# The Back-End of the Nuclear Fuel Cycle: An Innovative Storage Concept

Stephen M. Goldberg, Robert Rosner, and James P. Malone

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Cover image: The interior of a storage facility for highly radioactive nuclear waste in Borssele, The Netherlands. September 30, 2003. © Michel Porro/Getty Images.

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# Preface

For more than five decades, the American Academy of Arts and Sciences has played an integral role in nonproliferation studies, beginning with a special issue of *Daedalus* on arms control published in 1960. Today, the Academy's Global Nuclear Future (GNF) Initiative is examining the safety, security, and nonproliferation implications of the global spread of nuclear energy. Through innovative scholarship and behind-the-scenes interactions with international leaders and stakeholders, the Initiative is developing pragmatic recommendations for managing the emerging nuclear order.

A safe nuclear future depends in great measure on how the nuclear fuel cycle is managed. In 2010, the Academy published *Multinational Approaches to the Nuclear Fuel Cycle*, which considered spent-fuel management in an international context. The present volume draws on that paper but also moves the debate forward. Robert Rosner (University of Chicago), Stephen M. Goldberg (Argonne National Laboratory), and James P. Malone (Lightbridge) outline a concept to transform the existing international nuclear fuel cycle market. Their proposal addresses the economic decisions that businesses and governments need to make as well as the established competition in back-end services. The model reflects and expands on the recommendations in the recent report from the U.S. President's Blue Ribbon Commission on America's Nuclear Future.

The leaders of the GNF Initiative are working with decision-makers and stakeholders in nuclear consumer states to advance this new business model. Project leaders will work with international colleagues in South and East Asia to develop regional partnerships for managing used nuclear fuel. These agreements could then serve as a building block for similar arrangements in other regions.

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Leslie Berlowitz
*President and William T. Golden Chair*
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### SUMMARY

The American Academy's Global Nuclear Future (GNF) Initiative continues to advance effective policies and procedures that help minimize the international security and nonproliferation concerns associated with the spread of nuclear power. The Initiative's leaders and advisors have identified several interconnected questions that must be addressed simultaneously in order to arrive at pragmatic recommendations for a sustainable new nuclear regime, both in the United States and abroad. These include:

- Most terrorist prevention plans focus on protection against external threats. What impact do insider threats have on the security of nuclear facilities?
- How can nuclear fuel cycle management options and advances in nuclear energy technologies promote or mitigate the dual-use security risk? How will multilateral fuel cycle arrangements support a safer and more secure expansion of civil nuclear energy programs?
- How will the increasing number of nuclear newcomers (nations developing or aspiring to have civilian nuclear energy programs) affect national, regional, and international nonproliferation policies? How can we ensure that emerging exporters of nuclear technology will coordinate policies to minimize proliferation dangers?

Some of these questions are addressed in the paper *Nuclear Collisions: Discord, Reform & the Nuclear Nonproliferation Regime*, by Steven Miller.[1] Our paper covers two of the main themes from *Nuclear Collisions*: namely, that nuclear aspirants should use realistic economics when making decisions about nu-

1. Steven E. Miller, *Nuclear Collisions: Discord, Reform & the Nuclear Nonproliferation Regime*, with responses from Wael Al-Assad, Jayantha Dhanapala, C. Raja Mohan, and Ta Minh Tuan (Cambridge, Mass.: American Academy of Arts and Sciences, 2012). Miller is Codirector of the GNF Initiative and Director of the International Security Program at the Belfer Center for Science and International Affairs at the Harvard Kennedy School.

clear energy programs; and that international bodies such as the International Atomic Energy Agency (IAEA), the Nuclear Suppliers Group, and other formal and informal bodies should respect the interests and rights of nuclear aspirants.

A significant focus of the GNF Initiative has been the back-end of the nuclear fuel cycle,[2] specifically in the international context. This paper addresses the question of whether it is possible to design a consensus-based approach to the back-end that, if fully executed, would limit proliferation risks. We consider this complex question by examining the possibilities for a viable back-end arrangement in the South and East Asia regions. These regions are the trendsetters; energy-security worries dominate discourse in East Asia and the developing countries in South Asia, where nuclear energy is seen as an important supply source to meet electricity needs.[3]

We describe an innovative regional storage concept that provides a built-in safety valve; that is, if recycling technology advances sufficiently to provide a proliferation-resistant and economically advantageous fuel cycle, and if future energy-security concerns require revisiting the uranium supply-and-demand balance, then the used fuel stored at an interim site could potentially be considered a valuable commodity. We recognize that our proposal requires further study and refinement, and we are cognizant of the formidable challenges ahead, including (1) preserving the inalienable rights of a state,[4] whether as a customer or a provider of services; (2) making our proposal economically attractive to potential customers; (3) attracting a state to host an interim storage facility; and perhaps the most difficult challenge (4) fusing together interests that run the gamut from immediate fuel recycle with current technology to a permanent ban on any current or future advanced partitioning and potential recycle technology. To address the last point, the character and scope of a back-end R&D program located in a host state will need further development than what is documented in this paper. In our opinion, the character and scope of the R&D program is crucial to ensuring that we have a safer and more secure nuclear energy future. We offer preliminary thoughts on this matter, in full recognition that they will require additional input from all stakeholders.

We emphasize four specific actions in this paper:

- *Expanding the playing field*. India and China are key in influencing future international arrangements, specifically in terms of their R&D endeavors. Both countries are important because of their explosive growth and their

2. The back-end of the nuclear fuel cycle encompasses, at minimum, on-site pool storage, either on-site or off-site dry storage, and long-term waste disposal.

3. For example, China's surging economy runs mostly on coal, which fulfills four-fifths of the country's demand for electricity. Throughout China, the consequences of that dependence are apparent: its major cities are swathed in smog; regional blackouts ensue when coal trains are bogged down on clogged rail networks; and coal mining routinely causes thousands of fatalities each year. China needs alternatives to coal-fired power.

4. In this paper, we use *state* to indicate a nation-state that derives its political legitimacy from serving as a sovereign entity.

influence in the East and South Asia regions. If the promise for developing and deploying more proliferation-resistant technology is to be fulfilled, China and India will have to play a significant role.

- *Expanding participants and providing flexibility in a multilateral deal.* Adequate capitalization is important for any nuclear fuel cycle venture. For our proposal, we designated a portion of the payments made by legacy holders of used fuel to provide working capital for the back-end venture; the proposal has been designed so that nuclear aspirants have the opportunity to opt in and out over time. We present a market-based approach that provides sufficient cash flow to sustain long-term fuel storage activities.
- *Incentivizing the host state of a back-end facility.* Sufficient incentives need to be put on the table to attract a host state. We have designed two incentives: (1) one-time fee payments that the host can use as collateral for its infrastructure upgrades; and (2) a robust R&D initiative, including the possibility of siting a demonstration facility within the host state. In addition, our proposal would require a relatively small footprint, thereby mitigating siting issues for the host state.
- *Breeding success.* In establishing a multinational fuel cycle regime, whether focused on the front-end or back-end, it is unlikely that one size will fit all. International fuel storage is a worthy goal, but previous efforts to create macro fuel supply and disposition approaches have revealed this task to be very large and likely too expensive. We have designed a region-centric approach, one that would initially have a relatively small footprint. Once a workable approach is demonstrated in one region, other regions will follow when they see success.

These actions are fully consistent with long-standing U.S. policy that does not encourage new civil use of separated plutonium but that does maintain existing commitments regarding the civil use of plutonium in established civil nuclear programs, particularly in Japan and Europe.

We should not lose sight of the significant challenges ahead. In general, countries in good standing with the IAEA may want to preserve *all* their fuel cycle options. For nuclear aspirants and for many existing nuclear states, energy-security concerns may trump all other geopolitical issues; therefore, used fuel may be viewed as an asset and not as waste. We continue to address these challenges in our discussions. Still, we believe that with additional consultations, our proposal will move the debate in a positive direction.

## BACKGROUND

The GNF Initiative is addressing the safety, nonproliferation, and security concerns that arise as civil nuclear energy expands, including an emphasis on the back-end of the nuclear fuel cycle. This paper, we believe, will generate discussion among international stakeholders, and from these discussions, will help identify common interests between nuclear weapon states and non-nuclear weapon states. We consider international proposals to address used fuel management and nuclear waste disposal, and we examine how these solutions could play an integral part in international or multinational fuel supply and assurance options. Indeed, many emerging nuclear states have indicated that they do not need continuous fresh fuel assurances beyond those in normal contractual terms; rather, they would prefer assistance on the back-end to deal with used nuclear fuel and nuclear waste management. Therefore, we are exploring ideas involving the provision of nuclear waste and used fuel disposal options as incentives to join fuel supply agreements.

We are also cognizant of the findings of the U.S. president's Blue Ribbon Commission on America's Nuclear Future. On January 26, 2012, the Commission issued its final report, which charts a new strategy for managing the back-end of the nuclear fuel cycle. The Commission states: "The United States cannot exercise effective leadership on issues related to the back-end of the nuclear fuel cycle so long as its own program is in disarray; effective domestic policies are needed to support America's international agenda."[5] The Commission highlights the need for the United States to employ and adequately fund a consensus-based approach. It provides several proactive recommendations, including the creation of a fair and open process for siting back-end facilities, and a reminder to maintain vigilance and pay careful attention to the lessons learned from the Fukushima Daiichi accident in Japan. As nuclear aspirants make decisions about ordering new nuclear capacity in the coming decades, these states will likely not await U.S. actions in response to the Commission's recommendations. Appendix I summarizes the Commission's findings and compares our proposal with several of the findings.

### *Meetings*

A group of scholars, government officials, and industry leaders, including representatives from the United States, Japan, Malaysia, South Africa, Egypt, and the IAEA, convened in 2009 at Argonne National Laboratory to consider how best to design and promote solutions for used fuel and multinational disposal facilities while meeting their mutual nonproliferation objectives. The group examined options for minimizing the need for independent conventional-reprocessing capabilities and addressed pragmatic steps toward regional and multinational collaborations on key facilities and activities at the back-end of the

5. Blue Ribbon Commission on America's Nuclear Future, Report to the Secretary of Energy, January 2012, http://www.brc.gov/index.php?q=announcement/brc-releases-their-final-report; hereafter cited as Report of the Blue Ribbon Commission. This point is accentuated by recent remarks from Exelon CEO John Rowe: "The Blue Ribbon Commission has offered a road map. But it will take the federal government and national political will to make it a reality. Unfortunately the federal government is further away from keeping its promise on waste disposal than ever and this condition cannot be met"; John Rowe, "My Last Nuclear Speech," American Nuclear Society Utility Working Conference, Hollywood, Florida, August 15, 2011.

nuclear fuel cycle. Participants agreed that a better understanding of previous efforts to achieve back-end solutions—both the failures (for example, attempts to establish international facilities) and the successes (for example, the national facilities in Sweden and Finland)—as well as a better understanding of user concerns and values will be necessary to arrive at a common perspective on how to engage successfully on these issues.[6]

As further background to this paper, we recently participated in an American Academy GNF conference held in Singapore; the conference convened experts and policy-makers from Southeast Asian non-nuclear weapon states, including states pursuing nuclear energy programs, to discuss the feasibility and acceptance of interim and long-term nuclear-waste storage options. The stakeholders and decision-makers[7] at the Singapore meeting outlined three key points:

1. The regional participants expressed a desire to work collectively to solve regional issues, following the model of existing regional organizations such as the Association of Southeast Asian Nations (ASEAN). However, to date, no state in Asia or elsewhere, including Mongolia, appears to have volunteered to be the first to host a regional storage facility.
2. The demand for used fuel services in Asia, dominated by the growth spurt in China, will expand significantly and will require at least four Yucca Mountain-sized repositories (with capacity for at least 280,000 MT) by the middle of this century.
3. The participants representing nuclear fuel consumer states expressed a strong desire to participate in follow-on discussions and research on viable back-end approaches; in their view, the nuclear fuel supplier states and the nuclear fuel suppliers should not be the "exclusive" architects.

To facilitate further discussions with decision-makers and stakeholders in the Middle East and Southeast Asia, as well as to reflect on the findings and recommendations of the Blue Ribbon Commission, this paper focuses on both the

6. At the same time, work with the planners of a possible European Repository Development Organization (ERDO) potentially will move forward. Thomas Isaacs (Lawrence Livermore National Laboratory) has represented the American Academy in efforts to explore collaborative policies and proposals on joint regional nuclear-waste repositories in Europe. The initial meeting of this group, attended by representatives from both the Alfred P. Sloan Foundation and the William and Flora Hewlett Foundation, included participation from fifteen states and resulted in plans to develop a proposal for ERDO. Alongside ERDO, it is our understanding that Arius Association is continuing to evaluate whether similar regional shared solutions would be appropriate for and of interest to emerging nuclear power programs in the Middle East and Southeast Asia. The overall aim is to assess the interest within each region in working toward regional Repository Development Organizations (RDOs) similar to ERDO. In 2011, the United Arab Emirates' permanent representative to the IAEA raised the possibility of a regional repository. Arius Association has not yet identified a specific business proposal for regionally shared back-end facilities.

7. The AREVA representative at the conference expressed the industry view not to perturb the existing viable fuel supply network. Regional storage arrangements would be best served by harmonizing with the existing industry contractual arrangements.

potential mechanisms for establishing regional, multinational used fuel storage facilities and the feasibility of shared ultimate disposal. We draw on the findings from the two meetings described above.

## SETTING THE STAGE

To construct a viable back-end approach, it is important to consider how stakeholders—customers, fuel suppliers, and host states, among others—would answer the following questions.

1. Are price and supply of uranium ongoing concerns for individual states?
2. In a related vein, is the availability of the co-products of conventional reprocessing, namely, fissile uranium and plutonium, critical to the calculus of countries to consider used nuclear fuel as an asset?
3. Could the cost of any back-end technology option be a deal breaker in deciding whether nuclear energy is too expensive?
4. Does conventional reprocessing capacity limit any back-end solution?
5. Are there precedent-setting steps a country takes when it adopts a conventional reprocessing pathway?
6. Can we go forward with interim storage without knowing the final disposition option(s) for nuclear waste?
7. How do we adapt the existing fuel supply network to any back-end approach?

We debate each of these questions and posit our views in Appendix II. In sum, energy-security issues weigh heavily in each state's calculus of how to approach the back-end. States with plans for a small number of nuclear plants cannot economically justify the investment in conventional or advanced reprocessing. However, for states that already have nuclear energy, and that have or will have a relatively large number of nuclear plants (providing greater than 10 GW of installed power), any cost penalties associated with conventional reprocessing and recycling are likely dwarfed by the capital costs of constructing new nuclear plants. For all states, the opportunity to consider a robust interim storage program would outweigh a precipitous decision by emerging states to commit to conventional reprocessing and recycling using current technologies. As further background, Appendix III identifies current activities and plans for back-end services in countries that have existing nuclear power programs. Appendix IV highlights China's plans for nuclear energy growth and attendant back-end activities.

In the following section, we discuss the view of many in the international community on how to secure a nuclear fuel cycle that would limit the spread of fuel enrichment and conventional fuel reprocessing and recycling capacity. Coupling the front- and back-ends of the nuclear fuel cycle is important, but the task of arriving at a viable back-end solution has been more challenging.

