The Woodrow Wilson School's Graduate Policy Workshop

A Proposal for Spent-fuel Management Policy in East Asia

The Current State and Future Plans of South Korea, China, and Japan – An Outside Perspective

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This report is the product of research conducted during the Fall of 2010, by a team of graduate students from Princeton University's Woodrow Wilson School of Public and International Affairs and School of Engineering and Applied Science.

Team members traveled to South Korea, China, and Japan where they interviewed elected and appointed government officials, academics, scientists, and members of nongovernmental organizations. The group also conducted research in the United States, including interviews with experts on nuclear fuel cycle issues, and discussions with officials from the United States Government.

Most officials spoke candidly about sensitive issues on the condition that their comments remain off the record. In accordance with their wishes, attribution of opinions and insights has been restricted where necessary.

We thank all who generously gave their time to meet with us. We are grateful also for the financial support of the Woodrow Wilson School, without which our field research would have been impossible. Above all, we would like to thank Frank von Hippel and Fumihiko Yoshida, who conceived this project and offered invaluable advice and expertise throughout. Responsibility for any errors or omissions contained herein, however, remains with the authors.

Table of Contents

Executive Summary

South Korea, China, and Japan all have near-term plans to embark upon or expand on closed nuclear fuel cycles – including spent fuel reprocessing and fast breeder reactor (FBR) development. The core reprocessing supporters in each country are government nuclear energy research and development (R&D) labs focused on the closed fuel cycle's promises of access to "domestic" fuel resources and the hope of reduced waste volume. However, these efforts pose real proliferation dangers by expanding access to weapon-usable plutonium.

Asia is also emerging as a major center of the nuclear power industry. China, Japan, and South Korea all have ambitious light water nuclear reactor (LWR) construction programs, driven by concerns about over-dependence on imported fossil fuels and increasingly by fears of global warming as well. Expanded reprocessing efforts in these three countries could therefore shift accepted norms both regionally, and globally, toward a closed fuel cycle.

We propose the following overarching policy conclusions for facilitating the development of nuclear energy in East Asia and for preserving the strongest possible barriers to the proliferation of fissile material:

1) ***Broaden multinational R&D efforts relating to all phases of the nuclear fuel cycle.***

2) ***Establish an international effort to investigate and formulate best practices for public safety and for participation in nuclear waste repository siting.***

3) ***Continue exploring possibilities for siting international long-term spent fuel storage facilities or repositories.***

The existence of an international or regional spent fuel storage facility could be a powerful argument against Japan and South Korea's view that reprocessing is the only solution to their domestic spent-fuel storage problems. The US has consent rights over the disposition of much of the spent fuel in these two countries. The recently approved 123 agreement between the US and Russia may make it possible to discuss Russia's interest in hosting an international spent fuel storage site.

In addition to these overarching conclusions, we have country-level policy recommendations for South Korea, China, and Japan that could be pursued in support of strengthening the global non-proliferation regime.

South Korea

The spent fuel pools associated with South Korea's operating reactors are projected to begin reaching maximum capacity by 2016, with no foreseeable prospect for a centralized interim storage facility or final repository in the near future. Meanwhile, nuclear energy researchers and policy makers in South Korea have focused their back end fuel cycle attention almost exclusively on long-term proposals for reprocessing (in the form of pyroprocessing) of spent fuel.

1) *The US should postpone any decision on whether to permit changes to the current US stance on pyroprocessing R&D on South Korean soil until the feasibility study has concluded.*

2) *The US should emphasize that pyroprocessing in South Korea would negatively affect efforts to eliminate North Korea's nuclear-weapons program.*

3) *The US should advocate for wide US and South Korean government representation in the joint feasibility study process to ensure that it is balanced and serves to educate key government officials throughout both governments.*

China

While China's policy is to eventually transition to a closed fuel cycle, the urgency of that transition can and should be challenged. Instead of arguing with China's reprocessing policy directly, the US should take a more indirect approach that targets China's key concerns and interests.

1) *Emphasize the geologists' perspective on uranium reserve estimates and its implications for the cost advantages of the once-through fuel cycle for the foreseeable future.*

2) *Try to establish a close working relationship with China's nuclear energy sector in the areas of technology and safety.*

3) *Attempt to further engage China on the regional proliferation risks that would come with the spread of national reprocessing plants.*

Japan

Japan is unlikely to give up its reprocessing policy in the near future. As the original rationale for this policy continues to erode, however, it may be possible to delay further large-scale commitments to reprocessing.

1) *Clarify the lack of radioactive-waste benefits from using MOX fuel in light water reactors and highlight the low likelihood of the ultimate commercialization of fast reactors.*

2) *Promote interim storage as an independent alternative for the near-term.*

3) *Underscore the proliferation risk posed by stockpiles of separated plutonium and engage Japan as a leading partner in nonproliferation efforts.*

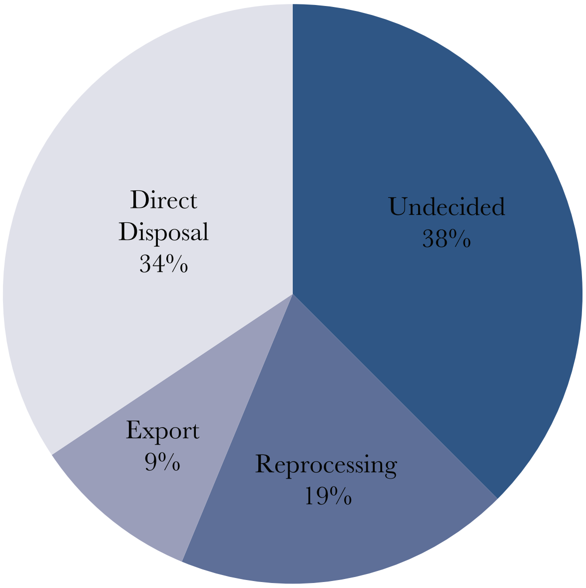
I. Introduction

After a period of relative quiet, the dream of the plutonium breeder reactor and a closed nuclear fuel cycle are again subjects of debate. Their potential benefits are tempting as they promise to ease state concerns about fuel security and difficult waste storage politics.

Most of the world's spent fuel is currently managed without reprocessing.[1] However, several near term decisions in East Asia threaten to shift this balance toward reprocessing as the accepted global norm:

- South Korea seeks the right to "pyroprocess" its spent fuel in the negotiations recently begun with the United States for a new nuclear Agreement for Cooperation.
- China is discussing the purchase of a reprocessing facility from the French-government-owned Areva, as well as one or more breeder reactors from Russia.
- Japan is continuing efforts to launch full-scale operations at the Rokkasho Reprocessing Plant and plans to build a second reprocessing facility.[1] Primarily as a result of reprocessing contracts with France and the U.K., Japan manages the largest stockpile of separated civilian plutonium owned by a non-nuclear-weapon state.[2]

Figure 1: Global Distribution of Country Fuel Cycle Policies



South Korea, China, and Japan all have ambitious nuclear reactor construction programs planned in the coming decades, driven in part by concerns about global warming and over-dependence on imported fossil fuels.

