global Nuclear Energy Partnership, the six-country concept, and the World Nuclear Association proposal—that required non-supplier states to forgo domestic development of sensitive fuel-cycle technologies. Such preconditions were met with strong disapproval. These proposals can be blamed for giving rise to a false impression that multilateral fuel-cycle mechanisms necessarily imply discrimination between nuclear technology haves and have-nots.

### ***Regional Cooperation on Nuclear Energy with the DPRK***

North Korea's current and planned use of nuclear technologies may present severe problems with regard to nuclear security and safety. Here we refer to possible loss of control of nuclear materials and/or nuclear weapons due to instability in the DPRK itself associated with a leadership transition, or during a conflict with the ROK and its allies, in the disorder associated with the middle of a war or when the DPRK regime is facing impending defeat. In this context, the DPRK may be a source of fissile material and even weapons that may no longer be under strict central control. This possibility presents an extreme imperative to neighboring states and to other parties to the Korean conflict to intervene to ensure that nuclear materials do not cross borders or fall into the hands of individuals likely to use them.

Short of such disorder in the DPRK itself, the DPRK's "routine" nuclear security on fuel cycle sites and its nuclear material- and weapons-related sites is likely to be very stringent. Nonetheless, it may be important to engage the DPRK to ensure that its domestic legislation is fully developed with respect to the obligations that all states must observe after the 2004 UN Security Council resolution 1540 was passed. Resolution 1540 obliges states to "...refrain from supporting by any means non-State actors from developing, acquiring, manufacturing, possessing, transporting, transferring or using nuclear, chemical or biological weapons and their delivery systems" ([United Nations Security Council \(UNSC\) 1540 Committee 2016](#)). Also, the DPRK should provide (but has not provided) regular reports on its implementation of the required measures to the UNSC 1540 Committee. Training is also available to enable the DPRK to fulfill these obligations. Such measures may be a suitable confidence-building measure in the early stages of engagement of the DPRK to induce it to cease its nuclear weapons program.

With regard to nuclear safety, it is understood that the DPRK electric power system in general operates with very low standards for technical performance and maintenance, in large part due to the DPRK's many decades of isolation from the international community, and also due to the related lack of spare parts and materials, leading to remarkable improvisation but also to a system prone to constant breakdown. Similar practices were observed at Yongbyon nuclear sites during the period of US and IAEA monitoring in the 1990s, and there is little reason to think that this proclivity to take short cuts, conduct speed campaigns and proceed with regard for worker health and safety that is typically lower than international norms has changed. There is certainly reason to be concerned about the DPRK's construction practices in its construction of the experimental LWR (ELWR) at Yongbyon that has been in process for most of the last decade. Indeed, when Professor Siegfried Hecker observed the ELWR construction site on his last visit (Hecker 2010), he noted that the concrete foundation was being poured without proper preparation and reinforcing; and that site access was also amenable to flooding and being cut off from emergency vehicle access and other support that might be needed in the event of an emergency.

The two main reactors at Yongbyon – the plutonium production reactor and the (apparently) not-yet-commissioned (but perhaps nearing operational status) ELWR are shown in Appendix A-1 of the online materials accompanying Part I of this paper. These two reactors (ignoring the tiny research and isotope production reactor also present at Yongbyon) could experience accidents (von Hippel and Hayes 2014). The



most problematic would be a fire in the graphite core of the older plutonium production reactor. Such an accident could lead to radiation being released into a thermal plume and spreading downwind, similar to the 1957 Windscale accident in the UK.

The experimental LWR core could also be disabled accidentally due to poor design, operator error, or hardware failure, but it is too small a thermal mass to lead to a fuel meltdown as occurred at Fukushima, Chernobyl or Three Mile Island. If some other accident or attack disabled the reactor, however, it could release a relatively small amount of radioactive material, but the plume will affect mostly local areas close by Yongbyon (von Hippel and Hayes 2014). In such an accident, the “worst-case” scenario for an accident or attack involving the ELWR involves a situation where 20 years have elapsed and the spent fuel pool is filled up and dense-packed, but even then significant radiation releases do not reach even large population centers in the DPRK and beyond.