States that are interested in coupling the ends of the fuel cycle, such as Russia, China, India, France, and the United Kingdom, believe that because of energy-security concerns, it is important to close the fuel cycle. In their estimation, the availability of a mixed oxide (MOX) fuel inventory would provide them with a so-called hedge in case of supply interruptions or price spikes for fresh fuel.

## GOALS FOR MULTILATERAL FUEL ASSURANCE AND DISPOSITION

Mohamed Mustafa ElBaradei, former IAEA Director General, articulated a three-stage process for an international fuel cycle regime.[8]

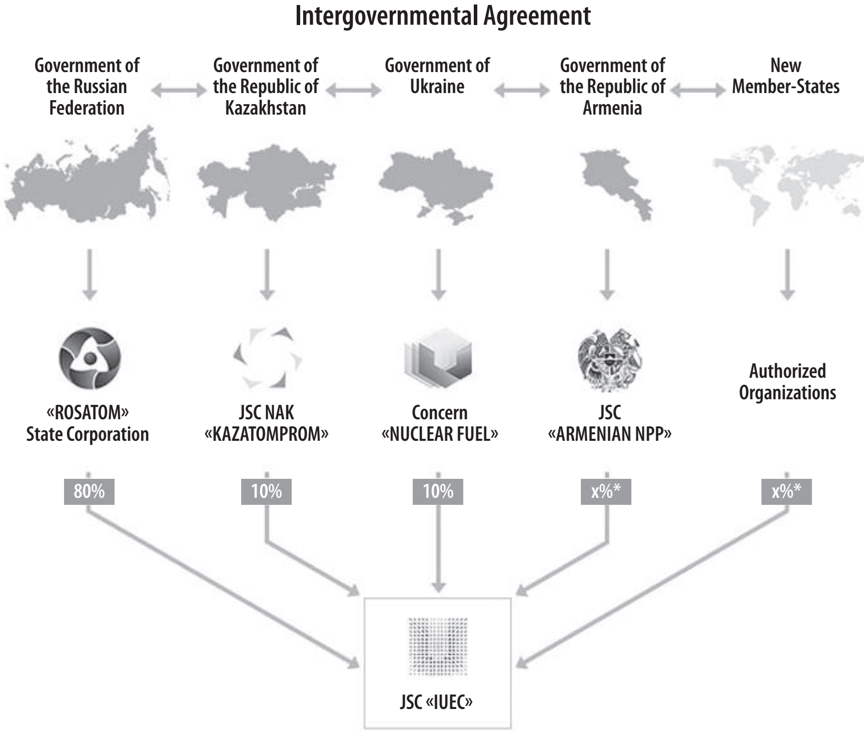
- First, establish a system for assuring the supply of fuel for nuclear power reactors.
- Second, in the future, place all new enrichment and conventional reprocessing or other chemical partitioning activities exclusively under multilateral control.
- Third, convert all existing enrichment and conventional reprocessing or other chemical partitioning facilities from national to multilateral operations.

The first step was achieved with the recent establishment of the Nuclear Fuel Bank. On December 3, 2010, the IAEA Board of Governors further authorized the Director General to establish an IAEA-owned and -managed low enriched uranium (LEU) bank supporting the multilateral effort to assure LEU supply for power generation. Donors have pledged roughly US$125 million and €25 million to cover the establishment of the bank and its initial operational expenses. Although a location for the bank has not yet been identified, on December 17, 2010, the Russian Federation initiated an LEU reserve at the International Uranium Enrichment Center (IUEC) in Angarsk, Russia, as a “last instance” supplier to IAEA member states.[9] (Figure 1 identifies the most current organizational structure.) In 2010, Kazakhstan also proposed that it would host a nuclear fuel bank. On February 8, 2012, Yerzhan Kazykhanov, Foreign Minister of Kazakhstan, stated that his country hopes to have a fuel bank facility in operation by late 2013.

8. Mohamed Mustafa ElBaradei, “Statement of the Director General,” International Conference on Nuclear Fuel Supply: Challenges and Opportunities, Berlin, Germany, April 17, 2008, http://www.iaea.org/newscenter/statements/2008/ebsp2008n004.html.

9. Following adoption of the necessary enabling legislation in January 2007, the Russian Federation established the IUEC at the Angarsk Electrolysis Chemical Combine “to provide guaranteed access to uranium enrichment capabilities to the Center’s participating organizations.” On May 10, 2007, the first agreement in the framework of the IUEC was signed by the Russian Federation and the Republic of Kazakhstan. A mechanism is being developed to set aside a stockpile of LEU that might contribute to a broader assurance-of-supply mechanism. Further, “a regulatory basis will be developed in the sphere of export control such that the shipment of material out of the State at the request of the Agency is guaranteed.”

Figure 1. IUEC Organizational Structure, as of December 2010




*Acquisition of shares from the Russian share provided that the Russian Federation maintains control (50 percent + 1 share). JSC stands for joint-stock company. Source: IUEC; Yury Yudin, ed., *Multilateralization of the Nuclear Fuel Cycle: The First Practical Steps* (Geneva, Switzerland: United Nations Institute for Disarmament Research, 2011). Reprinted with permission from the International Uranium Enrichment Center, http://www.iuec.ru.

In his remarks at the 2006 IAEA General Conference in Vienna, then-President of the Nuclear Threat Initiative (NTI) Charles Curtis best captured the virtues of a multilateral fuel mechanism for the front-end of the nuclear fuel cycle:

> Proponents of the establishment of an international back-up mechanism for assured supply of nuclear power reactor fuel assert that it would have a dual-objective, i.e., to address: (a) the possible consequences of interruptions of supply of nuclear fuel due to political considerations that might dissuade States from initiating or expanding nuclear power programs; and (b) the vulnerabilities that create incentives for building new national enrichment and reprocessing capabilities.[10] Thus, an assurance of supply mechanism would be envisaged solely as a backup measure to the operation of the commercial market, for those States that want to make use of it, in order to assure supply in instances of interruption for political reasons. It would neither

10. In light of long-standing U.S. policy objectives, this phraseology likely refers to conventional reprocessing capabilities.

be a substitute for the existing commercial market in nuclear fuels, nor would it deal with disruption of supply due to commercial, technical or other non-political reasons. While an assurance of supply mechanism would be designed to give supply assurance to States that voluntarily choose to rely on international fuel supply, rather than build their own indigenous fuel cycle capabilities, a State availing itself of such a mechanism would not be required to forfeit, or in any way abridge, its rights under Article IV of the NPT [the Nuclear Non-Proliferation Treaty], in connection with peaceful uses of nuclear energy.[11]

EU Foreign Policy Chief Javier Solana provided a larger context in which ideas about nuclear fuel services play out. In a speech to the European Parliament, he called for a fuel bank to be established before the 2010 NPT Review Conference: "The creation of a fuel bank will have a positive impact on the general climate of the NPT review conference. . . . We cannot afford to fail. If we do we may face more problems—new States that are tempted to cross the red line and go nuclear. . . . But if we succeed, we will strengthen the multilateral nuclear non-proliferation system which is a core EU objective."[12]

Beyond these worthy pronouncements, there is an international consensus along three key points[13]:

- Any multilateral mechanism should not disturb the international market for nuclear fuel cycle services. Multilateral fuel cycle arrangements should be implemented step by step.
- No uniform approach would be satisfactory for all technologies and all states, and successful implementation of the multilateralization would depend on the flexibility of its application.[14]

  –The international commercial market for nuclear fuel services generally functions well, but the push for an internationalized LEU fuel bank sig-

11. Charles Curtis, "New Framework for the Utilization of Nuclear Energy in the 21st Century: Assurances of Supply and Non-Proliferation," Vienna, Austria, September 19–20, 2006, http://www-pub.iaea.org/mtcd/meetings/PDFplus/cn147-chairman.pdf.

12. Javier Solana, "European Proposals for Strengthening Disarmament and the Non-Proliferation Regime," September 12, 2008, http://www.europa-eu-un.org/articles/fr/article_8354_fr.htm.

13. We believe that Sweden's paper to the IAEA provides important insights: "It would also be desirable to pay attention to joint multilateral schemes in relation to the back-end of the fuel cycle, i.e., reprocessing of spent fuel and/or final storage of spent fuel, including from other States. Final storage is a difficult proposition considering public opinion in most States, but it is possible that in large supplier States and in certain regional contexts such cooperative schemes for intermediate and perhaps final storage could be achievable"; 2010 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, NPT/CONF.2010/WP.7, March, 19, 2010. Sweden is moving ahead on a national repository (with the possibility of extending it on a regional scale in Scandinavia); local support for repository location is very strong in Sweden.

14. These two points may be at variance with the views of many nongovernmental organizations, which tend to favor the belief that nonproliferation may trump market concerns, and that a "comprehensive," rather than "step by step," approach may be preferable (and more realistic).

nals the perceived interest in adding a safety net by way of LEU reserves and, in the longer term, considering new joint undertakings to accommodate increasing demand.[15] As currently conceived, arrangements for assured LEU fuel supply would need to be financially supported by the international community and administered by the IAEA.

- Any multilateral nuclear fuel supply arrangement should offer a competitive economic advantage over indigenous development of enrichment and conventional reprocessing or more advanced chemical partitioning activities.

As pointed out in the Report of the Blue Ribbon Commission (see Appendix I), take-back of used fuel has always been viewed as a goal of these policies. Take-back entails moving fuel from nuclear consumer states to either states that can provide fuel services or states that will store used fuel on an interim or longer-term (several decades) basis. The Reliable Fuel Supply (RFS) approach is currently being explored, under the auspices of the International Framework for Nuclear Energy Cooperation (IFNEC), as a follow-on activity previously established as the Global Nuclear Energy Partnership (GNEP). The RFS objective would allow states without extensive nuclear infrastructure to more confidently adopt nuclear power as a low-carbon energy source. In the long run, the program would provide the nonproliferation advantage of centralized high-security storage for the resulting irradiated fuel.

With the RFS concept, private companies, backed by a substantial government commitment, could offer a variety of reliable fuel supply and disposition services, including interim storage and disposal, at a substantially lower cost than those associated with comparable indigenous services. In turn, these services could appeal to a variety of nuclear energy aspirants. The RFS concept seeks to explore opportunities for multinational arrangements for fuel assurance regimes, encourage discussions between and among nuclear consumer states, and prepare the way for discussions within the broader set of participants through the RFS mechanism. In this context, the RFS concept is structured so that it does not alter the stated goals and objectives of those members of the IFNEC that have chosen to use conventional fuel reprocessing technology to close the nuclear fuel cycle. As stated earlier, energy-security concerns lead several states to place significant value on closing the fuel cycle; the availability of a MOX fuel inventory, they believe, provides a so-called hedge in case of supply interruptions or price spikes for fresh fuel. France is actively pursuing a conventional reprocessing and recycling program that increases the stocks of civil separated plutonium. India and China have publicly endorsed comparable conventional reprocessing programs. To address back-end waste management concerns, the Republic of Korea is planning to undertake pyroprocessing, a batch process that could also potentially increase the stocks of civil separated plutonium.

15. This is the concept for the NTI Fuel Bank.

Russia has been actively engaged in promoting both a fuel bank (as pointed out above) and potential storage of Russian-origin fuel on their territory. This arrangement would be part of a bundled reactor sale arrangement.[16] The Russian proposal comes closest by accepting take-back of nuclear fuel that originated in Russia. However, their proposal lacks a commitment to either a time or a location for the disposition of used nuclear fuel. Also, the fuel cycle must fit into their plans for future reactors, taking into account the type and number of reactors that will be deployed. In our opinion, it is unlikely that Rosatom, the state company in Russia that would be charged with this effort, would take back a significant amount of used fuel from Russian-designed reactors.

Any plans for an "optimal" internationalization of the nuclear fuel cycle (defined as a sustainable, economic, and secure approach) must include a viable transition from the current state of affairs. A transition plan must take explicit account of how the existing fuel cycle arrangements will morph into the proposed future arrangements, thereby providing a sustainable pathway for a nuclear energy sector that is likely to grow in the future. Developing a transition plan—without which any future fuel cycle plans will be moot—requires extensive discussions between all affected parties, from suppliers to consumers. It is precisely such discussions that we seek to promote.

An LEU fuel bank[17] is only a partial step toward providing the infrastructure for realistic fuel supply assurance. The missing component is the fuel fabricator: that is, the entity that transforms the LEU into a physical form compatible with loading fresh fuel assemblies into light water reactors (LWRs)—in other words, an entity that fashions (and delivers) completed fuel assemblies ready to be deployed and installed in operating reactors. The difficulties inherent in adopting a common international approach cannot be overstated; in the existing competitive market for fuel fabrication, the details of fuel assemblies are treated as business-sensitive information by fuel fabricators. That is, the competition in this arena is not solely related to fuel cost, but also to fuel (and thus

16. In 2009, major developments for the international nuclear fuel cycle came in the form of Russia's marketing of new reactors with bundled fuel services and the agreement between Toshiba and Atomenergoprom on the possible joint construction of facilities for stockpiling enriched uranium. Interpreted narrowly, such stockpiles would support Toshiba's expanding international nuclear energy business. However, if Japanese nuclear utilities were to participate in the initiative, then the stockpile would become a national enriched uranium reserve. We are unable to project a definitive account of how nuclear power will evolve in Japan in the post-Fukushima era; this remains a story to be written. Therefore, the Toshiba-Atomenergoprom agreement may not be less relevant for Japanese nuclear utilities but may be more relevant for nuclear utilities that purchase or operate Hitachi-designed reactors. If the other Asian states and the United States took part as well, it would be the beginning of the kind of international nuclear fuel bank that the IAEA has advocated. Therefore, the proposal for cooperation between Japan and Russia on enriched uranium stockpiling facilities has raised the expectations that back-end services might be part of the deal.

17. In many ways, the LEU fuel bank is a response to states such as Iran, which has claimed that states that forgo reprocessing and enrichment are vulnerable to supply cutoff for political reasons. Reprocessing in this context is likely to mean all forms of chemical partitioning, in light of the security and proliferation risks countries such as Iran present to the world community.

reactor) performance. Fuel fabricators optimize fuel performance by dealing with issues such as crud formation and fretting (related to cladding deterioration of the fuel pins); the details of fuel composition and structure; and effective mixing of the heat transfer fluid (related to optimized heat transfer and overall reactor power balance). The means by which such issues are resolved are prized intellectual properties that are not readily (if ever) shared; and the consequent highly optimized, but closely held, nature of the design of fuel assemblies means that effective operation of LWRs cannot be carried out in the absence of participation by the fuel fabricators. Therefore, it is not at all clear how a functional multilateral fuel fabrication construct would be fashioned, given currently proposed fuel bank approaches. (We will address this inherent challenge in a subsequent paper.)

The final issue involves the complex question of incentives for a state to serve as host to a multilateral storage facility, a disposal facility, or both. Incentives are usually presented in terms of opportunities to create high-value employment and, in particular, to enhance the state's scientific and technical knowledge. We include the views of a variety of parties interested in this subject as commentary to this paper (see pages 15–17).

## BACK-END CONCEPTS

In Appendix V, we describe two models that capture the state of play to form multilateral mechanisms. Deficiencies common to these models include: (1) insufficient start-up capital to bring a multinational fuel storage or disposal scheme online; (2) a likely reversion to back-end systems that emphasize conventional reprocessing and recycling, thus increasing the supply of civil separated plutonium; and (3) fated attempts to adopt a "one size fits all" approach, creating protracted discussions over contract and payment terms. These models are not complete; they do not provide a path to move both nuclear fuel suppliers and consumers away from the status quo,[18] and they would likely increase reliance on at-reactor pool storage and conventional reprocessing technology. In a post-Fukushima context, with heightened concerns about on-site pool storage of used nuclear fuel, moving as soon as feasible to consolidated dry cask storage would support a safer and more secure expansion of nuclear energy.