The actual and proposed reprocessing programs in these three states provide a model for other states planning to build nuclear power plants in the coming years. Reprocessing programs in the three nations may also set an important precedent as the US renegotiates a series of Agreements for Cooperation on Civil Uses of Atomic Energy (123 agreements), in addition to the Korea-US Agreement that expires in 2014.

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[1] See Figure 1 for global distribution of national spent nuclear fuel policies. Export: Italy, Netherlands, Ukraine. Reprocessing: China, France, India, Japan, Russia, UK. Direct Disposal: Canada, Finland, Hungary, Germany, Lithuania, Romania, Slovakia, Spain, Sweden, Taiwan, US. Undecided: Argentina, Armenia, Belgium, Brazil, Bulgaria, Czech Republic, Mexico, Pakistan, Slovenia, South Africa, South Korea, Switzerland.

Thus, the purpose of this report is to:

- Briefly present our understanding of the economic and technical basis for a comparison of the closed and open fuel cycles.
- Describe the current status of reprocessing policies, and their drivers, in South Korea, China, and Japan.
- Provide specific policy recommendations on ways to facilitate the development of nuclear energy in East Asia, while still preserving the strongest possible barriers to the proliferation of nuclear-weapon-usable fissile material.

II. Background on the Closed Fuel Cycle

Proliferation Risks

Reprocessing increases the accessibility of weapon-usable plutonium to both governments and non-state actors. A country with a reprocessing plant or a stockpile of separated plutonium has easy access to the material needed for a nuclear weapon.[3] Even an "engineering-scale" facility, such as the one the Korea Atomic Energy Research Institute (KAERI) has proposed to launch by 2016, would have the capability to annually reprocess ten tons of spent nuclear fuel, and separate enough plutonium for more than ten nuclear weapons per year.[4] Unlike spent fuel (which is considered self-protecting), separated plutonium is susceptible to theft because it does not emit much penetrating radiation.[5][II] In a large reprocessing facility, enough plutonium is separated (8,000 kg per year at Japan's Rokkasho Reprocessing Plant operating at design capacity) that multiple weapon-quantities could go unaccounted for years.[6]

World Uranium Resources

If a state has access to international uranium markets, reprocessing should not be required to ensure a future supply of fuel for nuclear power plants during this century. Identified uranium reserves are widely dispersed across six continents.[7] According to the latest edition of the "Red Book" published by the OECD-Nuclear Energy Agency and IAEA, global uranium consumption could be maintained at 2008 levels for about a century using only identified reserves of uranium. Under a fast-growth scenario for the expansion of nuclear power, less than fifty percent of identified uranium reserves would be consumed by 2035.[8] According to the national estimates collected from the Red Book, "undiscovered resources" of uranium are about 150 percent of identified reserves.[9] However, some consider these estimates to be very conservative and expect that identified reserves will increase as the price of uranium increases, stimulating exploration. A 2010 MIT study concluded that 430 one-gigawatt reactors (roughly today's global nuclear capacity) could operate for 10,000 years before the price of uranium would rise to a point where the cost of the once-through fuel cycle would rise to that of closed fuel cycles.[10]

Economics of a Closed Fuel Cycle[III]

A closed fuel-cycle is more expensive than the direct disposal of spent nuclear fuel, even under conservative assumptions. The capital costs of breeder reactors are expected to be at least 25 percent higher than for light-water reactors.[11] A 2003 Harvard study found that "the margin between the cost of reprocessing and recycling [in light water reactors] and that of

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[II] The fission products emit gamma rays and neutrons, which are very hazardous to human health. Plutonium decay emits primarily alpha particles that cannot even penetrate the skin and therefore is a relatively minor radiation hazard when processed in a glove box to protect against inhalation.

[III] See Appendix II for a more in-depth discussion of this topic.

direct disposal [of spent fuel] is wide, and is likely to persist for many decades to come."[12] The study found that reprocessing and fast reactors—assuming fast reactors have a capital cost of $200/kW$_e$ greater than a light water reactor—would not be competitive unless uranium cost $340/kgU.[13] The cost is about $170/kgU today.[14]

Prospects for Fast Breeder Technology

The widespread deployment of commercial fast reactors is at least decades away. France closed its only active fast reactor in 2009 and is planning for another prototype to be operational in 2020.[15] Japan's fast reactor has been almost continuously offline due to a 1995 sodium fire and a 2010 refueling accident.[16] Japan is not planning commercialization of fast reactors before mid-century.[17] In spite of fifteen sodium fires, Russia's prototype BN-600 fast reactor has operated at about a 74 percent capacity factor since 1980.[18] Moscow is building a demonstration BN-800 breeder reactor based on the same technology.[19] India is also constructing a demonstration fast reactor.[20] China's small experimental fast reactor went critical in 2010, and China may buy one or two BN-800 breeder reactors from Russia.[21] Germany, the United Kingdom, and the United States, which had major breeder development programs, no longer plan to commercialize fast reactors.[22]

Waste Disposal Realities

A nuclear power program requires interim and long-term storage of waste regardless of what type of fuel cycle is used. For example, Japan's closed fuel cycle policy has required the construction of an interim storage facility for solidified high-level reprocessing waste and will require a geological repository for its disposition.[23] A closed fuel cycle in light-water reactors produces waste of varying long-term heat outputs that collectively have no storage space advantage over direct disposal of spent fuel without recycling. The US Congressional Budget Office in 2007 found that: "Consequently, for reprocessing to reduce the need for—and cost requirements of—long-term storage, previously recycled [light-water reactor] spent fuel would have to be allowed to accumulate at some location outside the repository."[24]

Safety and Reliability Concerns

The fast-neutron reactors commonly planned for closed fuel cycle use in the longer term have a history of safety and reliability problems. All fast-neutron reactor prototypes have used liquid sodium as a coolant. The primary safety advantage of using liquid sodium is the fact that the danger of loss of coolant caused by a pipe break is reduced because the sodium is kept below its boiling point. However, the sodium must be kept separated from both water and air to avoid fires. Sodium fires have occurred in several countries' breeder reactors. The problems associated with the use of liquid sodium to cool fast-neutron reactors has resulted in the reactors having a poor reliability record compared to conventional light-water reactors. A final safety issue of fast-neutron reactors (which caused Germany to not operate its prototype breeder reactor) is that a melt-down and collapse of the core could cause a small nuclear blast.[25]