Nonetheless, there are many ways to engage the DPRK with regard to safety and nuclear fuel security, once we are in a realistic framework for denuclearizing the DPRK’s weapons program. Such an engagement could entail some or all of the following steps:<sup>3</sup>

- Immediately deploying a small barge-mounted reactor (possibly Russian) to provide power in a coastal North Korean town;
- Helping the DPRK to make or contribute to the production of low-enriched uranium to fuel such a barge-based reactor;
- Jointly designing with North Korea a made-in-DPRK small reactor that meets international safety and manufacturing standards, possibly in a joint project with ROK LWR manufacturing firms;
- Undertaking power system planning for the rational development of a national grid capable of supporting a fleet of small LWRs over a decade;
- Creating a multilateral financing scheme (possibly linked to a regional grid connecting the ROK with the Chinese and Russian Far East grids) for the manufacturing and construction of small LWRs in the DPRK over time, starting with a survey of DPRK manufacturing capabilities capable of contributing to or being upgraded to international standards required for safe, reliable LWR production;
- Creating a regional enrichment consortium involving Japan, the ROK and the DPRK (among other possible partners) whereby DPRK enrichment capacities are either incorporated into a safeguarded scheme, possibly operated as part of a multinational facility, in return for which the DPRK would reveal all its enrichment acquisition history;
- Development of a small reactor export program as part of an inter-Korean nuclear export push; and
- Provision of a program of training and institutional development needed to support each of the above activities, which is likely currently almost completely missing in the DPRK today.

An engagement on nuclear energy issues including the types of activities described above cannot occur in a vacuum. LWR engagement should be accompanied by

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<sup>3</sup>These and other approaches are outlined in more detail in von Hippel and Hayes (2010).



engagement on a host of other policy, economic and humanitarian issues, but most importantly, as noted below, it must be accompanied by engagement on a wide range of other energy sector issues, ranging from electricity transmission and distribution grid redevelopment, conventional power and fuels supply, and development of energy markets, to energy efficiency, renewable energy, with capacity-building across a broad spectrum of energy topics to make implementation possible.

The more that the region has already developed a regional enrichment facility or cooperation framework, and similarly, is cooperating to improve nuclear security and safety (as the ROK has pushed for in recent years, without much support from other states in the region), the easier it will be to frame ways to integrate the DPRK at affordable cost, and to identify proliferation-proofed options to improve their nuclear security and safety practices.

With regard to regional or US cooperation to respond to an accident at a DPRK site, the region has not been able to achieve any meaningful progress on post-Fukushima cooperation protocols applicable to actually significant risk from large-scale reactor accidents, as was proposed most realistically by the ROK (Park 2015).

### ***Cost-Benefit Implications of Cooperation Scenarios***

The key findings of the cooperation scenario analyses summarized in section 3 of this paper, when combined with other findings of previous related research efforts, have a number of ramifications.

First, it is clear that the costs of fuel cycles including reprocessing will be higher than those including alternative methods of spent fuel storage, including dry cask at-reactor or centralized storage, unless the costs of raw uranium and enrichment services rise far higher than levels of the recent past. Using base-case assumptions, scenarios involving reprocessing by 2050 are projected to cost several billion dollars per year, region-wide, more than “once through” scenarios in which spent fuel is simply placed in dry cask storage after a period of cooling in spent fuel pools.

That said, even several billion in the full context of the region’s electricity system as of 2050 is a relatively small sum of money. All of the fuel-cycle costs tracked in this analysis amount to on the order of a few percent of overall costs of power from all sources in the region, and are thus dwarfed by uncertainties in the future costs of electricity provision. Future electricity costs are rendered uncertain by potential changes in costs of generation technologies, costs associated with climate change mitigation (for example, carbon taxes) and pollution reduction, and/or costs related to regulatory compliance, particularly as civil society becomes more active in scrutinizing infrastructure plans in the region.

These findings with regard to the relative overall direct financial cost of different cooperation options suggest that decisions with regard to how spent fuel is managed, and whether cooperation is attractive for spent fuel management, largely boil down to political decisions that weigh proliferation and radiological risks with other, largely non-cost factors. This is not to say that certain nuclear sector actors – including nuclear plant operators, nuclear technology vendors, government regulators and, ultimately, consumers – may be affected economically in different ways, but the overall unit costs

of nuclear electricity generation to society will be affected relatively little by spent fuel management decisions.