More specifically, the models we identify in Appendix V lack a detailed transition plan that describes explicitly how the proposed regime would systematically supplant the existing fuel supply regime. This absence is a particular issue for the multilateral fuel lease plan because it would entail substantial reengineering of the legal frameworks and business models of the existing fuel supply regime.

18. Our proposal has the added advantage of encouraging new service providers to enter the market.

As discussed above, delivery of fresh fuel assemblies is highly dependent on the critical role of the fuel fabricator. In the current regime, fuel fabrication is carried out by firms or other institutions that are subject to either extensive governmental regulation and oversight or management (or both). Consequently, neither model is truly effective in assuring nuclear operators that they will have access to fabricated fuel: that is, to fresh fuel assemblies that can be inserted into operating reactors. As a result, these models do not provide the level of fuel supply assurance that operators need. Thus, the existing fuel fabrication market must be sufficiently robust to mitigate this constraint. Two conditions would further mitigate this concern: standby capacity of fabricated fuel at utilities in nuclear consumer states; and premium prices to fabricators for supplying those utilities with fresh fuel assemblies. In our opinion, this premium would still represent a very small increment (less than 5 percent) of nuclear fuel costs.

## A SPECIFIC PROPOSAL: AN INNOVATIVE STORAGE CONCEPT[19]

In light of the preceding discussion and review, we propose the development of a commercial dry cask storage facility for international customers. This proposed regional storage facility (known in the industry as an independent spent fuel storage installation) would be designed to store up to 10,000 MT of used nuclear fuel (on a relatively small footprint) for up to a hundred years; it could be hosted in a state with or without an established nuclear industry. The capacity and lifetime of the facility are considered practical estimates and are used for the financial model contained in this paper. The values could change based on the needs of the region served.

### *The Concept*

*The parties.*[20] The concept of offering dry cask storage as a fuel cycle service to international customers is not new. Various models have been presented within the international nuclear community. Recently, the concept of reliable fuel services, wherein a fuel supplier could offer fuel take-back as part of the supply contract, has received increased attention. Our proposed storage concept is innovative because it is not tied exclusively to new fresh fuel supply and can be utilized for storage of both legacy and future used fuel inventories. Legacy used fuel could be delivered from countries such as the Republic of Korea and Taiwan. In our opinion, the facility would likely hold some interest for Japanese utilities as well.

19. This proposal has been crafted with the cooperation of Aaron Totemeier of Lightbridge Corporation. The proposal tries to balance the concerns of all parties and provides a flexible path forward to technology choices with regard to ultimate fuel disposition.

20. All parties have, and are likely to have in the future, significant government ownership.

Given that the majority of established nuclear states have yet to demonstrate an ultimate disposal solution, consolidated, dry cask storage could become an efficient, demonstrated mechanism to relieve on-site fuel pools that are nearing capacity. Many plants within established nuclear states have relatively low quantities of used fuel (for example, Taiwan, Mexico, and Brazil); establishing a dedicated dry storage facility would be economically unattractive because used fuel amounts below approximately 2,000 MT do not benefit from economies of scale.[21]

Used fuel from new facilities, operated by nuclear utilities, would follow the legacy used fuel and could be sourced from emerging utilities in states such as the United Arab Emirates. These emerging states would benefit politically from shipping legacy used fuel to a safe location that would be under international safeguards. Sentiment in many states with respect to nuclear power is positive; however, there is still concern about what to do with used fuel.[22] Many issues factor into this decision, and no one solution is appropriate for all nuclear countries.

Though various chemical partitioning schemes and disposal solutions have been suggested and demonstrated (to varying degrees of success), many utilities and their respective countries hesitate when asked to choose the best approach for moving forward. Our storage concept provides an interim used fuel management solution, one that nuclear electricity producers can utilize to mitigate the immediate burden of used fuel management while further technological solutions are developed and political decisions are made. Our storage concept provides breathing room, giving current R&D activities in advanced fuel cycle technology time to mature and allowing for the possibility that used fuel may become a future asset.

Fuel suppliers could also use the facility as a storage site for their cradle-to-grave services. This arrangement would allow the existing front-end fuel cycle industry to continue operating as planned while maintaining flexibility on the back-end, as it does not presume an ultimate outcome for the used fuel.

A distinct advantage of our proposed concept relates to nonproliferation interests.[23] If, in the future, an advanced chemical partitioning regime that is acceptable from a nonproliferation perspective and viable from an economic point of view should emerge, an amendment to any future government-to-government agreement could be put in place to maintain flexibility for the client states. With respect to existing conventional reprocessing capacity, the requirements to

21. José L. Rojas de Diego, "Economics of Spent Fuel Storage," *IAEA Bulletin* 3 (1990).

22. The ultimate disposition of used fuel is a concern across the nuclear industry. Development of economic post-storage solutions will benefit nuclear utilities, their customers, and their governments. The proposed regional facility in no way reduces the necessity of developing final use/disposal options; it provides breathing room, allowing existing and new reactors to operate while permanent solutions are developed. Furthermore, the regional facility obviates the political challenge of the nuclear utilities and their advocates "selling" an in-state disposal site.

23. We would prefer that participation in our storage concept be contingent on aspiring states agreeing to forgo enrichment on their territory and conventional reprocessing anywhere; however, we do not believe that states would forgo these rights.

forgo conventional reprocessing could also be imposed on those states with legacy fuel that wish to take advantage of the opportunity to store their used fuel away from their reactors. Additional nonproliferation and security benefits associated with such a facility have been discussed by many authors[24] and will not be revisited here.

*The deal.* We believe that there is significant flexibility in how our concept could be implemented. For example, because the facility would operate on a commercial basis, individual storage contracts could be tailored to the specific needs of each customer. The storage contracts could be signed in short-term increments (that is, twenty years) such that at the end of each segment, the customer and the regional facility operator can decide whether to renew the contract or pursue an alternative use for the material. The storage contracts could be structured so that upon acceptance of used fuel for storage, additional fuel assemblies would be transferred to an internationally sanctioned research facility.

There are several reasons to suggest a commercial approach, in the form of an international entity,[25] for the operation and ownership of the regional facility. These reasons are primarily associated with the capabilities and responsibilities of the host-state entities, which may not be fully mature. In the case of a host state that does not have an established nuclear industry, it may not be necessary for the host state to develop the technical expertise or monetary backing to own and operate the regional facility on its own. These tasks could be more easily achieved by a commercial entity comprised of existing nuclear entities, which could form a consortium outside the host state. Likewise, the host state would not have to be solely responsible for funding the infrastructure developments necessary to operate the facility; revenue to the host state could be paid in the form of a land lease or other agreement with the consortium. The expertise and capital investment of the management entity[26] would support expedited deployment of the facility and ensure that industry best practices are in place. If the entity is a multinational consortium that holds other nuclear facility ownership interests, it would likely invest significantly in facility safeguards, thus diminishing political mistrust over proliferation concerns among all parties to the transaction.

### *Benefits and Concerns for the Parties Involved*

Of utmost concern when evaluating international programs is the potential benefit to the prospective parties, which include, in this case, the host state, the customers, the management entity, and the global nuclear community. Given the

24. Jor-Shan Choi, "Managing Spent Nuclear Fuel from Nonproliferation, Security and Environmental Perspectives," *Nuclear Engineering and Technology* 42 (3) (June 2010).

25. One multinational corporation would provide optimum organizational structure; broadening this entity to include several international organizations would complicate the management and legal requirements. We plan to carry out more research to develop our concept in this area.

26. We plan to carry out more research to develop our concept in this area.

complexities of the nuclear fuel cycle and the hardened positions from a history of disagreement over what the optimum future nuclear fuel cycle should be, motivating the parties to adopt this proposed venture will require more than monetary benefits alone.

For *customers*, the important feature of the proposed regional facility is the alleviation of increasing used fuel inventories at reactor fuel pools. The recent events at Fukushima Daiichi have heightened public concerns about long-term storage at these pools. In addition, and as pointed out in the previous section, the proposed regional storage facility could reduce back-end fuel cycle liability for emerging nuclear states. Some emerging states, such as the United Arab Emirates, have expressed a desire to mitigate back-end fuel cycle concerns altogether, and would thus consider it a welcome option for used fuel to be stored long-term outside of their state in an internationally safeguarded facility. Aside from states with small used nuclear fuel inventories, it is worth noting the benefit to those states where use of nuclear power may decline from its current level; for example, as a consequence of heavy political pressure, German policy-makers recently announced an end to that state's nuclear power industry. This concept would prompt such states to remove their used fuel stockpiles to a regional facility.

For the *international nuclear community*, the primary attraction of the proposed facility is the nonproliferation benefits associated with having a centralized, safeguarded storage facility as opposed to numerous isolated facilities. This facility would provide a much more economical solution than development of in-state conventional reprocessing, advanced chemical partitioning, or disposal capabilities, thereby reducing the incentive for emergent nuclear states to pursue their own back-end fuel cycle capabilities. The primary concern of the international community would be siting the facility in a state with a stable government and a strong, transparent relationship with the international nuclear community.

For the *host state*, fees charged to the facility would generate revenue; operation and maintenance needs would create jobs; and the owner of the facility would generate revenue through long-term storage contracts with customers. Further, the host state could be home to a research facility dedicated to advanced waste forms, pre-treatment options, and understanding used fuel and storage canister behavior over extended storage periods (that is, beyond the nominal sixty-year expected life of existing dry storage systems). Additionally, the host state would benefit from infrastructure development; indeed, improvements to roads, rail, electricity, fresh water, and water treatment would all be required to move fuel into and out of the facility. Thus, the host state would profit directly, from fees related to the facility, but would also benefit from long-term employment related to facility operation, security, maintenance, and regulatory functions, as well as opportunities created by a back-end R&D facility.

The majority of host states are likely to require assurance that the facility will not become a de facto disposal solution for the region's used fuel.[27] Therefore, some means for removing the material at the end of the agreed-upon storage period should be maintained or developed. Material could be returned to the generating state if no agreeable solution is achieved, though over the long term of storage (potentially a hundred years) it is reasonable to assume that multiple solutions will be developed. The host state should also require assurances that government instability in customer states does not affect the terms of their storage contracts. Some type of monetary penalty or agreed-upon removal option may be needed for customers that default on their contracts. Likewise, as historical evidence suggests, states will do whatever they perceive to be in their best interest; therefore, it may be desirable to provide a safety mechanism to avoid returning used fuel to a state that does not intend to honor its previous nonproliferation agreements. Additional benefits could include job creation at facilities that manufacture used-fuel transportation and storage units. There will also be a need for used-fuel canisters as well as transportation overpacks and the attendant auxiliary systems and equipment.[28]

In sum, we believe that the proposed concept offers significant benefits to the international nuclear community (through enhanced proliferation resistance) while presenting a reasonable and manageable set of concerns. Our proposal represents a good starting point for further discussions among interested parties.

### *Initial Stage of Implementation and Potential Private-Sector Partners in Dry Cask Storage*

Clearly, such a venture will require, at the initial stages, international cooperation at the governmental level to establish the agreements and policies necessary for the facility to function. International assistance in devising and implementing world-class safeguards and accountability measures would increase the transparency and overall acceptance of the facility.

The first step in implementing the facility would be to identify a suitable host, interested commercial fuel storage partners, and potential early customers for initial storage contracts. A public education campaign should be conducted within the host state to inform the populace of the risks and benefits related to storing and transporting used nuclear fuel. Public acceptance of the facility will be critical to its success.

Potential commercial partners should have demonstrated experience in dry cask storage operations; they might include cask manufacturers, nuclear utilities

27. Where the financial incentives are present, such as cases in which countries can secure lucrative reactor supplier contracts that include take-back services, this concern is likely not present. Russia is one such case, and China may potentially be another. In addition, because the regional storage facility operator and its host state government are unlikely to have a strong economic bargaining position with respect to most nuclear states, some internationally agreed-upon guarantees may be necessary.

28. U.S. industry is capable of providing these back-end components.

with current dry cask storage operations, facility designers, experienced nuclear fuel transporters (both land and sea), and used nuclear fuel handling and logistics experts.

Each customer may need to establish an agreement with the commercial entity[29] representing the host state, though we would not expect such arrangements to involve significant effort relative to the overall scope of the program. The international legal framework necessary for this form of commerce requires additional legal analysis.

The terms of use for the customer should also be discussed early in the process. An agreement to at least one full storage term (for example, twenty years), with subsequent terms to be decided at set intervals, would provide assured revenue for the facility and allow the customer to take advantage of new developments that may occur in used-fuel management. In order to reduce capital outlay and borrowing on the part of the facility, pre-payment of the fuel acceptance fee prior to delivery may be required. An annual, per-cask storage fee would also ensure funds for maintenance and security of the casks during the storage term. A summary of an illustrative cash flow is presented in Table 1 (below) and is further discussed in the business case analysis.

*Further Implementation Steps*

- Security, Safeguards, and Safety. Bilateral agreements between the host state and customer states will need to be signed to define the nature of storage contracts and clearly delineate who holds the title and who assumes risk of loss of the material. The form that such agreements will take should be a topic of early, high-level discussions among the interested parties; whether the agreements must allow for both commerce and transfer of sensitive nuclear technologies (such as the U.S. "123 Agreements") will depend on the level of technology transfer required to store used fuel in a given candidate host state. In our opinion, a mechanism directed solely at dry cask storage and used fuel title transfer may allow for faster implementation than an agreement permitting the much more general sharing of technologies necessary for controlled nuclear material and technology transfers. Though it is reasonable to assume that the host state may wish to pursue peaceful nuclear energy at some future date, the host state concerned could sign that agreement at an appropriate time in the future.

  Successful implementation of the program will require multilateral assistance to the host state in the area of regulatory oversight. The host state will need an independent nuclear regulator—preferably with close ties to an existing regulatory body and a transparent mode of operations—to provide assurance not only to the citizens of the host state but also to the international nuclear community. The regulator would be charged to protect public health and safety by licensing the facility and the storage and trans-

29. The commercial entity is classified as the owner-operator of the regional storage facility.

portation of used fuel for the regional facility owner/operator within the host state. If the host state already has a regulating body in place, then ensuring its independence and transparency would be the primary concern. If not, the process of establishing a regulator would greatly benefit from the assistance of international regulatory bodies as well as regulators in states with established nuclear programs. Existing regulatory best practices and experience with establishing new regulators in emergent nuclear states offer a framework for the host state's regulatory needs.[30]

Regulations and guidelines for implementation should be defined early in the process. Though the regulator should be an independent body, the regional facility owner/operator should maintain regular communication with the regulator to ensure timely implementation of the program.