III. Reprocessing:
in South Korea, China, and Japan

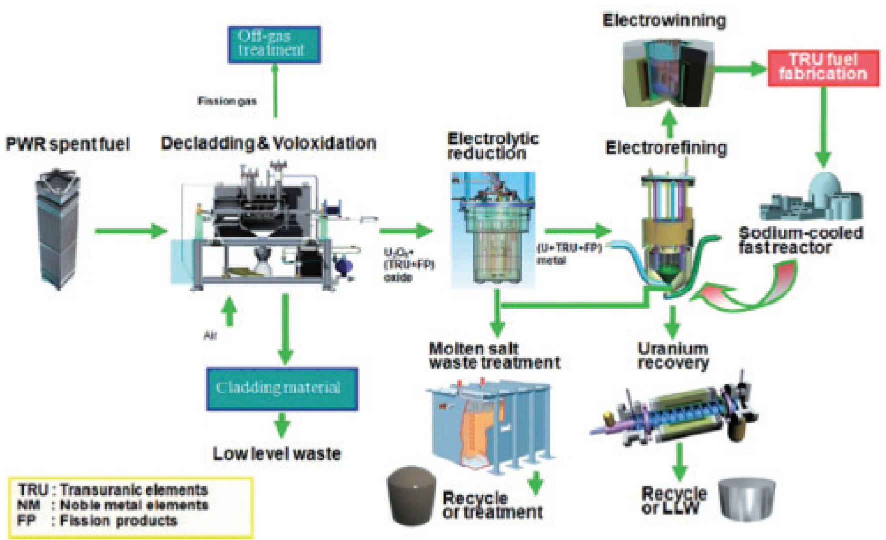
1. South Korea

South Korea's Back-End Fuel Cyle Challenges

The spent nuclear fuel (SNF) management situation in South Korea is reaching a critical point. While South Korea imports uranium to fuel its nuclear power plants, nuclear power is seen as its primary mechanism for gaining greater national energy security. South Korea's government therefore plans to significantly increase its nuclear energy capacity by building 18 more reactors before 2030.[26] The government, however, does not have a clear way forward for managing spent fuel from this rapidly expanding nuclear power program. At the outset of its nuclear program, the government decided to store all spent fuel on-site in temporarily in water-filled storage pools for its sixteen light water reactors and in nearby dry storage for its four CANDU reactors until it could find a centralized interim storage facility to which it would move all temporary spent fuel. As a result of community pushback, however, the government has yet to site this facility.[27] The pools associated with operating reactors are projected to reach maximum capacity beginning in 2016.[28]

South Korea also plans to become a major exporter of nuclear reactors in the next few decades. In 2010, it won its first major $20 billion nuclear export contract with the United Arab Emirates. Galvanized by this success, South Korea now aims to capture a substantial share of the world's nuclear reactor export market by 2030.[29]

Figure 2: South Korea's Proposed Pyroprocessing Fuel Cycle



Term limits and public resistance over siting decisions for nuclear facilities have discouraged recent presidential administrations from taking responsibility for the spent nuclear fuel storage crisis. The next round of national elections will seat a new South Korean president in 2013, whose 5-year term will include the beginning of spent-fuel pools at the currently operating light-water reactors reaching capacity.

A Public Consensus Project started in January 2009 as an effort by the previous presidential administration to consult with the public on South Korea's spent fuel management program. It was halted by President Lee's administration in early 2010. Instead, three organizations (the Korean Nuclear Society, the Korean Radioactive Waste Society, and the Green Korea 21 Forum*)* have been asked to provide analyses on how to move forward with the issue.[30] The suspension has displeased the stakeholders previously involved in the process. Officially, the Public Consensus Project is slated to begin again in 2011, but some South Korean observers think that this is unlikely to happen.[31]

There does not appear to be much interest within the South Korean nuclear R&D community in exploring innovative ideas for storing spent nuclear fuel. Nuclear energy experts in South Korea have focused their fuel cycle attention almost exclusively on pyroprocessing, even while acknowledging that it could not make a significant contribution before 2050.

The group most interested in pursuing this technology is the Korean Atomic Energy Research Institute (KAERI), a government-funded research institute. KAERI's claim that pyroprocesssing could reduce the area required for an underground radioactive waste repository rests on the South Korean nuclear industry's ability to commercialize a fast-neutron breeder reactors. While other OECD countries have failed, KAERI proposes to have an experimental fast reactor on line in 2028 and hopes to commercialize fast-neutron reactors after 2050.

The future of pyroprocessing in South Korea is a contentious topic in the renegotiation of the US-South Korea Atomic Energy Agreement.[IV] At the present time in the negotiations, the US and South Korea have agreed on a joint pyroprocessing feasibility study. Negotiating teams have not reached a consensus on the duration of this study, but it is likely to range anywhere from four and

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[IV] South Korea proposes to continue its investigation into pyroprocessing during the next phase of the US-South Korea Atomic Energy Agreement and will likely press for the right to move to the next stage of the R&D process: experimentation with pyroprocessing on spent nuclear fuel. Under the current agreement, South Korean scientists can only participate in joint pyroprocessing experiments with actual spent nuclear fuel in US laboratories; the US has not agreed to this type of experiment on South Korean soil.

eight years. The fate of pyroprocessing research in South Korea during that time remains unresolved.[32]

Recommendations

1) *The US should postpone any decision on whether to permit changes to the current US stance on pyroprocessing R&D on South Korean soil until the feasibility study has concluded.*

During the feasibility study, South Korea would operate under the R&D constraints of the past Atomic Energy Agreement. This would mitigate any perception of changing US nonproliferation priorities.

In the meantime, it is important that pyroprocessing not be the only option considered. Therefore, the US should advocate for interim storage and final repository alternatives to be included in the feasibility study. This will expand the options for the back end of the fuel cycle in Korea and move pyroprocessing from the center of attention.

To deal with the immediate pressures of storing spent fuel, the U.S. should advocate that South Korea expand interim storage on-site. South Korean experts argue that both re-racking spent fuel rods more efficiently and transshipments of spent fuel rods from old reactors to the storage pools at the new reactors could extend the deadline by which on-site storage will reach maximum capacity by seven to ten years.[33]

2) *The US should emphasize that pyroprocessing in South Korea would negatively affect efforts to eliminate North Korea's nuclear-weapons program.*

South Korean nuclear community leaders dispute that pyroprocessing has a negative effect on efforts to convince North Korea to give up its nuclear-weapon program. Several policy experts in South Korea stated that North Korea's nuclear decisions are not likely to be influenced by South Korea's spent fuel management policies, even if the 1992 Joint Declaration of the Denuclearization of the Korean Peninsula forbids these activities. The US and members of the Six-Party Talks should work together to emphasize to South Korea that, in fact, its actions matter and could make negotiations with North Korea even more difficult.