If the conclusion holds that management of spent fuel will, or should, if incentives are properly structured, be decided by non-economic criteria, actual and perceived radiological risk from spent fuel management approaches becomes a more critical factor in the overall calculus, as does proliferation concerns. Both considerations point toward expanded use of dry cask storage in the near-term to reduce dense-packing in spent fuel pools in Japan and the ROK (and Taiwan), and to avoiding reprocessing. Getting spent fuel out of dense-packed pools and into much more attack- and accident-resistant dry casks is a key to reducing the radiological risk associated with accidents or non-state attack at nuclear energy facilities. Potential radiological risks associated with reprocessing facilities, though not a central topic of this project, would also be reduced by not moving forward with reprocessing, and by placing the spent fuel now in inventory at reprocessing plants into dry-cask storage.

Further, an emphasis on dry-cask storage in the near- and medium-term provides time for technologies for long-term storage and/or disposal of spent fuel and other similarly radioactive wastes (including high-level wastes from reprocessing and wastes from the Fukushima accident) to mature. This could include both geologic storage/disposal and deep borehole disposal, both of which will require decades for research, design and siting.

The prompt movement of spent fuel now stored in dense-packed spent fuel pools to dry cask storage would also provide a form of insurance against the difficult-to-calculate but potentially considerable cost of damages caused by an accident at terrorist attack on a vulnerable spent fuel pool. The damages from such an event could vary considerably depending on the plant affected, the prevailing wind direction in the days following the incident, and the proximity and vulnerability of local populations and economic infrastructure, as well, of course, as the effectiveness of the response to the incident by authorities. The worst case scenarios for such an event, for example, for the Tokyo area or for a reactor in South China, could cause damage to economic assets and human health due to radioactivity releases that could be on the order of hundreds of billions or trillions of dollars (von Hippel and Hayes 2017, 2018). As such, the relatively modest additional cost of moving to dry cask storage appears small in comparison with the potential benefits, even factoring in the considerable uncertainty of a worst-case event. Moving to dry cask storage could also, if communicated appropriately to residents of the area, provide an additional benefit in the form of reassurance that the worst risks of a radiological incident due to accident or attack are being avoided. The value of such a benefit (reassurance of safety) is of course very difficult to estimate, but might be compared, for example, with the peace of mind that residents and businesses purchase by measures designed to mitigate other risks, such as the risk of burglary or attack mitigated by guards and/or alarm and surveillance systems.

Regional cooperation in the nuclear fuel cycle could include shared uranium provision and enrichment services, but regional cooperation in spent fuel management is arguably more directly pertinent at present. Regional cooperation could contribute to spent fuel management by establishing or strengthening regimes for the oversight of nuclear fuel cycle activities and accounting for nuclear materials. Given the difficulties that some nations, most notably Japan and the ROK (and Taiwan) face in siting interim

or out-of-pool at-reactor storage of spent fuel, it is possible that regional cooperation could help to facilitate the establishment of intermediate, shared, away-from-reactor storage facilities. Further, international cooperation will be very helpful in undertaking deep borehole disposal of nuclear spent fuels (see below), as it will both help to spread the costs of research and development on deep borehole disposal technologies, and will help to overcome reluctance on the part of nuclear sector actors in individual countries to explore new options for spent fuel management.

Additionally, in the long run, if deep borehole disposal is to be undertaken, it may be that its operation on a regional scale will offer benefits in terms of accounting for nuclear materials disposed of, and thus build confidence between the nations of the region in the transparency of nuclear sector activities in other nations. This will likely be particularly critical if, ultimately, existing (or, if reprocessing starts/continues in nations of the region, new) stocks of plutonium are disposed of by blending with other materials, followed by deep borehole disposal. The process of accounting for plutonium disposal is particularly critical, because diversion of even a small fraction of existing stocks poses the threat of proliferation of nuclear weapons and/or “dirty bombs”, thus clear and open accounting for all of the nuclear materials disposed of in deep boreholes (or, for that matter, by other means) is crucial for maintaining the integrity of disposal practices from a non-proliferation perspective.

### ***Conclusions, and Interactions with Related Issues***

Nuclear power will certainly continue to play a significant role in the economies of the countries of East Asia and Pacific region for decades to come, but the extent of that role, and how the various cost, safety, environmental, and proliferation-risk issues surrounding nuclear power are and will be addressed on the national and regional levels, are not at all certain, and, in the wake of both the Fukushima accident and a host of recent and upcoming (for example, in the United States and the ROK) leadership changes, is perhaps more uncertain than it has been in decades.