- Storage Contracts. Dry cask storage has been demonstrated at many facilities around the world and requires no new technology development (that is, not for the nominal life of forty to sixty years). Thus, the most difficult task in implementing the regional storage facility may be negotiating storage contracts with customers. The terms of the storage contracts will likely need to be determined on a case-by-case basis with each customer; differences in national laws and capabilities will likely make turn-key contracts impractical. For example, state A may not allow title of its used fuel to be held by another state while state B may make this allowance but prohibit transportation of used fuel within its borders by a foreign entity. States with small quantities of used fuel that have yet to implement dry storage practices may require assistance with container loading and transfer to a shipping vessel—capabilities that other states have readily available. Part of the regulatory process within the host state should require characterization of the used fuel; this process will likely call for an agent to the owner-operator of the regional storage facility to be present during container loading to verify contents and loading procedures. These examples demonstrate the important role of high-level government-to-government support, at the initial stages, in successfully implementing the proposed concept.
- Siting and Development. Deployment of the regional storage facility may require infrastructure development within the host state, which will vary in degree depending on the particulars of the state's current situation. Geographic location is also a factor: if transporting used nuclear fuel to the facility requires traversing neighboring states, those states may need to be involved early in the planning phase. Ideally, this regional facility would have access to a port to prevent such scenarios. However, it is not necessary to locate the storage facility near a coast; in fact, it may be better to locate it well inland to avoid the risk of flooding.

30. The World Association of Nuclear Operators could be consulted to ensure that the highest standards of nuclear safety are adopted.

With regard to siting, the primary concern is the availability of a suitable facility site. The land-use requirements of a concrete pad to store 10,000 MT of used fuel are relatively small—only a few acres; and the engineering requirements for the concrete pad are similar to those of an airstrip. Operating procedures for this type of storage facility are well developed and have been demonstrated at many facilities around the world; no new or novel technology developments are required. Therefore, the proposed facility can be staffed by technical personnel from the regional facility owner-operator. In training staff, the development and maintenance of a strong safety culture within the facility should be paramount. The majority of operations can be performed during an initial transition/training period by experienced personnel. We believe that training of facility personnel can lead to self-sufficiency in most, if not all, areas of operation—including the transfer of canisters into concrete storage overpacks, which can, in turn, be fabricated on-site as needed.

- Long-term Storage. Little empirical evidence exists to model behavior of used fuel and dry cask storage systems for extended time periods (such as the proposed one hundred years). As extended dry cask storage will likely become the global industry standard, the concerns associated with this fact are ubiquitous; therefore, collaborative global R&D efforts, such as the ones proposed in this paper, are warranted to ensure continued safety and security for the stored used fuel. The U.S. Nuclear Waste Technical Review Board issued a report identifying several R&D areas, mostly associated with the ability to accurately understand and model long-term behavior of the various components of the dry cask system.[31] Implementation of the proposed regional storage facility and other extended-storage options should consider these areas and work with technical experts to identify and implement methods to monitor performance efficiently over the storage duration.

*Business Case*

The business case for the proposed regional storage facility must consider several areas in order to offer a convincing argument for success, and all stakeholders must understand and be comfortable with its terms. There are four general categories of stakeholders: the existing nuclear fuel cycle entities, the entities within the host state(s), the customer community, and the international community.

Similar to the NTI's support of the nuclear fuel bank, start-up or seed money provided by a philanthropist or foundation might be needed to facilitate establishing a business of this nature. The business would return the seed money

31. "Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel," U.S. Nuclear Waste Technical Review Board, December 2010, http://www.nwtrb.gov/reports/eds_execsumm.pdf.

upon reaching an early milestone, such as receipt of fees associated with the first 500 tons of used fuel. Further study is needed to determine the specifics, but the underlying point is that there is no need for the U.S. government to provide financial support.

An estimate of the costs and potential revenue of the regional storage facility suggests that, to service both existing and emerging nuclear power plants, capacity could be divided into 75 percent legacy material and 25 percent capacity for emerging markets.[32] Legacy material would be charged a one-time fee based, in this estimate, on the burn-up of the fuel. New markets could make recurring payments while the fuel remained in the reactor to cover the future cost of storage. This legacy material would provide supporting revenue and incentive to build the regional storage facility while the emerging states are utilizing, and subsequently cooling, their first fuel load.

Table 1 provides four cash-flow scenarios for four waste acceptance fee assumptions. The estimate is not intended to be a rigorous economic assessment of the regional storage facility; it is instead a high-level evaluation to encourage informed discussions and determine whether a more detailed future analysis is warranted. A variety of experts from across the nuclear fuel storage and transportation industry provided the cost estimates that we utilized for the scenarios.

The facility is projected to begin accepting used fuel in 2023. At that point, no emergent nuclear operators will have fuel ready for dry cask storage; therefore, revenue for the first several years will be provided by legacy material. A used fuel acceptance fee of 0.45 mill/kWe-hr is assumed for the reference case; the demand component is assumed to be forty canisters per year of 40 GW-day/MTHM burn-up fuel. An annual fuel storage fee of $25,000 per canister is assumed, which provides for ongoing security forces and payment of fees to the host state after the facility has reached capacity.[33]

Capital investments are included as expenditures prior to the first year of operation. These include the design of the facility; construction of administrative, maintenance, and concrete fabrication buildings; installation of the container transfer system and the equipment necessary for moving the containers; and fabrication and maintenance of the storage casks. Construction of the first portion of the concrete pad is included in these estimates.

The storage-related infrastructure can be built as needed and is included in the operations and maintenance cost. It includes the fabrication of storage overpacks, the concrete pad, and security infrastructure for the casks: fencing

32. The participation of legacy holders is the most critical aspect of obtaining sufficient start-up capital.

33. This estimate involves several assumptions but suggests that there is potential monetary value to the independent used fuel storage installation operator; that value could be realized early in the facility's life. Clearly, more detailed discussions and analyses are warranted.

Table 1. Innovative Storage Concept—Net Cash Flow

| Cases | Acceptance Fee ($0.001/ kWe-hr) | Storage Fee ($1,000/ cask-year) | Net Cash Flow in Operating Year ($1 Million USD) | | | |
|---|---|---|---|---|---|---|
| | | | 1 | 5 | 10 | Lifetime |
| Low | 0.38 | 25 | (80.7) | 35.6 | 202 | 1,615 |
| Reference | 0.45 | 25 | (45.8) | 138 | 390 | 1,872 |
| Medium-High | 0.75 | 50 | 101 | 580 | 1,219 | 4,309 |
| High | 1.0 | 50 | 223 | 947 | 1,892 | 5,227 |

These estimates assume 75 percent legacy holders and 25 percent new entrants. Source: Table created by authors.

and motion and infrared detectors, for example. We assume that a medium-sized used fuel transport vessel with a capacity of forty canisters will be hired for ocean-going transportation.[34]

As indicated in Table 1, positive net cash flow could be obtained by year five in the facility's operation for the low and reference cases.[35] Our initial analysis takes a conservative approach: payments by the customers would precede service by only one to two years. Positive cash flow could be achieved earlier if one-time fees were received at the time of commitment to this project. Depending on industry manufacturing capabilities, the transportation overpacks, which have the highest capital expense and longest lead time, may need to be ordered several years prior to the facility opening. These expenses could be offset by early payment of the fuel acceptance fee by legacy used fuel customers. If the regional facility can be demonstrated to have a sufficient level of assurance that operations will commence on schedule, the fuel acceptance fee, in whole or part, would likely be paid by both nuclear aspirants and legacy holders prior to transportation to this regional facility. Indeed, it is likely that both nuclear aspirants and legacy holders could begin paying their acceptance fees significantly earlier than when transport begins—as early as when the regional facility needs to begin procuring the initial container shipments for the customers. Such an arrangement would reduce the amount of money the facility would need to borrow initially, thereby reducing the overall cost of storage and potentially benefiting the customer and/or host state.

34. At this stage, estimating transport distances and routes is difficult; therefore, an assumption of a ten-thousand-mile sea journey is used as a conservative estimate, with no overland transport assumed.

35. During the planning and early construction phases, net outflows would likely exceed planned inflows.

The proposal of a commercially owned and operated regional storage facility allows for flexible execution and provides numerous benefits to the parties involved that may be difficult to achieve in a government-run operation. The facility would not only allow existing international fuel cycle markets to continue operation unimpeded, but it would also provide a potential economic opportunity for those markets to expand their services to include cradle-to-grave services. Based on our preliminary analysis, the cash flows are sufficient over the proposed time period to generate profits for the regional facility owner as well as revenue and job creation for the host state. The final negotiated pricing and payment terms will be a cost that the customers electing to avail themselves of the facilities should find attractive.

## EXPERT COMMENTARY TO DATE

We received commentary from four technical experts in the South and East Asia regions:

- Japan—Dr. Akira Omoto, Commissioner, Japan Atomic Energy Commission
- Republic of Korea—Dr. Joo Sang Lee, Director-General, Korea Hydro and Nuclear Power Company
- Malaysia—Dr. Noramly bin Muslim, former IAEA Deputy Director General and Chairman, Malaysian Atomic Energy Commission
- Singapore—Dr. T. S. "Gopi" Rethinaraj, Assistant Professor, Lee Yuan School of Public Policy, National University of Singapore

All four experts believed that the biggest challenge for emerging nuclear power in Asia is developing human capacity to address the likely growth of nuclear energy in the region. Except for China, India, and the Republic of Korea, deployment decisions regarding the nuclear fuel cycle for countries in this region are viewed as further downstream and not as immediate a concern as capacity-building. The pace of nuclear power growth for all countries, including China, India, and the Republic of Korea, will be influential in formulating policies on the nuclear fuel cycle. All the experts reinforced several of the positions articulated in our paper, namely:

1. All countries in good standing with the IAEA should be able to consider all fuel cycle options and not arbitrarily foreclose choices related to the back-end. Energy security concerns trump all other considerations; the used nuclear fuel could, in the near term (in the case of Korea and Japan) and in the long term (in the case of Malaysia and Singapore, if either or both countries deploy nuclear energy), be an asset and not a liability. Inherently, any chemical partitioning concept, including conventional reprocessing, and recycling of the uranium and plutonium cannot simply be "taken off the table." In

the case of Japan, Dr. Omoto has stated: "Reprocessing of used fuel is basically to be conducted within the country in view of securing the autonomy of the nuclear fuel cycle."[36]

2. One of the key provisions of our innovative storage concept—linking legacy with newly generated used fuel—is attractive, particularly in view of the difficulties all experts identified in using multiple sites for long-term on-site storage of used fuel. On-site storage is a significant issue now in the case of Japan and the Republic of Korea[37] and will be equally significant in the case of Malaysia and Singapore. Taipower in Taiwan is facing similar concerns.[38] Our proposal could possibly address the storage challenges for some of the reactors in Taiwan and the Republic of Korea.
3. Another key provision of our storage concept, technology deferral,[39] is also attractive to the experts we consulted, particularly in view of the need to reduce the future nuclear waste burden. Deploying reactor systems at-scale—in particular, ones that are designed to consume actinides—will require a large investment in transformational science and technology; institutions and states that participate in back-end services would benefit from these investments.
4. In a state that hosts a regional storage facility, a semi-scale storage facility colocated with an R&D facility for used fuel is more likely to be publicly acceptable than a full-scale commercial facility. Therefore, the initial storage capacity of the facility should be capped at 10,000 MT.

36. In a 2005 report, Dr. Omoto stated: "We have reached the conclusion that our basic policy is, aiming at using nuclear fuel resources as effective as reasonably achievable, to reprocess spent fuel and to effectively use the recovered plutonium and uranium, while ensuring safety, nuclear non-proliferation, environmental protection, and paying due attention to economics." See Japan Atomic Energy Commission, *Framework for Nuclear Energy Policy* (tentative translation), October, 11, 2005, 33. Post-Fukushima, it is striking that this policy has been unaffected.

37. Consider this language from Article 18 of the Special Act: "No addition of Silos and removal of legacy to another site in South Korea" (translation).

38. *The Mainichi Daily News* reported recently on Taiwan's plans for a dry storage facility:

> Taiwan's first interim dry storage facility for spent fuel rods is scheduled to be completed in the later part of next year and become operational in 2013, Atomic Energy Council officials said Sunday. Shao Yao-tsu, deputy director of the council's Fuel Cycle and Materials Administration, told Kyodo News that state-run Taiwan Power Co. will apply for permission to run the facility on a trial basis next month. Taiwan has three operational nuclear power plants and six reactors, while a fourth one is still under construction. Reactor fuel rods need to be replaced with fresh ones every 18 months. Discharged fuel assemblies must be continually cooled in water pools for many years after they are no longer useful for generating electricity. The water pools at the First Nuclear Power Plant in Chinshan, 41 kilometers away from the capital city of Taipei, are nearing capacity.

See "Taiwan's Dry Storage Facility for Spent Nuclear Fuel to be Completed," *The Mainichi Daily News*, October 31, 2011.

39. This provision is attractive for both newcomers and current used fuel generators.

5. The prospect of cooperation in South and East Asia on a regional repository was best characterized by Dr. Lee: "There seems to be no strong glue for all countries in the region to collaborate and to plan for a regional back-end facility." Therefore, it was suggested that a regional forum be held, possibly under the auspices of ASEAN and including policy-makers and thought leaders from Russia, China, and India.[40]
6. Dr. Rethinaraj pointed out that India is particularly interested in becoming self-sustaining with regard to nuclear energy. As part of its effort to diversify its economy away from fossil fuels and insecure sources of imported energy, India is pursuing advanced nuclear energy technologies. India is a strong proponent of recycling.[41] India needs to play a very active role in any innovative concept; broadening the R&D activities at the regional fuel storage complex, to encompass concepts that Indian scientists and engineers are considering, may encourage India to participate in such a project.

## FINAL THOUGHTS

Our focus in this paper has been on fashioning not only a feasible scheme for a sustainable multinational fuel cycle, but also a feasible scheme for transforming the existing international nuclear fuel cycle market into our target sustainable international fuel cycle, which would integrate the back-end of the fuel cycle into the international market. That is, we believe that the structure of proposed fuel cycles (for example, the "asymptotic" fuel cycle state: that is, the vision described by ElBaradei) cannot be independent of the processes and procedures that enable the transition from the current state to this asymptotic state; in the absence of an arguably feasible transformation process, no internationalized fuel

40. Thought leaders from India may include representatives from Bhabha Atomic Research Centre (BARC), Indira Gandhi Centre for Atomic Research (IGCAR), and the Atomic Energy Research Board (AERB).

41. According to Anil Kakodkar, former Chairman of the India Atomic Energy Commission: "Recycling of nuclear fuel is essential and inevitable for India in particular and the world in general. In fact, the world can look to India as a future leader in recycling of nuclear fuels like uranium and thorium"; quoted in *Times of India,* October 30, 2011. Current Atomic Energy Commission Chairman Srikumar Banerjee has also commented on India's future recycling plans:

> Integrated Plants for reprocessing of spent fuel from both thermal and fast reactors are being designed in India for the first time. . . . India also commenced engineering activities for setting up of an Integrated Nuclear Recycle Plant (INRP) with facilities for both reprocessing of spent fuel and waste management, as setting up adequate reprocessing capability has been an important element of the country's closed fuel cycle-based programme.

Quoted in "India Designs Integrated Plants for Spent Fuel Reprocessing," *Deccon Herald,* November 2, 2011. The article continues: "The Fast Reactor-based spent fuel recycling plants will be located at Kalpakkam (Fast Reactor Fuel Cycle Facility—FRFCF) while thermal reactor-based spent fuel recycle plants will be located at Tarapur."

cycle proposal—no matter how attractive from the safety, security, and nonproliferation perspectives—should be entertained with any seriousness. One must always be able to answer the question, how do we get there?[42]

We believe that our proposed initial concepts for multinational arrangements will benefit from input by decision-makers and stakeholders in nuclear consumer states. Listening to their goals and objectives, as well as what they see as the constraints, will inform discussions and the attendant R&D that could produce a true "game changer."[43] Up to now, leaders from the public and private sectors in nuclear supplier states have dominated the discussions. We expect to begin more inclusive conversations on these concepts in the Middle East (in the United Arab Emirates, in particular, and via the Arab League) and in the Asia region.