3) *The US should advocate for wide US and South Korean government representation in the joint feasibility study process to ensure that it is balanced and serves to educate key government officials throughout both governments.*

The joint pyroprocessing feasibility study recently agreed to at the start of the renegotiation of the US-ROK nuclear Agreement on Cooperation will assess the viability of pyroprocessing and alternatives on a commercial scale. The conclusions of the joint study will likely shape the future of pyroprocessing in South Korea. On the U.S. side, the participants will include US national laboratory experts and representatives from the US State Department. On the South Korean side, it is important that the full spectrum of concerned South Korean ministries and institutes be involved. These include the Foreign Ministry; the Ministry of Education, Science and Technology (which funds KAERI's work on pyroprocessing); the Ministry of Knowledge Economy (which regulates nuclear power in South Korea); the Korean Nuclear Society, Korean Radioactive Waste Society, and the Korean Institute for Energy Resources. Wide participation including these organizations will bolster the legitimacy of the feasibility study's results.

2. China

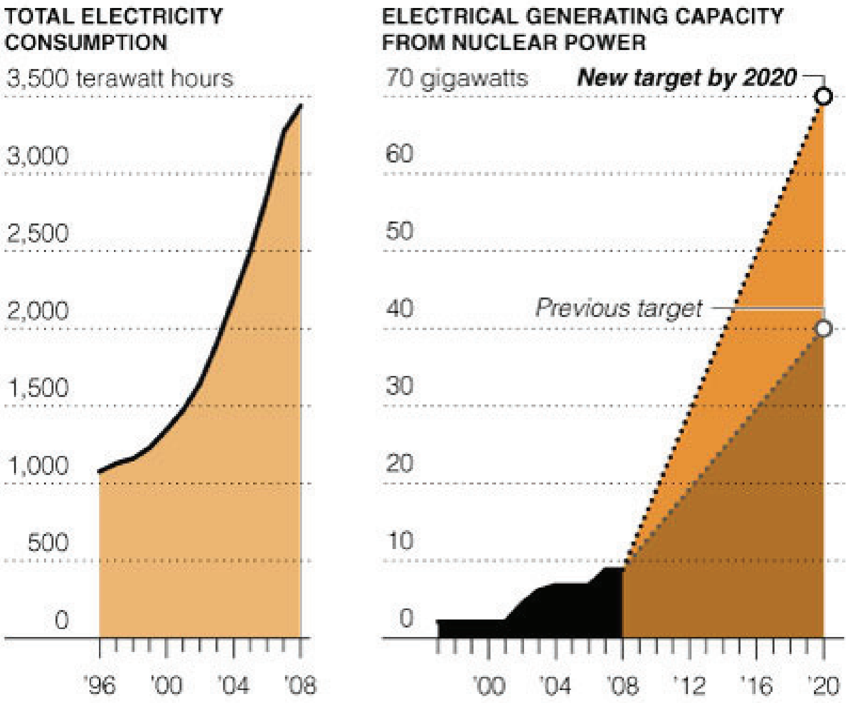
Energy Requirements and Plans for Reprocessing

With 1.3 billion citizens, decades of double-digit economic growth, ever-increasing domestic energy consumption and massive carbon emissions, China is planning for nuclear power to provide a greater share of national electricity in part to help China reduce its reliance on coal. As of the end of 2010, China had 13 reactors operating and 26 under construction,[34] and planned to start construction on dozens more units in the coming decade.[35]

Since the inception of China's civilian nuclear energy program in the 1980s, China has been working to achieve self-reliance or near-independence in the nuclear-energy sector. A core tenet of this vision is the pursuit of an indigenous supply chain for the construction of nuclear power plants and the provision of nuclear fuel. Government officials are concerned, however, that its nuclear program will be hampered by the lack of large-scale domestic uranium supplies. China is actively securing long-term contracts for uranium from around the world. However, there are fears in China that rapid global expansion of nuclear power will outstrip global uranium supplies, driving up uranium prices.

Thus, according to officials and experts familiar with the issue, the closed fuel cycle is viewed as attractive to many researchers and government officials in Beijing. A closed fuel cycle that would significantly reduce China's uranium requirements would include both reprocessing facilities and commercial fast breeder reactors. China is discussing with AREVA the purchase of a reprocessing plant similar to Japan's 800-ton/year capacity Rokkasho Reprocessing Plant. China also recently brought to criticality a small 65 megawatt

Figure 3: Planned Chinese Energy Consumption and Nuclear Generation, 2009



(thermal) fast reactor, and may purchase one or two 800-megawatt (electric) Russian fast-neutron BN-800 reactors.

The rate of China's policy development on reprocessing and fast reactors is not keeping pace with the rapid expansion of its nuclear energy program in general, however. Therefore, according to an expert familiar with the topic, it may not be indicative of a broad policy decision. A final decision has yet to be made on large-scale reprocessing in China and it appears that negotiations with France and Russia may have stalled.

Given its tremendous energy needs, China does not feel comfortable waiting for the market to find a solution. Therefore, while the history of fast reactor R&D is filled with expensive failures and abandoned projects, China is unwilling to constrain its technological options at this point. It has therefore built a pilot reprocessing plant in Gansu Province, as well as its experimental fast reactor outside Beijing. Many officials are resistant to the argument that fast breeder reactors are not a viable option. They are also extremely resistant to being "pushed" towards a specific fuel cycle by the United States or others.

Unlike Japan and South Korea, China has time as it is not under public pressure to move spent fuel and will have minimal difficulty siting interim storage and waste repositories. It is very important that China move cautiously with respect to reprocessing, however, because the scale of its proposed program could have great influence on the shape of the global nuclear-energy industry.

Recommendations

1) *Emphasize the geologists' perspective on uranium reserve estimates and its implications for the cost advantages of the once-through fuel cycle for the foreseeable future.*

China's main concern is maintaining a reliable fuel supply in a future containing the rapid growth of China's nuclear energy sector. The most straightforward way to delay China's reprocessing efforts is to alleviate this concern by promoting awareness of the recent studies estimating that global uranium resources can sustain the once-through fuel cycle even under a rapid growth scenario for the foreseeable future. The case for this perspective was introduced in the background section of the introduction and is explored further in Appendix II. Our interviews in Beijing revealed that there would be widespread interest in learning more about the economic advantages of the once-through fuel cycle with interim storage and/or direct disposal. US policymakers should build upon this desire for more information on global uranium reserves by promoting international efforts designed to expand knowledge of the size and extent of uranium deposits across the globe. These efforts should include further research into new methods of uranium extraction, including the potential of extraction from seawater.