Each of the nations in Northeast Asia has at least a general interest in international collaboration on spent fuel issues, but because of asymmetries between the nations, collaboration has been difficult to start. These asymmetries include China being a nuclear weapons state, while Japan and the ROK are not, and Japan having a reprocessing program and uranium enrichment capability, while the ROK does not, although it wishes to pursue a lightly modified form of reprocessing called “pyroprocessing”. Russia’s expressed interest in hosting fuel cycle cooperation has failed to gain much traction internationally, in large part due to resistance, for reasons including concerns about whether Russia would reprocess spent fuel accepted from other countries, on the part of the United States.<sup>4</sup> In addition, longstanding regional rivalries likely impede the potential for cooperation on the sensitive issue of nuclear materials transfer.

The analysis summarized above indicates that different policy choices today, particularly with regard to cooperation between nations on nuclear fuel cycle issues,

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<sup>4</sup>Whether the US stance on Russian reprocessing will change under the US Trump Administration is at this point (February 2018) entirely unknown, though Mr. Trump’s comments while campaigning and during his first year in office suggest a more sympathetic approach to Russia may be in the cards.

can lead to very different outcomes regarding the shape of the nuclear energy sector – and of related international security arrangements – over time. Regional cooperation on nuclear fuel cycle issues can help to enhance energy security for the participating countries, relative to a scenario in which several nations pursue nuclear fuel cycle development on their own. From a number of energy security perspectives, however, a regional nuclear fuel cycle approach (such as that modeled in Scenario 4) that rapidly phases out reprocessing and MOx fuel use, and uses interim spent fuel storage in dry casks (or similar technologies) to manage spent fuel until indefinite storage facilities – potentially including “deep borehole disposal” (see, for example, von Hippel and Hayes 2010) – has significant advantages. An approach that avoids reprocessing and MOx fuel use would be less expensive as well, though placed in perspective, the \$4–7 billion or so saved annually in 2050 under Scenario 4 relative to other scenarios is just a small fraction of the overall cost of nuclear power, and a tiny fraction of the overall costs of power in general. What this means is that relative fuel cycle costs, at least for the range of LWR-based fuel cycles cooperation/non-cooperation options explored here, should in most cases play a very minor role in decisions about nuclear spent fuel management, and the other considerations described here should thus dominate the policy development process. Of these, it is likely to be the least quantifiable considerations – social and cultural factors, preventing nuclear weapons proliferation, nuclear safety and military security issues – that are the most important to decisions regarding nuclear spent fuel policy. Unfortunately, these are the very issues that are some of the most difficult to address, particularly in the many instances where addressing those issues require a coordinated international, and intercultural, response.

Nuclear power choices intersect strongly with other energy policies and with security policy issues. As such, the exploration of the implications of different nuclear fuel cycle cooperation (or non-cooperation) options and opportunities in East Asia informs and potentially affects (and is affected by) issues such as deployment of new nuclear technologies, climate change, long-term storage/disposal of spent fuel and high-level wastes, management of radiological risk from spent fuel storage, and non-proliferation, but needs to be expanded to more fully address those issues.

### ***New Reactor Technologies***

A number of new types of reactors – including, for example, small, modular reactors, “fast” reactors using and producing plutonium fuels, and reactors based on a Thorium fuel cycle, to name just a few – have been proposed for implementation in the coming decades (typically after 2030, and often later). In addition, variants on the existing LEU/MOx fuel cycle, including a version of reprocessing called “pyroprocessing”, have been proposed by various groups, including, most prominently, by ROK nuclear researchers and officials. How might the implementation of these new nuclear technologies affect the form or prospects of nuclear fuel cycle cooperation in East Asia? Given that, for example, small and medium reactors and “Gen IV” reactor designs are likely to be at least 15–20 years from commercialization (see Goldberg and Rosner 2011), it seems clear that such reactors will play only a small role in the overall reactor fleet by 2050, or perhaps at most a moderate role in a “MAX” nuclear capacity expansion path. There is considerable

uncertainty as to which next-generation reactors will be deployed, how much they will cost, and as to the implications their deployment may have for the region's nuclear fuel cycle. Given these uncertainties, consideration of the impact of next-generation reactors has been beyond the scope of this paper, but should be included in future work.