We believe that we have considered this complex question using the best principles of a *Rogerian approach*; that is, we have addressed a divisive and controversial issue through dialogue that is nonconfrontational and aims for consensus-building. Traditional argument structure begins with an assertive stance and frequently incites resistance on the part of one's "target" audience. To soften this resistance and, concurrently, to find common ground with our audience, we have attempted to remain neutral toward the back-end issue. In place of the traditional argument structure—claim, support, counterargument, and conclusion—we have wrestled with the nonproliferation, safety, and security questions surrounding the back-end issue; we have considered and proposed al-

42. There are several key elements inherent in fashioning a realistic transition plan. The first is the idea that all participants—from the fuel suppliers and fabricators to the reactor operators and the ultimate operators of the used fuel facilities—must see profit in the new arrangements. While this notion might seem obvious, it turns out not to be obvious what all "players" gain during the transition, even though they might ultimately profit in the "asymptotic" fuel cycle regime. This is in part the reason why attention to the details of a transition to a new multinational fuel cycle regime is so essential. The second key element is the up-front realization that technological development in the area of used fuel management has not yet fully matured; and that, aside from political considerations, reasonable people can therefore differ on the present-day management of used fuel. For this reason, any transition plan must allow for these differences in viewpoint. This element has led us to the realization that the base case for multilateral fuel cycle arrangements to be realized today must involve interim (and thus retrievable) used fuel storage, coupled with various incentives for the host nation of the interim storage facility. (This is not to exclude the possibility that some used fuel host candidates might be willing to entertain nonretrievable storage—for example, final used fuel disposal in a permanent repository—but rather is meant to broaden the range of possibilities [and candidates] for used fuel disposition today.) The incentives could take a variety of forms, including support of R&D activities related to strengthening the robustness and longevity of interim storage technologies. That is, the "carrot" for used fuel storage hosts should not be limited solely to financial incentives; rather, it might be better focused on technology development within the host nation.

43. The GNEP and cradle-to-grave activities are characterized by the fact that supplier states have developed the proposals. Our conversation provides a complementary component for developing proposals from the vantage point of the consumer states.

ternatives; and we have posited a conclusion/compromise position. After all, the goal of Rogerian argument is to "win" by building bridges between opposing views.[44]

The time has come to discuss tangible as well as intangible incentives to support a proliferation-resistant fuel assurance regime. Commercial, nonproliferation, and sovereign interests all have to be a part of the conversation. This paper has attempted to elucidate the conditions for discussion and has presented an initial proposal that requires refinement, but that can begin the conversation nevertheless.

44. An alternative, less-workable approach is the Ringi-sei System, whereby decisions are made from the bottom up. This process was common in eighteenth- and nineteenth-century Japan, especially in the bureaucracy. Under this system, low-ranking officials (lower-level managers in the private sector) draw up an initial plan, which is then circulated among higher-ranking officials to receive their seals of approval. We believe that this system is still at work in Japan and may have contributed to the management flaws surrounding the Fukushima Daiichi accident.

# Appendix I

## Findings of the Blue Ribbon Commission Applicable to the International Aspects of the Back-End of the Nuclear Fuel Cycle

Part A—Overall Strategy and Our Response to Selected Elements Applicable to the Regional Storage Proposal Outlined in This Paper

The Commission identified the following elements of a new waste management strategy[45]:

1. *A new, consent-based approach to siting future nuclear waste management facilities.* The Commission identified lessons learned from successes at several facilities, including the Waste Isolation Pilot Plant in New Mexico, the Swedish repository near Forsmark, and the Finnish repository at Olkiluto. Our regional storage proposal adopts many of the steps identified by the Commission. The Commission's report identifies benefits to the host community/state from a back-end facility. Our proposal models its approach on a concept also identified by the Commission, namely, the one used in Spain. Spain's efforts to find a volunteer host for a storage facility for spent fuel and a small amount of high-level radioactive waste (HLW) included a technological research laboratory that would deal with waste processing, waste forms, and disposal of HLW and spent fuel as an integral part of the facility.
2. *A new organization dedicated solely to implementing the waste management program and empowered with the authority and resources to succeed.* The Commission recommends a federally chartered government corporation; our proposal makes no specific recommendation on the organization responsible for the regional storage proposal, noting that several existing international and national entities would need to be involved. We strongly endorse the Commission's recommendations on a hybrid, business-oriented, government-responsible approach.
3. *Access to the funds nuclear utility ratepayers are providing for nuclear waste management.* In the Commission's strategy, access to these funds would be provided over an extended period; it would employ a phased approach to access the needed amount of financing available to construct and operate

45. Find the full Report of the Blue Ribbon Commission at http://brc.gov/sites/default/files/documents/brc_finalreport_jan2012.pdf. Italicized language in this appendix is lifted either in whole or in part from the report.

the back-end facilities. Our regional storage approach builds on the Commission's strategy and accelerates the needed capitalization for back-end facilities.

4. *Prompt efforts to develop one or more geologic disposal facilities.* Our proposal is consistent with this element of the Commission's strategy.
5. *Prompt efforts to develop one or more consolidated [interim] storage facilities.* The Commission highlights the need to deploy these facilities as rapidly as possible to enhance the overall safety and security of back-end operations in the United States. Our approach has identical goals, with the expectation of a more expedited deployment schedule.
6. *Early preparation for the eventual large-scale transport of used nuclear fuel and HLW to consolidated storage and disposal facilities.* Our approach is consistent with this element of the Commission's strategy.
7. *Support innovation in nuclear energy technology and in workforce development.* Our approach enhances this element of the Commission's strategy (details below).
8. *Active U.S. leadership in international efforts to address safety, waste management, nonproliferation, and security.* We commend the Commission's findings in this area. Our proposal assumes that the highest standards in safety, nonproliferation, and security are adopted.

Part B—Selected Commission Findings and Our Response

On closing the fuel cycle:

> As stated in the final report: "We concluded that while new reactor and fuel cycle technologies may hold promise in achieving substantial benefits in terms of broadly held safety, economic, environmental, and energy-security goals, and therefore merit continued public and private R&D investment, *no currently available or reasonably foreseeable reactor and fuel cycle technology developments—including advances in reprocessing and recycling technologies—have the potential to fundamentally alter the waste management challenge this nation confronts over at least the next several decades, if not longer.* Put another way, we do not believe that today's recycle technologies or new technology developments in the next three to four decades will change the underlying need for an integrated strategy that combines safe storage of SNF [spent nuclear fuel] with expeditious progress toward siting and licensing a disposal facility or facilities."[46]

In the short and intermediate terms, our proposal encompasses an aggressive R&D program on advanced chemical partitioning approaches. It includes significant R&D cooperation with India and China. In the longer

46. Report of the Blue Ribbon Commission, 100.

term, many scientific researchers and their organizations are promoting more advanced technologies that the claimants suggest could have a momentous impact on solving the nuclear waste problem. Examples include the Atomics International Reduction Oxidation (AIROX) concept (being marketed today by General Atomics as a way to cap the generation of nuclear waste) and the Myrrha (Multipurpose Hybrid Research Reactor for High-tech Applications) project (being developed and marketed by the Commissariat à l'énergie atomique as an accelerator/reactor concept to transmute nuclear waste). These technologies and many others await a favorable "proof of principle" verdict from the scientific and engineering communities. It is unclear if there will ever be investments sufficient enough to move such concepts to commercially deployable technologies. For the purposes of achieving near-term consensus on the pressing safety and security issues pertaining to the back-end of the nuclear fuel cycle, we strongly believe that it would be counterproductive to promote these more advanced technologies as "game changers."

On international nuclear safety:

> "In sum, the United States should work with the IAEA and other interested nations to launch a major international effort, encompassing international organizations, regulators, vendors, operators, and technical support organizations to enable the safe application of nuclear energy systems and the safe management of nuclear wastes in all countries that pursue this technology."[47]
>
> Our proposal endorses this important Commission finding. Successful implementation of our proposal will require multilateral assistance to the host state in the areas of safe management practices and regulatory oversight of these practices. Our proposal includes the adoption of an independent safety nuclear regulator to provide assurance not only to the citizens of the host state but also to the international nuclear community. This safety regulator would be charged to protect public health and safety by licensing the facility and the storage and transportation of used fuel within the host state.

On international safeguards, particularly those applicable to new enrichment and reprocessing technologies:

> "The Commission endorses R&D efforts on modern safeguards technologies and urges continued U.S. government support for the IAEA's work in this area."[48]

47. Ibid., 111.

48. Ibid., 112.

We commend the Commission's findings in this area. Our proposal for an enhanced R&D program would include expanded work on international safeguards that would improve the transparency of practices for advanced chemical partitioning technologies such as UREX and pyroprocessing technologies.

On multinational fuel cycle facilities:

"Longer term, the United States should support the use of multi-national fuel-cycle facilities, under comprehensive IAEA safeguards, as a way to give more states reliable access to the benefits of nuclear power while simultaneously reducing proliferation risks. U.S. sponsorship of the recently created IAEA global nuclear fuel bank is an important step toward establishing such access while reducing a driver for some states to engage in uranium enrichment. But more is needed. The U.S. government should propose that the IAEA lead a new initiative, with active U.S. participation, to explore the creation of one or more multi-national spent fuel storage or disposal facilities."[49]

This Commission finding is fully consistent with our proposal to establish initially a multinational storage facility in the East and South Asia regions; this proposed regional storage facility, in our opinion, would serve as a blueprint for the establishment of similar facilities in other regions.

On take-away arrangements:

"The United States should support the evolution of spent fuel 'take-away' arrangements as a way to allow some states, particularly those with relatively small national programs, to avoid the costly and politically difficult step of providing for spent fuel disposal on their soil and to reduce associated safety and security risks."[50]

Our proposal is consistent with this Commission finding. In addition, our proposal stipulates that (1) multinational fuel cycle arrangements not be discriminatory to countries without large nuclear programs; and (2) an informal minimum threshold of 10 GW be adopted before a state pursues front-end or back-end nuclear technologies.

On domestic programs and policies:

"The United States will increasingly have to lead by engagement and by example. . . . [T]he United States cannot exercise effective leadership on issues related to the back end of the nuclear fuel cycle so long as its own program is in disarray; effective domestic policies are needed to support America's international agenda."[51]

49. Ibid., xiv–xv.

50. Ibid., xv.

51. Ibid., xiv.

As nuclear aspirants make decisions about ordering new nuclear capacity in this decade, we believe that they will likely not await U.S. actions in response to the Commission's recommendations. As we in the United States debate and discuss the path forward, it is imperative that the nuclear aspirants, together with the international nuclear fuel supplier community, coalesce around a pragmatic approach—such as our innovative regional fuel storage concept.

# Appendix II

## Key Issues for the Back-End of the Nuclear Fuel Cycle

Seven macro propositions[52] about the nuclear fuel cycle, in general, consistently arise in conversations on the back-end of the nuclear fuel cycle, in particular.

1. *Uranium is either scarce or too expensive.* Based on estimates of the world's economically accessible uranium resources, the existing reactor fleet could run for more than 200 years at current rates of consumption. That is, given that the fleet of present-day reactors requires about 70,000 to 80,000 MT of natural uranium per year, estimates of identified and undiscovered natural uranium totaling 16 million MT would provide a roughly 215-year supply at today's consumption rate. This estimate does not include extraction of uranium from seawater, which could potentially make available 4.5 billion MT of uranium—a 60,000-year supply at present rates. Thus, on a timescale covering the next several decades, a uranium-based fuel cycle appears to be sustainable.[53] On the cost side, supply and demand for uranium

52. On an individual, state-by-state basis, some of these propositions may be at variance with policy considerations that a state may adopt to hedge future supply interruptions.

53. The 2010 edition of the so-called Red Book, the authoritative biennial report produced jointly by the Nuclear Energy Agency of the OECD (Organisation for Economic Co-operation and Development) and the IAEA, estimates the identified amount of conventional uranium resources. According to the Red Book, worldwide uranium resources, production, and demand are all increasing. Total identified uranium resources will last for more than 100 years at current consumption rates. The amount of uranium identified that can be economically mined rose to some 6.3 million tons, a 15.5 percent increase compared with the previous edition. The IAEA projects that nuclear power will expand from 375 GWe today to between 500 and 785 GWe by 2035. Such growth would cause an increase in uranium demand from 66,500 MT per year to between 87,370 and 138,165 MT. Based on geological evidence and knowledge of unconventional resources of uranium, such as phosphates, the Red Book estimates that more than 35 million MT will be available for exploitation. Given that in the entire 60-year history of the nuclear era the total amount of uranium that has been produced totals about 2.2 million MT, the availability of uranium is not a limiting factor at this stage of nuclear power development. For timescales stretching to the end of this century and beyond, the situation may be different. On that timescale, there are two options (not mutually exclusive) for dealing with potential uranium constraints: first, the fuel cycle could be closed to achieve very high (for example, above 90 percent) burn-up; second, an aggressive program could be launched to improve the ability to locate and recover uranium resources economically. A potential backstop for both options is the recovery of uranium from seawater. Currently, only Japan is pursuing this option in a significant way, and Japanese researchers are advocating recovery costs of $1,000 per kilogram. That is an order of magnitude more expensive than standard uranium production costs, but the Japanese experience suggests that an eventual goal of $150 per kilogram may be achievable. Natural uranium currently accounts for only 3 percent of the total cost of nuclear generation; thus, even $300 per kilogram would be attractive and well below the break-even cost for competition with a MOX fuel cycle scheme involving plutonium recycling in LWRs or fast burner reactors. See Richard K. Lester and Robert Rosner, "The Growth of Nuclear Power: Drivers & Constraints," *Daedalus* 138 (4) (Fall 2009): 19–30.

will determine prices in the long run. Long-term prices have recently been trading in the $50 to $75 per pound range and do not have an impact on choices for or against nuclear energy.[54] Thus, while there is the potential that the number of reactors will grow significantly—increasing capacity to somewhere between 400 and 500 GWe and causing the demand for uranium to rise markedly and result in higher costs for uranium ore—the price of uranium is not likely to be a critical factor in determining the practical deployment and sustainability of nuclear power.[55]

2. *The economic penalty associated with conventional reprocessing and recycling is outweighed by the noneconomic benefits that would accrue*. In the past, advocates of conventional reprocessing have emphasized its contributions to extending fuel supplies and increasing energy-supply security. Today, the principal claim is that conventional aqueous reprocessing (that is, chemically partitioning the fissile material[56] and relatively small quantities of related actinide materials from the waste products) will facilitate and simplify the management and disposal of nuclear waste. To fully understand this assertion, it is important to ascertain how large the cost penalty associated with conventional reprocessing and/or recycling is likely to be. We cannot determine an exact answer because some of the most important contributing factors are uncertain or otherwise difficult to estimate. The greatest source of uncertainty, with the largest impact on overall cost, is associated with the chemical partitioning process itself. Other important uncertainties center on the cost of MOX fuel fabrication and the relative cost of disposing reprocessed HLW as compared to the direct disposal of used fuel.[57] However, if technology for advanced reactors included safer, more economic designs, and if these technology advancements included meaningful actinide consump-

54. According to an interdisciplinary study from MIT, “The cost of uranium today is 2 to 4% of the cost of electricity. Our analysis of uranium mining costs versus cumulative production in a world with ten times as many LWRs and each LWR operating for 60 years indicates a probable 50% increase in uranium costs. Such a modest increase in uranium costs would not significantly impact nuclear power economics”; *The Future of the Nuclear Fuel Cycle: An Interdisciplinary MIT Study* (Cambridge, Mass.: Massachusetts Institute of Technology, September 2010), http://web.mit.edu/mitei/docs/spotlights/nuclear-fuel-cycle.pdf.