Figure 4: Global Distribution of Identified Uranium Resources, Less Than $130/kg

2) *Try to establish a close working relationship with China's nuclear energy sector in the areas of technology and safety.*

While it is unlikely that the US can directly influence China's reprocessing policy, the Department of Energy and Nuclear Regulatory Commission could work with their Chinese counterparts to share technology options and perform joint research in the time period where China is rapidly increasing the number of nuclear power plants. This type of collaboration can help build US – Chinese relations in the nuclear energy sector, establishing a higher level of cooperation and trust. Through this collaboration, the US can promote the advantages of once-through fuel cycle technologies.

3) *Attempt to engage China more on the regional proliferation risks that would come with the spread of national reprocessing plants.*

While China's policy of avoiding involvement in other states' domestic policies will likely continue, it can be engaged when an issue is framed within a regional stability context. China's leadership in the Six-Party talks on North Korea's nuclear weapons program is evidence of this willingness. The Carnegie Endowment, which sponsors the Carnegie-Tsinghua Center for Global Policy, has begun efforts toward non-governmental multi-party talks on reprocessing issues in the next year to include participants from China, the US, Japan, and South Korea. These efforts, and others like them, should be supported.

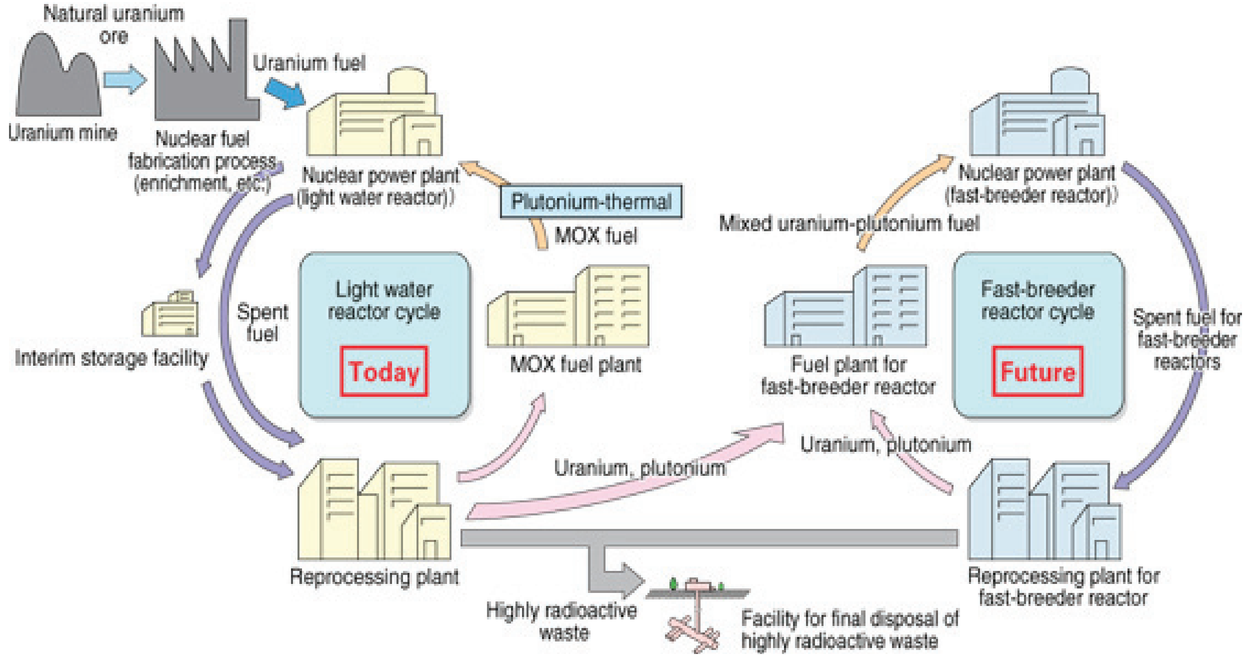
3. Japan

History of Energy Program and Fuel-Cycle Decisions

Nuclear power provides approximately 30 percent of Japan's electricity today and is projected to meet 50 percent of the nation's electrical demand by 2030.[36] Japan has the third largest nuclear capacity (after the US and France) and its direction and choices will have far-reaching impacts on both the regional and world stages.

Japan remains committed to a closed fuel cycle but has encountered serious difficulties. Its commercial-scale reprocessing plant at Rokkasho, which was originally slated for completion in 1997, is currently scheduled for full operation in 2012 at a cost several times the initial estimate.[37] Similarly, the Monju Fast Breeder Reactor went critical in 1994 but quickly shut down in 1995 after a sodium fire. After a long delay, it finally reopened in 2010, only to cease operation again for years due to damage incurred during fueling. As a result, commercial fast reactors – which were originally expected in Japan by the 1970s – are now not expected to operate until after 2050.[38]

Figure 5: Japan's Official Nuclear Fuel Cycle Policy



Japan has reprocessed much of its spent fuel in France and the U.K., and at the Tokai Pilot Reprocessing Plant. Furthermore, Japan plans to ramp up its domestic reprocessing program after Rokkasho's delayed opening.[39] Since commercial fast reactors do not exist to use most of the plutonium, some light water reactors are beginning to recycle it in mixed oxide (MOX, uranium-plutonium) fuel. Japan plans to have 16 to 18 plants accepting MOX fuel by 2016.[40] Japan's already large stockpiles of plutonium could continue to grow for some time, however, before its rate of plutonium recycle catches up to its rate of plutonium separation

Japan's Nuclear Waste Management Organization (NUMO) is currently seeking communities to volunteer to host a geologic repository for final high-level waste disposal. Although none have yet stepped forward, Japan hopes to open a repository by the mid-2030s. In the meantime, fuel from light-water reactors is dense-racked on site and some is to be sent to a dry-cask interim storage facility scheduled to open in Mutsu City near Rokkasho in 2012. Due to an agreement with the Aomori prefectural government, the spent fuel at Mutsu City must be removed within 50 years. Since Rokkasho will not have the capacity to accept all of Japan's spent fuel, a second reprocessing plant, originally planned to open in 2010, is currently planned for 2050.[41]

Table 1: Cost Comparison of Fuel Cycle Options by the Japan Atomic Energy Commission, 2004

	Scenario 1 (status quo policy)	Scenario 2 (stop reprocessing after Rokkasho)	Scenario 3 (Cancel Rokkasho, move to Direct Disposal)	Scenario 4 (Interim storage and decide later)
Power Generation Cost	5.2	5.0~5.1	4.5~4.7	4.7~4.8
Cost due to Policy Change	-	-	.9~1.5	.9~1.5
Total Cost	5.2	5.0~5.1	5.4~6.2	5.6~6.3

Today, Japan's nuclear fuel cycle policy is dominated by inertia and concern about policy change. This affects Japan's evaluation of the relative costs of different fuel cycles. While it is generally accepted that a closed fuel cycle is more expensive than a once-through fuel cycle at today's uranium prices (and perhaps for the foreseeable future[42]), Japan's Atomic Energy Commission nevertheless concluded in a 2005 report that change would increase costs.[43]

Finally, the proliferation risks associated with Japan's adoption of a closed fuel cycle are not widely recognized. Defenders of Japan's reprocessing policy often invoke Japan's unfortunate circumstance as the only victim of a nuclear attack; Japan's stockpile of separated civilian plutonium is therefore not seen as legitimizing similar latent proliferation by other countries.