### *Climate Change Considerations*

Climate change is a major and growing concern worldwide, with countries and sub-national jurisdictions making plans not just for reducing GHG emissions, but for adapting to impacts of climate change that seem inevitable. Nuclear power has to some degree enjoyed a resurgence of interest worldwide. As yet, however, with the significant exception of China, relatively little new reactor construction is underway worldwide.<sup>5</sup> A part of the interest in nuclear power is related to nuclear power's potential role in meeting energy needs without substantial GHG emissions. Some of the major issues associated with the linkages between nuclear power and climate change include the environmental implications of a "nuclear renaissance" for GHG emissions reduction, the economic, social and political implications of a broad program of nuclear power development, relative to other GHG mitigation strategies (including increasingly stiff competition for nuclear technologies from renewable energy and related technologies, such as electricity storage using batteries and other means), and the benefits and challenges posed by nuclear power in terms of adaptation to a changing climate, including, for example, the availability of water for reactor cooling as climates change, particularly at inland sites.

### *Long-Term Storage/Disposal of Nuclear Wastes, Including Deep Borehole Disposal*

Although not considered directly in the analysis presented here, the nations of the region, and indeed all nations using nuclear energy, will at some point within the next few decades have to make plans for long-term storage/disposal of nuclear wastes. Deep borehole disposal (DBD) of nuclear spent fuel and high-level wastes, which was the topic of an earlier project,<sup>6</sup> seems likely to be an attractive possibility, and there are areas within the Korean peninsula and China, as well as in other countries of the region, though possibly not in Japan, that would make good hosts for deep borehole facilities from a geological point of view. Deep borehole disposal facilities may well even have cost advantages over other forms of disposal (such as mined repositories). Deep borehole disposal, however, will require both technological advances to assure that key operational elements, such as emplacement of wastes, can be done safely and in a reliable manner, as well as domestic and possibly international policy agreements to allow the siting of deep borehole facilities. In addition, materials stored in deep

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<sup>5</sup>In the United States, for example, the recently completed Watts Bar 2 reactor, on which construction started in the 1970s and was halted for many years, is the first new US reactor to be commissioned in decades. Four additional units are under construction in the United States at present, representing about 4% of the total US reactor fleet. These additions will roughly offset the nuclear capacity decommissioned between 2010 and 2014 alone, and more US plants may be decommissioned in the next few years. See, for example, Mooney (2016) and World Nuclear Association (2018).

<sup>6</sup>See, for example, participant papers related to deep borehole disposal of spent nuclear fuel prepared for the Nautilus Institute Security of Spent Nuclear Fuel (2012–2014) 2013 Working Group Meeting, available at <http://nautilus.org/projects/by-name/security-of-spent-nuclear-fuel/2013-working-group-meeting/papers-and-presentations/>.

boreholes should likely be considered essentially irretrievable, as a huge effort will be required to remove emplaced materials from boreholes, not least because waste emplacement in boreholes would be between 3 and 5 kilometers underground. This isolation can well be considered a significant advantage, from a risk-of-diversion-of-nuclear materials point of view, but it brings up significant design considerations, and is of concern to those who see spent fuel as a potential future resource for energy production. Dr. Neil Chapman summarized the status of readiness of deep borehole technologies, despite their potential simplicity and low cost relative to mined repositories, as probably being 30 or so years from full-scale implementation, or about the same as other disposal options or, for that matter, the closed nuclear fuel cycle options involving the use of fast reactors that are under consideration in Japan, the ROK and China (Chapman 2013a, 2013b). What this means is that it is inevitable that intermediate spent fuel storage, and most likely dry cask storage, must be employed by most or all of the nations of the region in advance of any final disposal option.

Among the perceived favorable characteristics of deep borehole disposal of nuclear materials are its inherently modular nature, potentially lower costs, and widespread applicability. As a result, there is the possibility of sharing international R&D, and ultimately, of separately licensing the borehole technology and the disposal facility that allows nuclear waste to be disposed of in boreholes, analogous to generic reactor design licensing of different technologies.

Discussions on borehole operations focus on the need to understand drilling damage (extent and properties of the disturbed zone close to the borehole) and on the need for high integrity, low permeability seals to assure long-term isolation. Characteristics of the interface between the seals and the borehole wall will be particularly important. Potential operational problems during emplacement, including damage to canisters and waste during the trip down the borehole, should be minimized, and it may be desirable to line the hole for its entire length with steel casing. A reference design concept to provide a baseline for evaluating performance and impacts of alternative approaches may be useful. International cooperation, including, perhaps, cooperation between the countries of Northeast Asia, could help to move the concept forward through evaluation of the generic aspects of the technology. Such an effort would be amenable to an international co-operation project, and there is potentially sufficient interest from a number of countries to consider such a shared multinational project. The project would ultimately need a host country for the engineering trials. A first step in consideration of DBD by the countries of Northeast Asia, however, might be convening a regional meeting, attended by researchers and officials responsible for designing and managing nuclear waste disposal in the countries of the region, at which DBD concepts are described, and discussions are held on the specific barriers, especially institutional barriers, to DBD in the countries of the region.