55. “This view does not reflect the argument that energy security proponents make: that enhancing ownership of uranium resources provides a security guarantee, or buffer, in case of temporal shortfalls or price spikes. If supply is interrupted, a relatively small stockpile would be needed—200 MT of natural uranium, or 20 MT of 4.5-percent enriched uranium per GWe/year (roughly 100 times smaller than BT-equivalent coal, oil, or natural gas storage amounts)”; ibid.

56. The aqueous fissile streams are designed to include separated fissile plutonium.

57. Assuming all these services were available and were used as a partially open cycle, a U.S. nuclear power plant opting to use them would incur a total nuclear fuel cycle cost of at least 2.5 to 3 mills/kWh for back-end services. By comparison, the total cost for back-end services for an open or once-through fuel cycle is about 1.3 mills/kWh. The once-through fuel cycle includes a projected cost of disposal and long-term dry cask storage; see *The Future of the Nuclear Fuel Cycle*, 103.

tion opportunities, the heat load and toxicity of the HLW stream would be substantially reduced. This key benefit of closing the fuel cycle (a benefit that is normally not included in costs for near-term back-end fuel services) would be a waste disposal game changer: specifically, it would jettison the siting of multiple HLW repositories,[58] one of the most contentious public policy bottlenecks that influence public acceptance of nuclear energy expansion.[59] As long as uranium prices remain in the $50 to $75 range[60] and, more important, as long as we lack deployable, cost-effective technologies to change dramatically the approach to waste disposal, the benefits of treating used fuel are not sufficiently compelling today.

3. *Because fuel cycle expenses account for less than 10 percent of the total cost of nuclear electricity from unamortized nuclear power plants (capital-related costs account for most of the remainder), adopting a more expensive fuel cycle scheme that includes more advanced chemical partitioning techniques (that is, above and beyond conventional reprocessing technology) and fabricating MOX fuel would have a very small impact on the levelized cost of electricity paid by consumers of electricity.* A long-term interim storage option may be a preferred alternative; this approach could be viewed as a long-term financial hedge if uranium prices spike and there are economical, safe, and secure technologies to close the nuclear fuel cycle.[61]

4. *The current infrastructure (capacity that has already seen significant investments) for all types of chemical partitioning facilities is not fully utilized.* To date, approximately 90,000 MT (of a total 290,000 MT) of used fuel has been conventionally reprocessed. Annual conventional reprocessing capacity is now approximately 5,600 MT per year, and some of this capacity is

58. Such an outcome would require a novel technological approach that would dramatically reduce the heat load and radiotoxicity of the waste packages destined for a HLW repository.

59. Various scientific researchers and their organizations are promoting a variety of advanced technologies that will have a momentous impact on solving the nuclear waste problem. Examples include the AIROX concept (being marketed today by General Atomics as a way to cap the generation of nuclear waste) and the Myrrha project (being developed and marketed by the Commissariat à l'énergie atomique as an accelerator/reactor concept to transmute nuclear waste). These technologies and many others await a favorable "proof of principle" verdict from the scientific and engineering communities. It is unclear if there will ever be investments sufficient enough to move such concepts to deployable technologies. For the purposes of achieving near-term consensus on the pressing safety and security issues pertaining to the back-end of the nuclear fuel cycle, we strongly believe that it would be counterproductive to promote these technologies as "game changers."

60. However, Cameco's CEO Tim Gitzel has warned that "[d]isruptions in mine production, the difficulty faced by development companies in raising funds for new mining projects, and the end of a Russian deal to supply uranium from scrapped atomic warheads may help create a supply deficit . . . and result in increases in uranium prices"; Christopher Donville, "Cameco's Gitzel Says Investors Underestimate Possible Uranium Shortfall," Bloomberg, December 5, 2011.

61. At present, advocates for using MOX assert that, at minimum, plutonium and uranium credits offset the added cost of fabricating MOX fuel.

underutilized.[62] Already deployed (though not necessarily operating) capacities include La Hague, France (1,700 MT/yr); Sellafield, United Kingdom (2,350 MT/yr); Mayak, Russia (400 MT/yr); Rokkasho, Japan (800 MT/yr); and Kalpakkam, India (275 MT/yr). Additional capacity could be deployed for both aqueous and pyrometallurgical processes.[63] There are expansion opportunities at the French and Russian facilities. Based on what already exists and is likely to exist (and be operational) within this time period, a shortage of conventional reprocessing or, in the future, advanced chemical partitioning capacity is not likely to become a bottleneck.[64]

5. *Individual policy decisions to develop indigenous enrichment and conventional reprocessing or, in the future, advanced chemical partitioning capabilities can be viewed on a case-by-case basis and do not have long-term implications.* Siting new enrichment facilities or conventional reprocessing or advanced chemical partitioning facilities outside the current locations may send a negative signal, encouraging other states to pursue these technologies. Thus, analyses of potential indigenous fuel cycle facilities, while necessarily constrained by local conditions, must take the global context into account.[65]

6. *As a credible long-term interim storage program is developed, the geographic location for final disposal can remain in the exploratory stage, and the schedule for ultimate disposal can be deferred*. Because long-term (but interim) storage is a viable technology, there are many credible scenarios for multinational storage as a relatively long-term endeavor (eighty to one hundred years). However, the siting of a long-term interim storage facility is likely to be inextricably linked to the identification of, and "early and positive" dialogue with, stakeholders on a final disposal site (or sites). Therefore, long-term interim storage can be an operative current-term back-end approach, with the full acknowledgment that progress toward establishing a final disposal site (or sites) cannot be deferred indefinitely.

62. Sellafield's continued conventional reprocessing operations are currently at risk. On August 3, 2011, the National Decommission Authority (NDA) announced that it would close the Sellafield MOX plant, citing the significant negative impact to the Japanese nuclear industry in the aftermath of Fukushima.

63. The Korean Atomic Energy Research Institute's (KAERI) advanced used-fuel conditioning process, known commonly as a pyrometallurgical process, is at the heart of negotiations for the renewal of the bilateral U.S.-Republic of Korea nuclear cooperation agreement. KAERI plans to deploy a first-stage facility in 2016 and become a commercial-scale demonstration plant in 2025. Further, one must keep in mind China's eventual back-end plans and intentions, which are not likely to be firmly settled within the next decade while China thoroughly examines its technological options.

64. With regard to China's expansion plans, it is possible (looking out several decades) that servicing China's used fuel would require significant new conventional-reprocessing capacity.

65. We believe that an informal minimum threshold of 10 GW should be adopted before a state pursues front-end or back-end nuclear technologies.

7. *Evolving a viable multilateral nuclear fuel supplier regime must take into account existing fuel supply arrangements.* There are existing relationships among nuclear fuel suppliers and their customers; some of these relationships include conventional reprocessing (possibly, in the future, advanced chemical partitioning) and MOX services. The prospect of rolling back such services is bleak. Furthermore, the existing actors in the current fuel supply regime are likely to be key players in any future fuel cycle regime. Thus, their "buy in" to any proposed evolution of the international fuel supply market will be essential for successful and practical implementation of any such new regime.

# Appendix III

## Civil Back-End Fuel Technologies—Pursuit of the Closed Fuel Cycle

There is constant debate about whether conventional reprocessing and recycling (that is, the closed fuel cycle) should be commercially deployed, given the sensitive processes inherent in these aspects of the fuel cycle. As technologies become more widely available, the debate increasingly circulates around which states are already incorporating these aspects of the fuel cycle, which states intend to do so, and whether these policies pose problems for the international community. Numerous reports have compared conventional reprocessing technologies, but as each one points out, it is tremendously difficult to create a uniform system of analysis or baseline for comparison. In hopes of contributing an additional perspective to the conversation, Appendix III approaches the civil back-end fuel cycle issue by outlining national policies and providing commentary on the leaders in conventional reprocessing as well as advanced chemical partitioning technology; Appendix IV presents a more detailed discussion of the program in China.

The motivations behind conventional reprocessing—that is, PUREX (plutonium-uranium extraction) and fabrication of the uranium-plutonium product streams into MOX fresh fuel—have evolved along with the technology. What was initially a process intended to separate plutonium from the used reactor fuel for its use in weapons and breeder reactors has become a method for using plutonium stockpiles as fuel in reactors. In addition to modifying plutonium for fuel and thereby lowering the proliferation risks of idle stockpiles,[66] conventional reprocessing and recycling the fissile material fuel from a nuclear reactor also allow approximately 25 percent more energy to be extracted from the uranium or other fuel resource.[67]

Advanced chemical partitioning concepts enable various waste streams to be separated from one another. When fissile material is separated from all the actinides, the collective heat load can be removed from the used fuel, thereby potentially reducing the amount of repository space that is needed. Given that the price of uranium is not volatile in the near term and that there is enough uranium to support the present rate of worldwide consumption for many

66. Matthew Bunn, Steve Fetter, John P. Holdren, and Bob van de Zwaan, "The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel," Project on Managing the Atom, Harvard University, December 2003, http://www.publicpolicy.umd.edu/files.php/faculty/fetter/2003-Bunn-repro.pdf.

67. World Nuclear Association, "Processing of Used Nuclear Fuel," January 2011, http://world-nuclear.org/info/inf69.html.

decades, the arguments for pursuing a closed fuel cycle are best framed either as a waste management tool and/or as a hedging strategy in the case of energy-security concerns, including temporary or long-term disruptions in uranium supply or price spikes for individual states.[68] Also, because of the expense of conventional reprocessing, as well as the likely additional expense of more chemical partitioning techniques, the recovered uranium will have to be enriched and, therefore, is generally not economically competitive with mined uranium.[69]

Some states, such as France, view the opportunity to use a resource more completely and efficiently as worth the pursuit of chemical partitioning, recycling, and burn-up.[70] Based on very optimistic scenarios in which heat load controls the amount of real estate at the repository, proponents of fully closing the fuel cycle assert that repository space could be reduced to approximately 800 cubic meters, compared with 16,000 cubic meters if the fuel cycle is not fully closed.[71] For states facing particularly difficult storage constraints, such as China and India, advanced chemical partitioning technologies may become a critical component of their respective fuel cycles.

The decision calculus is different for each state, and these calculations inevitably change in line with technology advancements and the increasing abundance of used fuel accumulation. As Table 2 illustrates, given the varying inventories and used fuel policies of key nuclear consumer states, national policies on conventional reprocessing are diverse and dynamic. Below is a summary of policies and technologies (as of the end of 2007) of states that are still pursuing recycling today.

*France*

Presently, treating used nuclear fuel is the national policy of France, as it has been since the beginning of the country's nuclear power industry. France sets the standard for conventional reprocessing: it is the only state actively performing conventional reprocessing on a large scale. AREVA estimates that 17 percent of all the electricity generated in France is from recycled fuels.[72] Using the PUREX technology developed by the United States as a method to generate plutonium for nuclear weapons during World War II, La Hague, the sole plant

68. China is a clear outlier; for it to be less dependent on foreign sources of uranium and meet its projected nuclear power targets, China views reprocessing and recycling as its so-called strategic fissile material reserve.

69. Bunn et al., "The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel."

70. Based on 373 typical 1,000 MWe-pressurized water reactor (PWR) power plants with 34 percent efficiency; a capacity factor of 90 percent; 4,500 MW days/ton burn-up; and 21.5 MT of fuel annually, the approximate amount of open-cycle, used fuel to be disposed of is 8,000 MT. However, utilizing a PUREX recycling scheme, projected estimates could be reduced to about 400 MT. See Marilyn Waite, "Cradle to Cradle: Turning Nuclear 'Waste' into Nuclear Fuel," 2009, http://energy.sigmaxi.org/wp-content/uploads/2009/10/waite_recycling.pdf.

71. Ibid.

72. Ibid.

Table 2. Inventories of Dry and Wet Stored Used Fuels, as of the End of 2007

| Country | Used Fuel Inventory (tons of heavy metal) | Used Fuel Policy |
|---|---|---|
| Finland | 1,600 | Direct disposal |
| France | 13,500 | Conventional reprocessing |
| Germany | 5,850 | Direct disposal (now) |
| Japan | 19,000 | Conventional reprocessing |
| Russia | 13,000 | Conventional reprocessing |
| Sweden | 5,400 | Direct disposal |
| United Kingdom | 5,850 | Conventional reprocessing |
| United States | 61,000 | Direct disposal |

Source: Modified from Harold Feiveson, Zia Mian, M. V. Ramana, and Frank von Hippel, "Spent Fuel from Nuclear Power Reactors: An Overview Study by the International Panel on Fissile Materials," International Panel on Fissile Materials, June 2011. Table reprinted under the Creative Commons Attribution-Noncommercial License, http://creativecommons.org/licenses/by-nc/3.0/.

in France, is capable of treating 1,700 MT of used fuel every year.[73] During the PUREX process, the reusable uranium and plutonium are extracted from the other fissile material using an acid solvent. The plutonium and uranium are then sent to other plants in southern France and Russia where MOX fuels are made from both the plutonium and the uranium; in addition, other uranium is enriched for reuse.[74] France is also in the planning phase for constructing a national deep geological storage facility in Bure, where storage experiments are under way. This storage facility will operate in conjunction with the fast-breeder program that France is also committed to launching as the next generation of reactors begins to become available; however, there are no power-scale breeder reactors presently in operation in France.

### *Russia*

The existing infrastructure and capacity for conventional reprocessing in Russia is less mature than that of France. At Ozersk, the Mayak facility processes used fuel using the PUREX technology and has a yearly capacity of 400 tons.[75] Currently, it employs only 25 percent of its capacity.[76] The site produces ura-

73. AREVA, "Recycling Used Fuel from Reactors," http://www.areva.com/EN/operations-1092/areva-la-hague-recycling-used-fuel.html (accessed July 10, 2011).

74. World Nuclear Association, "Nuclear Power in France," http://www.world-nuclear.org/info/inf40.html.

75. World Nuclear Association, "Processing of Nuclear Fuel," http://www.world-nuclear.org/info/inf69.html.

76. World Nuclear Association, "Russia's Nuclear Fuel Cycle," http://world-nuclear.org/info/inf45a_Russia_nuclear_fuel_cycle.html.

nium that is used in Russia's nuclear reactors, that is, the WER-440-MWe LWR plants (two of which are located in Ukraine); in its nuclear icebreaking ships; and in the fast-neutron reactor, Beloyarsk (560 MWe). The Mayak facility does not function on a scale large enough to deal with the used fuel from the thirty-one operating nuclear power plants in Russia or those in Ukraine; however, Russia intends to expand its PUREX process, use built-up stores of plutonium for MOX fuel production, and incorporate fast breeder reactors back into the nuclear program.[77] According to a recent calculation, there are upwards of 80 tons of plutonium stored in Russia for reuse (50 tons of reactor-grade and 34 tons of weapons-grade).[78] The old site of a second, never-completed conventional reprocessing plant in Zheleznogorsk has become a storage location, in addition to the Mayak facility, for most of the used fuel in Russia; typically, fuel is transported there after an initial on-site cooling period in pool storage. A dry storage facility is under construction on the Mayak site as well and will increase the available storage capacity by 8,600 tons.[79] To support the increase in nuclear energy production, geological repository siting is now under way in Russia.