Recommendations

1) *Clarify the lack of radioactive waste benefits from using MOX fuel in light water reactors and highlight the low likelihood of the ultimate commercialization of fast reactors.*

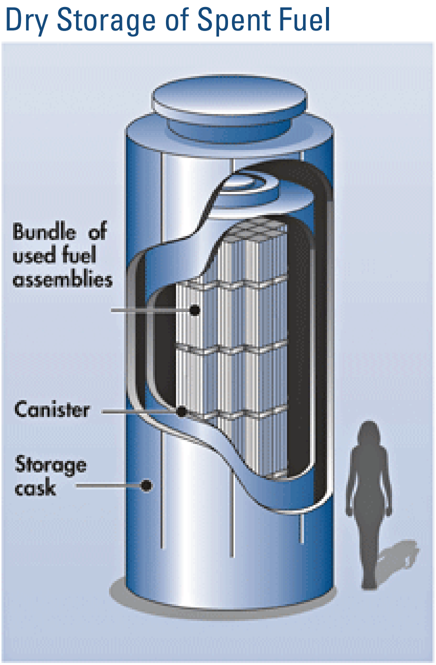
The radioactive waste benefits and most of the uranium-conservation benefits of Japan's current policy depend on the commercialization of fast reactors. Without fast reactors, recycling plutonium and uranium in light-water reactor fuel only reduces uranium demand by up to 20 percent (according to JAEC estimates)[44] and therefore does little to insulate Japan from the global market price of natural uranium. Furthermore, without fast reactors, spent low-enriched uranium fuel is simply replaced by a smaller quantity of spent MOX fuel but the repository requirements do not change significantly because of the higher heat output of spent MOX fuel per ton.[45] The US, as one of several countries that abandoned its efforts to commercialize fast-neutron reactors when it became clear that they were not cost-competitive, should promote broader awareness of the poor track record of fast reactors.

The same argument applies to expectations regarding reduction in repository size made possible by separating plutonium from the remaining spent fuel. One reprocessing advocate in Japan claimed that a repository storing only reprocessing waste will only be 1/3 as large as an equivalent repository for spent fuel. However, this is contingent upon reprocessing and recycling the transuranic elements in spent MOX fuel in fast-neutron reactors.

2) Promote interim storage as an independent alternative for the near-term.

In Japan, interim storage is defined in relation to reprocessing and is not seen as a viable option in and of itself. Though Japan's nuclear-energy establishment claims that siting interim storage facilities is extremely difficult, it expects to build several more in order to accommodate the spent fuel that Japan cannot reprocess in the coming decades. The US should promote interim storage and emphasize its flexibility and independence from the rest of the fuel cycle. If greater flexibility is written into future agreements with local communities where interim storage sites are located, then it will be easier politically to modify the ultimate destination of the spent fuel to a geologic repository directly instead of first going to a reprocessing plant. The geologic repository should also be designed flexibly, to be able to accept direct disposal of spent nuclear fuel as well as high-level waste.

Figure 6: Interim Spent Fuel Storage in Dry Casks



3) Underscore the proliferation risk posed by stockpiles of separated plutonium and engage Japan as a leading partner in nonproliferation efforts.

While Japan feels that it has a central role to play in the pursuit of international nuclear disarmament, government and industry officials alike do not acknowledge that large civilian stockpiles of separated plutonium might be perceived by other countries as a latent weapons capability. If the US engaged Japan as a leading partner in efforts to promote a more proliferation-resistant international system, it might be forced to recognize the disconnect between its domestic policies and the policies that it promotes for other countries.

IV. Overarching Conclusions

The following conclusions support the country recommendations, while providing a larger perspective on how the US can promote non-proliferation activities separate from the "123 Agreements" it forges with individual countries.

1) Broaden multinational R&D efforts relating to all phases of the nuclear fuel cycle.

The US can take a lead role in international cooperation on wider R&D efforts in other phases of the nuclear fuel cycle to address the concerns of countries in the region that see reprocessing as a necessary option. For example, the US can participate in international efforts to improve the technology and safety of nuclear power as a means to build international trust. The US can also indirectly build the case for the once-through cycle and assuage states' concerns about dwindling global uranium supplies by leading international cooperation for research on uranium resources and on alternate methods of uranium extraction from sources like seawater.[V]

Future R&D, such as the joint US /South Korean feasibility study on pyroprocessing, should be expanded to include the whole range of fuel cycle back end choices. This should include multinational efforts funded both by the US Department of Energy and foreign counterparts focused on siting of interim storage, repository siting, and deep borehole disposal.

2) Establish an international effort to investigate and formulate best practices for public safety and participation in nuclear waste repository siting.

Reprocessing efforts are driven in part by concerns that waste repositories are politically difficult to site. However, countries like Sweden and Finland are making progress toward opening spent fuel repositories while the US has succeeded in opening the Waste Isolation Pilot Plant (WIPP) for a different, more circumscribed class of waste.

An international working group convened by the US, and including Sweden and Finland, could help draw lessons learned on what has worked and what has not in these processes. South Korea, Japan, and China, as well as the other major nuclear energy countries that are engaged with the repository siting issue, such as Canada, France and Russia, should also be included to help educate those governments for whom the disposal issue is most pressing.

[V] The 2005 Harvard study by Bunn et al cites cost estimates of seawater uranium extraction as ranging from $100-1000/kg U. According to the authors, "If uranium could be recovered from seawater at costs below the breakeven cost for reprocessing and recycling, the use of plutonium fuels could be deferred for many centuries," ("The Economics of Reprocessing versus Direct Disposal of Spent Nuclear Fuel," *Nuclear Technology* 15, no. 3, p. 15). However, seawater extraction and its associated R &D to this point have been largely dismissed as overly expensive.