In the China–Japan–ROK region, the amounts of radioactive material to be disposed of make shared disposal facilities look less attractive, for many reasons, but shared R&D could be highly appropriate, particularly given some of the potential institutional resistance to DBD (due to nuclear sector priorities) in many of the countries of the region. That is, it may be easier for a country to participate in a multi-nation project exploring DBD in than to negotiate internally for funding and support for a national DBD program.



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

### ***Management of Radiological Risk from Spent Fuel Pools***

Another issue of potential intersection between international cooperation on fuel cycle management and spent fuel security is in the management of radiological risk from spent fuel pools. Reducing spent fuel density at existing and future reactors would require changes in design and operation, especially in BWRs (boiling water reactors). The resulting incremental cost of these changes per unit of electricity is highly likely to be tiny, but the benefits in terms of avoided risk of radiological emissions and damage could be huge, as could the benefits of avoided public anxiety. Conversely, the risks of not changing spent fuel pool practices could be catastrophic. Moreover, reducing pool density implies choices with regard to dry cask storage versus surface or underground spent fuel pools outside existing secure reactor containment buildings, posing different and new risks of technological accident and/or malevolent attack (in the ROK or Japan, of DPRK missile or bomb attack; in China, of non-state actor attack, in particular). The decision to reduce spent fuel pool density has ramifications for potential cooperation on spent fuel management, as an aggressive program to de-densify spent fuels means that much more spent fuel, particularly in Japan and the ROK, will need to find homes in dry cask interim storage sited somewhere, whether at local, national, or international facilities.

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

In Japan, there is now a strong civil society and business constituency, as well as a well-informed nuclear-expert community, able and willing to address this issue in



policy contexts, as part of the overall battle to reform the “nuclear village”, and to reconstitute the social pact that sustains the LWR-reprocessing-breeder reactor strategy in Japan. In Korea, there is less public interest, but keen political and bureaucratic interest given the issue’s salience of the US-ROK nuclear cooperation “123” negotiations (World Nuclear News 2013). There are key political and social constraints on fuel storage options in both nations that need further exploration in light of recent events. Policy options are less constrained and therefore more open in China, and we believe that Chinese experts and policymakers will respond to new data and analysis.

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

Particularly in Japan and the ROK, dry cask storage at or away from reactor sites is clearly an attractive option for reducing radiological risks associated with spent fuel pools in the short-to-medium-term. There are, however, a host of legal, political and institutional barriers preventing the wider use of this technology in both countries. Better understanding these barriers, and how to overcome them in each nation, is therefore a key need. To that end, working with colleagues and civil society groups in the region to better understand the challenges to siting at-reactor or away-from-reactor dry cask storage options that would reduce risks associated with spent fuel pools is an attractive activity that would build on the results described in this paper, as well as other research efforts in the region.

### ***Nuclear Fuel Cycle Choices and Nuclear Weapons Proliferation***

Finally, there is a substantial link between nuclear fuel cycle choices and the risk of nuclear weapons proliferation, as indicated above. The presence of the DPRK in East Asia makes the proliferation issue especially pertinent in the region, as does the history of conflict between many of the region’s nations, including ongoing territorial disputes among many pairs of nations within and adjoining the region (such as China/Philippines). Choices of nuclear fuel cycle approaches will affect national and international security arrangements. Specifically, if a Nuclear Weapons Free Zone in the region is to be developed, the future of nuclear fuel cycle development and cooperation in the region will be an integral part of the discussion (Halperin 2012; Hayes and Kampmark 2018).

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No potential conflict of interest was reported by the authors.

## Notes on Contributors

*David F. von Hippel* is a Nautilus Institute Senior Associate based in Eugene, Oregon (USA), working on energy and environmental issues in Asia and elsewhere, as well as extensive analyses of the patterns of fuels use and prospects for energy sector redevelopment in North Korea. In addition to his work with Nautilus, David works and has worked for a number of private and public organizations in the US around the world on topics ranging from utility planning and energy efficiency to planning for reduction of greenhouse gas emissions.

*Peter Hayes* is Honorary Professor, Center for International Security Studies, Sydney University, Australia and Director, Nautilus Institute in Berkeley, California. His main research interests are nuclear weapons, climate change, and energy security, particularly in Northeast Asia.

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