### *United Kingdom*

The United Kingdom has been treating used fuel from both its advanced gas-cooled reactors and its Magnox reactors to make MOX fuel. While there are no plans to pursue a breeder reactor program in the state, there is significant interest in processing the 100 tons of stored plutonium into MOX fuel for later-generation reactors. Facing pending closure, the fuel fabrication plant at Sellafield is currently used for export fuel, and until recently, U.K. authorities held that it was not economical to make MOX for domestic use.[80] The United Kingdom already has two types of conventional reprocessing plants located at Sellafield—Magnox and THORP—with capacities of 1,500 and 900 tons of fuel per year, respectively.[81] Magnox fuel is uranium metal fuel (as opposed to uranium oxide) contained in magnesium alloy.[82] The processes used for THORP

77. Ibid.

78. Harold Feiveson, Zia Mian, M. V. Ramana, and Frank von Hippel, "Spent Fuel from Nuclear Power Reactors: An Overview of a New Study by the International Panel on Fissile Materials," International Panel on Fissile Materials, June 2011, http://www.princeton.edu/sgs/publications/Managing-nuclear-spent-fuel-BAC-June-27-2011.pdf.

79. World Nuclear Association, "Russia's Nuclear Fuel Cycle."

80. As noted above, Sellafield's continued reprocessing operations are at risk as a result of the NDA's announcement on August 3, 2011, that it would close the Sellafield MOX plant; the NDA cited the significant negative impact to the Japanese nuclear industry in the aftermath of Fukushima.

81. World Nuclear Association, "Nuclear Power in the United Kingdom," June 2011, http://www.world-nuclear.org/info/inf84.html; World Nuclear Association, "Processing of Used Fuel."

82. The Institution of Electrical Engineers, "Nuclear Reactor Types" (London: Institution of Electrical Engineers, 1993), http://www.carnegieendowment.org/static/npp/reports/nuclear_reactors.pdf.

and Magnox recycling differ because of the composition of the used nuclear fuel, but they result in a similar separation of uranium, plutonium, and the remaining fissile waste.[83] To create a long-term fuel cycle strategy, the United Kingdom has tried to engage the public as much as possible. It has no plans for geological storage repositories but is looking into siting intermediate storage facilities for the current used fuel and the future used fuel.

### *Japan*

The national policy in Japan, even though it is not operating a conventional reprocessing plant of its own, has always been to extract the maximum amount of energy from the purchased fuel; this approach is understandable (to the authors) for a state that does not have any uranium resources and must import the vast majority of its fuel for electricity.[84] Historically, Japan has shipped its fuel abroad to Europe for treatment, although it had planned to operate a slightly advanced chemical partitioning plant at the storage facility Rokkasho. Presently, the storage facilities at Rokkasho are open and being utilized; however, like so many other storage sites in Japan, even before the plant has opened, its 20,400-ton storage pool capacity has already been reached. All construction and planning for additional power reactors has been suspended following the unfortunate events at Fukushima Daiichi. Japan is reevaluating all its national energy policies, including operations at Rokkasho.

### *China*

Presently, China has a small pilot PUREX plant that maximizes capacity at 100 tons per year. In order to be less dependent on uranium from external sources, China's national policy is to add more capacity soon to harmonize with the rapid pace of new reactor builds in the state: twenty-five reactors are under construction—more than doubling China's present nuclear energy infrastructure of fourteen reactors.[85] AREVA has been collaborating with China to build a coextraction (COEX) facility for MOX fuels (with a capacity of 800 tons/year), which is scheduled to become operational in 2020. Additionally, the Gansu Province has been identified as the location for a geological repository. China intends to have a completely closed nuclear fuel cycle that includes the use of breeder reactors, and it appears to be equipped with both the resources and the political

83. Nuclear Decommissioning Authority, "Magnox Fuel," July 14, 2011, http://www.nda.gov.uk/strategy/spentfuelsmgmt/magnoxfuel/index.cfm; Sellafield Ltd., "Reprocessing Overview: Fuel Storage, Reprocessing, Uranium and Plutonium Recycling," http://www.sellafieldsites.com/UserFiles/File/new_brochures/Reprocessing.pdf (accessed July 2011).

84. World Nuclear Association, "Nuclear Power in Japan," June 2011, http://www.world-nuclear.org/info/inf79.html.

85. World Nuclear Association, "Nuclear Power in China," June 2011, http://www.world-nuclear.org/info/inf63.html.

will to accomplish that goal. The collaboration between China and states such as Russia and France is also greatly contributing to China's infrastructure development. See Appendix IV for a detailed discussion of China's program.

*United States, Finland, and Sweden*

Each of these three states has chosen an open fuel cycle. In the open cycle process, used fuel rods are removed from the reactor core; stored in used fuel pools to cool; and then stored either in dry storage (robust casks cooled by the air) or in deep geological storage using clay or salt materials. The United States is less committed to this route than Sweden and Finland. The economic and social hurdles are significant in deep geological storage, as the United States is acutely aware. Used fuel pool and dry cask storage are both relatively inexpensive—approximately 0.3–0.4 mills/kWh.[86] However, in the absence of a definitive national repository estimate in the United States, the U.S. disposal costs are unknown. In the case of Sweden and Finland, there is more knowledge, but these countries, too, lack final cost estimates of their disposal programs.[87] Both Nordic states are actively engaged in the deployment of deep geological waste repositories, while the United States has struggled with siting, licensing, and building a single repository.[88]

86. According to an interdisciplinary study from MIT, "The cost of uranium today is 2 to 4% of the cost of electricity. Our analysis of uranium mining costs versus cumulative production in a world with ten times as many LWRs and each LWR operating for 60 years indicates a probable 50% increase in uranium costs. Such a modest increase in uranium costs would not significantly impact nuclear power economics"; see *The Future of the Nuclear Fuel Cycle*.

87. Finland has adopted a robust system to adjust fees on waste generators that can certify a full cost-recovery program.

88. Feiveson et al., "Spent Fuel from Nuclear Power Reactors."

# Appendix IV

## The Increasing Role of China

China is rapidly increasing its national nuclear infrastructure to offset the rising demand for energy. This investment is one aspect of China's expanding energy portfolio as the state shifts away from its most abundant resource: coal. China's primary objectives include energy independence and security; to achieve these goals, the state intends to close its fuel cycle and increase its utilization of fossil fuels as well as renewable sources. From a health and environmental perspective, China must transition from coal to other cleaner sources of power. Presently, China is exploring for new oil fields, but as more fields are discovered and exploited, older fields are producing less.[89] The search for alternative energy sources is causing territory disputes in the South China Sea with Vietnam, the Philippines, the Republic of Korea, and Taiwan.[90] In 2001, to insulate the state from external oil market disruptions, China created a strategic oil reserve program.[91]

The Chinese nuclear industry transformed in tandem with the economy: in the case of the economy, from insular to market based; and in the nuclear industry, from military to civilian. Prior to 2005, China was focused on the military applications of nuclear technologies. Motivated by the need for cleaner base-load power, the new national energy strategy includes indigenous designs for reactors. Previously, China relied on nuclear technologies from the United States, Russia, and France[92]; currently, China is building twenty-seven new reactors. The models under construction are mainly of the Westinghouse AP-1000 and the AREVA EPR models as well as two Chinese designs: CPR-1000 and CPN-1000.[93]

The three state-owned companies leading China's nuclear renaissance are the China National Nuclear Corporation (CNNC), China Guangdong Nuclear Power Company (CGNPC), and China Power Investment Corporation (CPIC). The State Nuclear Power Technology Company (SNPTC) is working closely with Westinghouse, but does not yet have licenses to build or operate in China.

89. U.S. Energy Information Administration, "Country Analysis Briefs: China," November 2010, http://205.254.135.24/EMEU/cabs/China/pdf.

90. Ibid.

91. Ibid.

92. Yun Zhou, Christhian Rengifo, Chen Peipei, and Jonathan Hinze, "Is China Ready for its Nuclear Expansion?" *Energy Policy* 39 (2011): 771–781.

93. The two models are based on Framatome's 900-MW three-loop design. See World Nuclear Association, "Nuclear Power in China."

CNNC dominates the industry with its monopoly on nuclear-project construction companies and ownership of fuel cycle facilities. China does not have enough domestic uranium to support its growing consumption; the government uses the fact that the indigenous supply is limited to justify its pursuit of a closed fuel cycle.[94] The projected volumes of used fuel resulting from their increased capacity will exceed the cooling and storage facilities available (see Table 3).[95] In anticipation of the imminent overflow, China is strategizing the future of its fuel cycle. A recent study estimates that China will have enough storage space for the coming decades[96]; however, in order to have proposals passed and infrastructure built to meet its storage needs, many years of advance planning are necessary. "China intends to model its fuel cycle on France, India, Japan, Russia and the United Kingdom," according to Gu Zhongmao of the China Institute for Atomic Energy (CIAE). That is, China will pursue a closed fuel cycle. Unlike some other states, China has few environmental groups to oppose conventional reprocessing and, as a nuclear weapon state under the NPT, is relatively immune to complaints about proliferation. The new site chosen to pursue back-end processing will include a used fuel pool to help accommodate additional waste in the near term.[97]

China is also negotiating with AREVA over the construction of an 800 MT/yr COEX (coextraction) facility to be located at Jiuquan. In November 2007, France and China signed a memorandum of understanding "to undertake feasibility studies related to the construction of a spent fuel reprocessing-recycling plant in China."[98] In November 2010, AREVA and CNNC signed an industrial agreement on cooperation in the field of used fuel treatment and recycling. AREVA described that agreement as the final step toward a commercial contract.

## IMPLICATIONS

As discussed above, China is not currently under heavy pressure to treat used fuel. China has sufficient room at most of its reactors to store fuel for several years. Only one site, Daya Bay, has limited storage capacity and must ship its used fuel to the site in Gansu, which it has done since 2004. Even this is an artificial "crisis": CNNC successfully pressured the Chinese government to deny the oper-

94. Yun Zhou, "China's Spent Nuclear Fuel Management: Current Practices and Future Strategies," *Energy Policy* 39 (7) (July 2011): 4360–4369.

95. Ibid.

96. Ibid.

97. Ibid.

98. AREVA, "China: AREVA and CGNPC Sign the Biggest Contract Ever in the History of Nuclear Power and Enter into a Long-Term Commitment," November 26, 2007, http://contractchina2007.areva.com/scripts/events_home/publigen/content/templates/Show.asp?P=57&L=EN.

Table 3. The Current Status of Used Fuel Storage at PWRs in China

| NPP Name | Unit No. | Date of First Connection to the Grid | Spent fuel storage method | On-site spent fuel storage capacity | Year when storage capacity is expected to fill up |
|---|---|---|---|---|---|
| Qinshan | | 12/15/1991 | Dense-pack wet Pool size expansion | 35 years | 2025 |
| Daya Bay | Unit 1 | 08/31/1993 | Wet storage | 10 years | 2003 |
| | Unit 2 | 02/07/1994 | | | 2004 |
| Qinshan Phase II | Unit 1 | 02/06/2002 | Dense-pack Wet storage | 20 years | 2022 |
| | Unit 2 | 03/11/2004 | | | 2024 |
| LingAo | Unit 1 | 02/26/2002 | Dense-pack Wet storage | 20 years | 2022 |
| | Unit 2 | 09/14/2002 | | | 2022 |
| Qinshan Phase III | Unit 1 | 11/19/2002 | On-site wet/dry storage | 40 years | 2042 |
| | Unit 2 | 06/12/2003 | | | 2043 |
| Tianwan | Unit 1 | 05/12/2006 | Wet storage | 20 years * | 2026 |
| | Unit 2 | 05/14/2007 | | | 2027 |

*Newly planned reactor designs include a twenty-year on-site spent fuel storage capacity. Source: Yun Zhou, "China's Spent Nuclear Fuel Management: Current Practices and Future Strategies," *Energy Policy* 39 (7) (July 2011): 4360–4369. Reprinted with permission from Elsevier, http://www.journals.elsevier.com/energy-policy/.

ators of Daya Bay a license to re-rack their used fuel, forcing the operators to contract with CNNC for transport, storage, and other back-end services.[99]

China remains in need of more energy. There is no nascent environmental movement that might dissuade Chinese policy-makers from closing the fuel cycle.[100] As a nuclear weapon state, China faces few international barriers on nonproliferation grounds. With regard to China's pursuit of conventional reprocessing or more advanced chemical partitioning, the major barrier appears to be China's need for foreign technology and the high cost of purchasing a commercial-scale plant.

99. CSIS NTI Workshop, July 2011.

100. To the extent that some people in China are environmentally conscious, they tend to be urban elites more concerned about air pollution in China's major cities.

# Appendix V

## Back-End Concepts

### *Concept #1: Multilateral Arrangement for Emerging Nuclear Power Programs*[101]

The two key players in a multilateral arrangement are the multilateral entity (lessor) and the user nation (lessee), in the form of a special purpose entity (SPE)[102] (see Figure 2). Nuclear fuel leasing and nuclear fuel banks have recently been touted as workable mechanisms to facilitate agreements for providing what have often been called "cradle to grave" fuel cycle services to utilities that

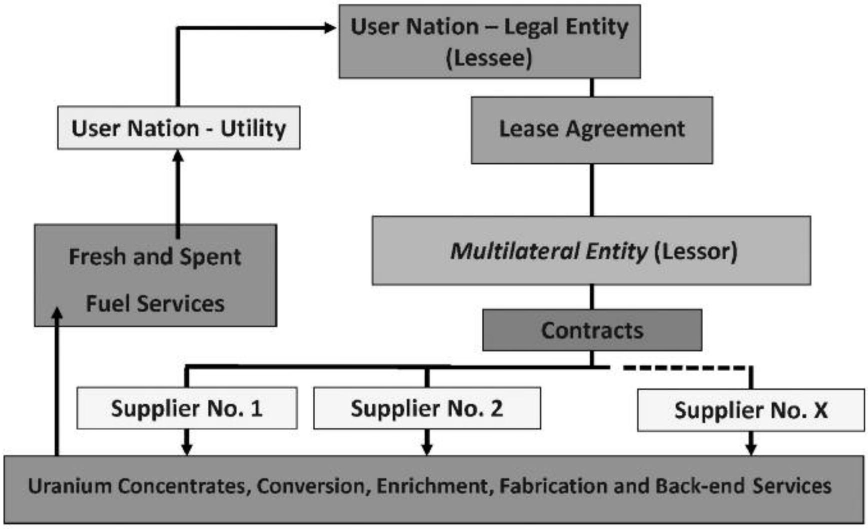
101. The description provided below is largely along the lines of the TRUST proposal. See James Malone, James Glasgow, Stephen Goldberg, and Peter Heine, "TRUST, An Innovative Nuclear Fuel Leasing Arrangement," NEI-WNA International Nuclear Fuel Cycle Conference, Budapest, Hungary, April 2007, 12.