3) *Continue exploring possibilities for siting an international long-term spent fuel storage facilities or repositories.*

An international spent fuel repository has long been a dream but local political opposition has thwarted efforts to open one, most recently, in the late 1990s, in Australia.[46] While potentially difficult to open, the existence of an international or regional spent fuel repository that could accept waste from Japan and South Korea would be a powerful argument against those countries' view of reprocessing as the only path forward in dealing with their domestic waste problems. The recently approved 123 agreement with Russia may offer an opening for the possibility of at least 50-year storage of foreign spent fuel in Russia. This would require US consent, under the US-Japan and US-South Korea 123 agreements for used fuel from American-designed nuclear power reactors in those countries.[47]

While China has large empty areas and few political limitations on siting a repository, local experts feel that any efforts to "internationalize" a Chinese repository to accept foreign waste would be difficult.[VI]

An effort to create international safety standards and regulations for nuclear waste storage could be an interim step towards international repositories. The debate over international fuel repositories is reviewed in Appendix I.

[VI] When asked about the possibility of China hosting Japanese waste, one local expert in China said this would be viewed as an "environmental invasion" and was very doubtful of it being politically possible.

Appendix I:
Debate on an International Fuel Repository

Permanent disposal of spent nuclear fuel in a small number of international geological repositories could be less costly than individual national repositories—especially for nations that have small nuclear programs or unfavorable geology for spent fuel storage. South Korea and Japan have extensive nuclear energy programs, dense populations, and local government veto rights that make siting and construction of any kind of permanent repository difficult. They could therefore find international repositories attractive.

Hosting an international spent fuel repository could provide great economic gains for the host nation.[48] However, while most countries support the concept, few are willing to actually host one, as the political costs are too great. States such as France, Sweden, and Finland, which are in the advanced stages of siting and construction of national permanent high-level waste disposal facilities, have pledged to ban the import of foreign spent fuel.

Mongolia and Russia have expressed interest in hosting an international repository. Mongolia's lack of extensive infrastructure and land-locked position deep within the Asian continent limits its feasibility as a possible site. According to an expert we interviewed, transit disputes may also arise with neighboring countries that would need to authorize the passage of foreign spent fuel through their territories.

In 2001, the Russian Parliament passed a law allowing the import of spent nuclear fuel. "Continuing lack of transparency and variable integrity in Russia's industrial and financial systems," combined with domestic opposition due to the safety and environmental history of the government and its Soviet predecessor,[49] however, has made permanent storage of foreign spent fuel a troublesome undertaking for Russian authorities. However, Rosatom, the state-owned company controlling Russia's nuclear complex, in 2006 stated it would not accept any foreign-origin[VII] spent nuclear fuel.[50]

In addition to domestic opposition, the international community is also unsure that Russian authorities would implement environmental "solutions" that reach the "highest international standards."[51] Although steps such as increased IAEA monitoring and oversight of a Russian site may improve international credibility, prospects for an international repository in Russia are currently limited, though it remains the most feasible option. New developments, such as the country's success expanding its own nuclear program and selling its technology abroad, could revive the political momentum for Russia to host an international spent fuel repository.

[VII] "Foreign-origin" spent nuclear fuel is that which is initially produced in another country.

Appendix II:
Overview of Fuel Cycle Costs

By David Turnbull

> *Since all of the central estimates for the breakeven price of uranium were well above $300/kgU, and the price is predicted to stay below this level for a century even with a high rate of growth in the nuclear industry, the conclusion is that recycling will not be cost-competitive with the once-through fuel cycle for the foreseeable future.*

For a once-through fuel cycle, a reactor operator must pay for interim storage of spent nuclear fuel as well as permanent disposal of the spent nuclear fuel in a geologic repository. A fuel cycle that employs reprocessing and recycling of the fissile material from the spent nuclear fuel reduces some fuel cycle costs but adds new costs that must be taken into consideration. If the recovered plutonium and uranium are used to fabricate mixed oxide and re-enriched uranium fuel for use in light water reactors, the need for interim storage is obviated but the operator must pay for reprocessing of the spent fuel and permanent disposal in a geologic repository of the high-level waste produced by reprocessing.

In order for this recycling scheme to be cost-competitive with the once-through case, the cost-savings from lower demand for natural uranium and geologic repository space must be comparable to the cost of reprocessing. Since projections for uranium price increases have historically motivated numerous countries to pursue reprocessing, one sensible way to compare the fuel cycles is to determine a "breakeven price of uranium" at which the cost of electricity from the once-through fuel cycle is equal to that of a closed fuel cycle. Several recent studies have analyzed the economics of various nuclear fuel cycles and tried to make reasonable estimates for the key parameters. The most sensitive parameters are generally found to be the cost of reprocessing, the cost difference for the disposal of wastes from the once-through and closed fuel cycles, the costs of MOX fuel fabrication, and interim spent fuel storage. For comparison with closed fuel cycles involving fast reactors, the difference between light-water and fast reactors capital costs must be taken into account as well.

A 2005 Harvard study found, based on an extensive review of cost data from existing facilities and cost estimates to determine uncertainty bands for the parameters affecting each fuel cycle, a breakeven price of uranium required to justify plutonium recycle in light water reactors of $368±70 per kilogram of uranium. This means that, at $368/kgU, the cost savings from reduced demand from uranium, no interim storage, and a smaller geologic repository, approximately balance the costs of reprocessing and fabricating mixed oxide fuel. The most sensitive parameter was determined to be the cost of reprocessing, for which the study adopted a central-value estimate of $1000/kgU, which is low compared to a wide range of stud-

Table 2. Sensitive Parameters Affecting Fuel Cycle Costs

Parameter	Parameter Value*			Breakeven Uranium Price (Central = $368/kg U)		Change compared to Central
	Low	Central	High	Low	High	
Disposal cost difference ($/kg HM)	300	200	100	298	438	±70
MOX Fuel fabrication ($/kg HM)	700	1500	2300	302	434	±66
Interim fuel storage ($/kg HM)	300	200	100	310	425	±57
*Low = best case for reprocessing; high = worst case for reprocessing.						

** Graph typed manually to enhance readability from original graph.*

ies and surveys of previous contracts. After the cost of reprocessing, the most sensitive parameters affecting the uncertainty of the central estimate are presented in the table above. [52]

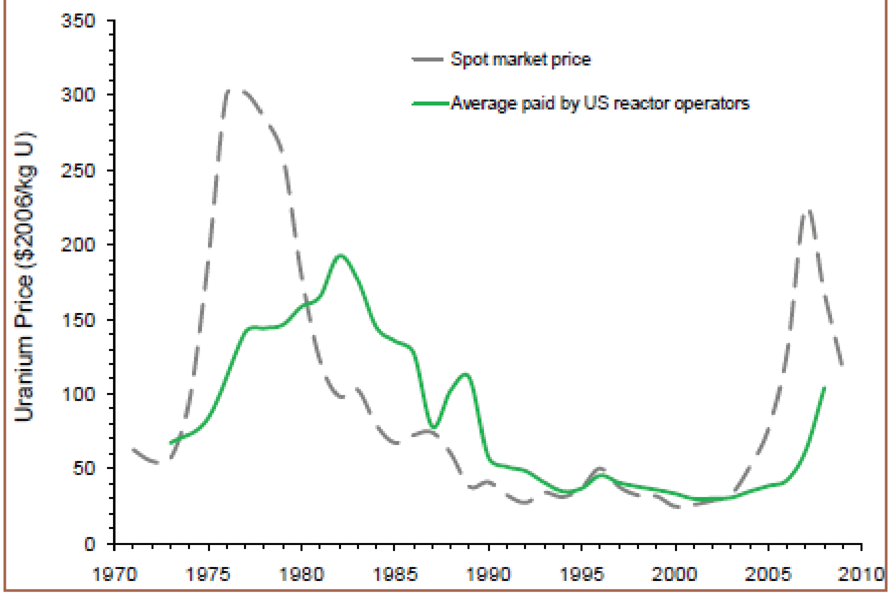
The next most significant factor is the waste disposal cost savings associated with disposing of reprocessing waste instead of spent nuclear fuel directly. The central estimate of $200/kgU represents a 50 percent cost savings, since the estimate for disposing of spent nuclear fuel is taken to be $400/kgU based on the most complete evaluation for a prospective geologic repository – Yucca Mountain in the United States.[53] However, some argue that such savings are too optimistic because the fission products would remain in the high-level waste, and they largely control the heat output– which constrains the packing density in a geologic repository – during the first several decades after discharge. Other studies have used slightly different assumptions to estimate the breakeven price of uranium, including a 2010 MIT report[54] that produced $579/kgU as the breakeven price.

Using separated plutonium to fabricate mixed oxide fuel for use in light water reactors has been resorted to in order to reduce plutonium stockpiles but was never supposed to be the end goal. Rather, the idea was to commercialize fast reactors that could produce more fissile material than they consume in operation. The goal of commercialization has proved elusive despite extensive R&D programs in many countries. Though much of the previous analysis still holds in terms of the added cost of reprocessing especially, the main difference in comparing the cost of the once-through fuel cycle in a light-water reactor with a closed fuel cycle in a fast breeder reactor is the capital cost difference of the reactors. Fast-neutron reactors cannot employ water as a coolant, so the main focus has been on using liquid metal sodium as a coolant. Because the sodium becomes intensely radioactive in the core, in order to isolate this radioactivity within the reactor building, a secondary non-radioactive liquid sodium loop is necessary. As a result, a 600 MWe Russian fast reactor has 50% more structural material than a 1000 MWe LWR.[55]

In the 1970s, the US Department of Energy predicted that fast breeder reactor capital costs would remain 25 to 75 percent higher than light water reactors.[56] France built the only commercial-scale fast reactor but in the late 1990s, its high price tag led officials to conclude, "the record of the fast breeder experience appears unfavorable today in any case on the financial level."[57] The Harvard study chose a central estimate of $200 per kilowatt of electricity as the capital cost difference between light water reactors and fast reactors. Considering light water reactors now have overnight costs of about $2,000 to 4,000/kW[58], this represents only a 5 to 10 percent increase in the capital cost of a reactor—a very conservative estimate. Using it, however, they found the breakeven price of uranium to be $340/kgU.[59]

To place these values in context, the spot price of uranium is about $170/kgU today.[60] While still well below the breakeven estimates of $368/kgU, and $579/kgU for recycling in light water reactors as well as $340/kgU for fast breeder reactors, this price is actually very high compared to the past few decades. This graph shows the spot price of uranium since the early 1970s. The price has generally been well below $100/kgU. The two price spikes are not indicative of long-term scarcity. In the 1970s, rapid expansion was expected in the nuclear energy sector, so demand for uranium (and therefore the price) shot up as countries accumulated large stockpiles. When these ex-

Figure 7. Price of Uranium Since 1970



pectations waned, demand fell again and the stockpiles were sold off over the next decades. Since 1995, Russia has supplied to the market a large amount of low-enriched uranium blended down from highly-enriched uranium recovered from surplus nuclear weapons. The recent price spike reflected the fact that those stockpiles are running out and there is concern that mining capacity has atrophied and will not be able to keep pace with the rapidly-growing demand, particularly from China. The expectation is that this will set off a new wave of exploration and development[61] that should bring prices back into equilibrium with production costs.

The IAEA "Red Book" has published uranium reserve estimates biannually for the past 40 years. As recently as the 2007 edition, reserves had either increased or remained the same since the 1980s despite the fact that IAEA has used the same cost categories for quite some time (in current dollars rather than real or constant dollars). The 2009 edition added a higher cost category in part to reflect the recent escalation in the cost of mining. The size of the identified reserves that are economic to produce at a price less than $130/kgU is currently given as 5.4 million tons, with the expectation that with further exploration another 6.5 million tons would be found. In 2007 global consumption was 67,000 t/yr and the IAEA projects a 1 to 3 percent growth rate for at least the next 20 years.[62] At a 2% growth rate, the current estimate for uranium reserves recoverable for less than $130/kgU is enough to supply reactors in a once-through fuel cycle for more than 75 years. At this price, the cost of uranium adds only .3 ¢/kWh to the cost of nuclear electricity. This may already sound like a large amount of uranium but there is reason to believe that uranium reserves will become substantially larger.

As price increases, new classes of reserves become economic. A 2010 MIT report revisited the 1980 work of Princeton Professor emeritus Kenneth Deffeyes, who concluded that a geological model that assumes a lognormal correlation between the abundance of trace elements in the earth's crust and their concentration was applicable to uranium. This effectively meant that reserves of lower-grade resources are much larger than the resources that are currently exploited. He concluded that a ten-fold decrease in ore grade would result in a 300-fold increase in recoverable resources.[63] The MIT report incorporated this geological model into an economic model, to which economy-of-scale and learning were added, and obtained a single function that outputs cumulative uranium extraction as a function of uranium price. One result was that, even for 100 years worth of uranium consumption at 10 times today's rate (equivalent to 3.6%/yr growth for 100 years), the price of uranium will remain below $300/kgU.[64]

Appendix III:
Interviews and Personal Presentations

Interviews conducted with subject matter experts at Princeton University and during a field research trip to Beijing, China; the Republic of Korea; and Tokyo, Japan from Nov. 1 to 7, 2010. If the interviews or presentation were conducted in a group, all group members are cited together starting with the individual who hosted the meeting.

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