102. Just as current leases for industrial equipment typically require the lessee to comply with all laws and regulations governing use of the leased equipment, a lease for the provision of fuel to a utility in an emerging nuclear power state should require that the utility comply with all applicable laws, conventions, and agreements concerning possession and use of that fuel, including IAEA safeguards agreements. Noncompliance with these requirements could be explicitly defined as an "event of default," which would trigger specified rights of the lessor. Economic penalties in the event of default could include, depending on the gravity of the violation, termination of the lease and forfeiture of the lessee's advance payments to the lessor. Such commercial sanctions would be imposed in addition to governmental sanctions and remedies, pursuant to applicable agreements for cooperation.

To help ensure that the lessor's remedies can be effectively enforced in the event of the lessee's default, the lessor could require that the lessee be in a state that is a party to the Hague Convention on the Recognition and Enforcement of Foreign Judgments in Civil and Commercial Matters or (for leases that specify arbitration), the New York Convention on the Recognition and Enforcement of Foreign Arbitral Awards. The efficacy of such remedies, coupled with recipient government guarantees, has been demonstrated by experience with the project finance agreement for fossil-fired generating stations and other industrial facilities in developing states.

Under existing U.S. law, any U.S. fuel assurance will be subject to the need for the U.S. government, as well as private-sector suppliers, to obtain an export license from the U.S. Nuclear Regulatory Commission, an independent regulatory body. Congress and the U.S. executive branch are likely, in any fuel assurance agreements, to retain the authority to refuse to perform U.S. supply assurances, even for reasons that are unrelated to any concerns about the recipient state's faithful performance of its nuclear nonproliferation commitments. Numerous judicial decisions and fundamental principles of U.S. constitutional law compel a conclusion that, regardless of whether U.S. governmental supply assurances contain the usual "subject to U.S. law" phraseology, those supply commitments will yield to any subsequent law enacted by Congress and to any regulation or executive branch order as well; such regulations and orders are part of U.S. law. In light of U.S. practice for many decades, such supply commitments are likely to contain a "subject to U.S. law clause." Moreover, the U.S. government, in accordance with its past practice in connection with substantive U.S. commitments in treaties and other international agreements, may insist on a broad right of the United States to terminate those commitments, without being in breach of any legal obligation.

Figure 2. Multilateral Fuel Lease Arrangement




*User nation* denotes a consumer state. Source: Adapted from James Malone, James Glasgow, Stephen Goldberg, and Peter Heine, "TRUST, An Innovative Nuclear Fuel Leasing Arrangement," NEI-WNA International Nuclear Fuel Cycle Conference, Budapest, Hungary, April 2007. Figure © Stephen M. Goldberg and Robert Rosner.

are only "consumers" of nuclear fuel. While implementation could vary widely, in one possible scenario a service provider or broker might arrange for the delivery of fresh fuel and the acceptance of used fuel at a centralized/regional interim storage facility and at a specified time following its discharge from the utility's reactor. This type of arrangement would enable small nuclear fuel users to obtain fuel supply and disposition services at competitive prices (see Figure 2).

U.S. utilities have long used lease arrangements through SPEs as a mechanism to finance their acquisition of equipment and nuclear fuel.[103] In these leases, utilities arrange for a financial institution to act as a trustee under a trust agreement between the utility and the lending bank.[104] Some leases involve a "heat supply contract" with the trustee, whereby the trustee agrees to buy the

103. The 1974 Annual Report of the American Bar Association Section on Public Utility Law states that "Virginia Electric and Power Company financed the fuel supply for its first nuclear unit by organizing a special corporation to own and lease the nuclear fuel." According to this report, "the lease term for this unit is five years with annual renewal options available therefore . . . and VEPCO can terminate the lease at any time upon sixty days' notice by purchasing the unburned fuel from the lessor." The lessor acquired the funds to purchase the fuel by "selling commercial paper, the credit of which is backed by a bank which issued irrevocable letters of credit which are attached to the commercial paper and provide for payment of the commercial paper if the lessor fails to make such payment directly."

104. The title to the fuel was held by the trustee. The funds to purchase the fuel "were acquired through the sale by the trustee of its commercial paper which is backed by the bank's irrevocable letters of credit and/or line of credit"; Malone et al., "TRUST," 2.

fuel, lease it to the utility, and base the "rent" payment to the lessor on the heat generated through the use of the fuel in the utility's reactor.[105] As these lease arrangements mature, some utilities have been able to dispense with the need to obtain letters of credit in connection with such transactions.[106] Other U.S. utilities have developed their own special financial arrangements to address their cash flow requirements.[107]

To the extent that states are able, under their national laws, to commit themselves to issue export licenses and grant retransfer approvals needed to establish meaningful long-term fuel supply assurances, those assurances should be incorporated in peaceful nuclear cooperation agreements that provide the legal framework for international nuclear commerce. To bolster governmental attempts to convince emerging state recipients of the binding nature of fuel assurance (assuming faithful performance of the agreement by the recipient), such agreements should incorporate an advance long-term programmatic assurance allowing the fuel and fuel components to be exported and retransferred for processing, and ultimately shipped to the intended destination. Nuclear fuel leases negotiated among private-sector participants should benefit from such assurances to the same extent as the governments under whose agreements for cooperation such commerce is carried out.

This approach offers the following advantages:

- In the long term, it could provide the financial and institutional support to develop, construct, and operate interim centralized and/or regional storage facilities.
- It could provide reliable fuel supplies buttressed by competitive pricing necessary for a viable commercial nuclear fuel industry.
- With regard to the front-end, such an arrangement could increase risk protection by mitigating the consequences of a fuel supply interruption for either physical or political reasons. Historically, states have managed this risk by maintaining large inventories. While prices for uranium and its attendant services (enrichment, conversion, and fabrication) have risen, and while it is becoming more expensive to dedicate capital to maintain inventory, fuel cost is a weak argument for sovereign (national) enrichment programs. The

105. Such leases typically require the utility to make periodic payments—similar to rental payments—related to the heat generated through the use of the fuel. When the fuel is fully "used" or "spent," such leases require the utility to purchase the fuel at fair market value; ibid.

106. In 1997, Aetna Casualty and Surety Company issued a "bond of indemnity to the trust which owned the fuel used by VEPCO," thus assuring "payment of the commercial paper issued by the trust to finance the acquisition of the nuclear fuel"; ibid.

107. Gulf States Utilities was said to have engaged in a transaction in which it sold its uranium oxide to a trust "with a provision permitting Gulf States to repurchase the fuel at a later date at the original sales price plus financing costs." This "transaction had considerable operating and financial advantages to Gulf States, in that it allowed the utility to raise cash while still retaining control over a future supply of nuclear fuel at a known price"; ibid.

opportunity for diversification of supply that is inherent in the proposed fuel supply model provides an alternative to maintaining large inventories as a way to manage the risks of supply disruption; and it remains effective regardless of the cost of carrying inventory.

- It could provide a hedge against likely cost increases for front- and back-end services.
- By pledging the revenues from electricity sales, it could facilitate the payment for infrastructure projects in the developing states; and it reduces the capital formation requirements of these states. We understand that the interest rate to finance such projects is significantly higher than commercially issued sovereign debt. Even if developing states were able to obtain lower concession rates from international development entities, the blended rates would not be substantially lower.[108] Therefore, the cost of borrowing capital to pay for nuclear fuel for entities in the developing world is substantial. In addition, some investment banks have suggested that binding contracts for supply of the nuclear fuel required by the plant over a substantial portion of its life would be a necessary condition for financing the construction of new nuclear power stations.

This approach offers the following disadvantages:

- It would likely require significant start-up capital.
- It would likely revert to a scheme that puts more emphasis on conventional reprocessing and recycling. In our general opinion, user or consumer states will put a value on the used fuel and will eventually want to burn the recycled MOX fuel.
- It would require multiple bilateral and multilateral agreements and commitments, likely calling for a new institutional entity to manage the leasing arrangements.
- It would likely require protracted discussions to iron out all the contract and payment terms. The discussions may take so long that by the time the agreements are ready to be implemented, consumer states may have already locked themselves into fuel supply and conventional reprocessing contracts.

108. Paul K. Freeman et al., "Infrastructure in Developing Countries: Risk and Protection," International Institute for Applied Systems Analysis, http://www.iiasa.ac.at/Research/RMS/june99/papers/pflug1.pdf.

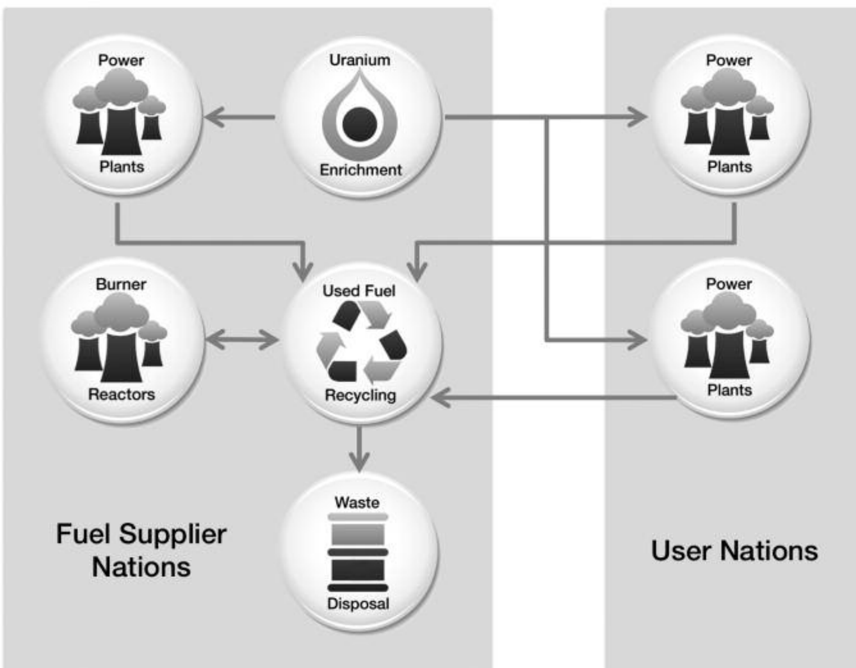
*Concept #2: A Linear Model—A Special Case for the Multilateral Fuel Lease Arrangement*

An alternative model that has received some attention is the linear model; in this case, a "bundled fuel supplier" (AREVA) offers bundled services, including conventional reprocessing and recycling services (Figure 3). This bilateral approach is more readily adapted to the current fuel supply regime.

This approach offers the following advantages:

- Start-up capital would likely not be a barrier to implementing this model.
- It could encourage aspiring consumer states to make deals with existing suppliers, which can supply fuel cycle services with "economies of scale."

Figure 3. A Linear Model




*User nations* denotes consumer states and *fuel supplier nations* denotes fuel supplier states. Source: Modified from Stephen Goldberg and James Laidler, "Financial Strategies for Future Reprocessing Facilities," World Nuclear Fuel Cycle Conference, April 6, 2006. Reprinted with permission from the World Nuclear Fuel Cycle.

- It could discourage developing states from building individual enrichment and conventional reprocessing facilities, provided that all services are available. (For example, if local waste disposal is not available, waste would be returned.)
- It could require significantly less effort in negotiating a fuel regime framework because it typically involves a much smaller number of critical partners; indeed, it can be viewed as a relatively modest evolution of the existing, already viable fuel supply network.

This approach offers the following disadvantages:

- It would indirectly encourage adding conventional reprocessing capacity.[109] The likely outcome is a short- to intermediate-term increase in the stocks of civilian separated plutonium.
- It is not conducive to a flexible technology (including advanced chemical partitioning, if proliferation-resistant) and final disposal opportunities. Thus, it will prematurely shut off choices on advanced technology opportunities.

Industry representatives' favorable view of the linear model is understandable, as industry would not want to perturb (any more than necessary) the existing viable fuel supply network. Furthermore, one can see how preserving the existing industry contractual agreements would best serve regional storage arrangements.

109. If fuel supplier states add to their existing enrichment and conventional reprocessing capability, such a capital investment could be underwritten by new contracts with new nuclear stations.

# Appendix VI

## Terms of Engagement[110]

*National.* This term should be used to describe fuel cycle arrangements conducted exclusively under the domestic legal, regulatory, and commercial framework of a single state.

*International.* Any activity involving participation by entities (whether natural or legal persons or governments) from more than one state could be considered "international." There are three possibilities, and combinations could occur among all three: (1) an arrangement conducted (owned and managed) by a fully international organization, such as the IAEA; (2) a wide spectrum of arrangements involving participation by differing entities (commercial, governmental, or other) that do not have a fully "international" character, such as URENCO or EURODIF; and (3) intergovernmental bodies that could own or manage arrangements between entities, such as the IUC. There are three subsets:

- *Multinational.* This term could be taken to mean an arrangement involving some form of participation by entities from several (not just two) states. It does not differ significantly from the term "international," except that participation in a multinational arrangement might involve a narrower participation than a fully "international" or universal organization.
- *Multilateral Agreement.* A multilateral agreement is defined as a binding agreement between three or more parties concerning the terms of a specific circumstance. The agreement could be structured in terms of investment, management, regulatory oversight, or other matters.
- *Regional.* However various regions are defined, this term implies that participation in an arrangement would be limited to entities from a coherent geographical area.

### ENGAGEMENT

*Participation.* Utilities in nuclear consumer states as well as nuclear fuel suppliers and take-back entities are key participants; they can participate in a range of activities, from providing a revenue source, to partial ownership interest, to concrete involvement in operation or facility management. The various rights,

110. Adapted from a presentation by Carlton Stoiber to MLA Workshop, Center for Strategic and International Studies/Nuclear Threat Initiative, July 2011.

responsibilities, and activities of participating entities must be defined. Allowing participation by entities (whether governmental, private, or other) would be established based on set criteria.

*Ownership/Investment*. Any new fuel cycle arrangement will need a clear indication of what entities are legally entitled to an ownership interest or other form of financial investment in the arrangement. Given the sensitive nature of fuel cycle technologies, many states have legal restrictions on foreign ownership or even investment in such activities conducted within their jurisdiction. However, there are examples of international or multilateral entities that accept ownership or investment by governments or private entities and sometimes a mixture of both. Because an ownership interest also has implications for management, control, access, and supply issues, the basic instruments establishing a new fuel cycle arrangement should be explicit in who can own or invest in the arrangement, and what rights or obligations flow from such investments.

## LEGAL RIGHTS

*Choice of Law*. For most purposes, the applicable law governing activities of a fuel cycle arrangement would be the law of the state in which a facility is located.

# Appendix VII

## Glossary[111]

**Actinides**
A series of chemical elements with atomic numbers from 89 to 109.

**Enriched uranium**
Uranium having a higher abundance of fissile isotopes than natural uranium. Enriched uranium is considered a special fissionable material.

**Enrichment plant** (or isotope separation plant)
An installation for the separation of isotopes of uranium to increase the abundance of U-235. The main isotope separation processes used in enrichment plants are gas centrifuge or gaseous diffusion processes operating with uranium hexafluoride (UF6) (which is also the feed material for aerodynamic and molecular laser processes). Other isotope separation processes include electromagnetic, chemical exchange, ion exchange, and atomic vapor laser and plasma processes.

**Fast reactor** (fast neutron spectrum reactor)
A reactor that, unlike thermal reactors, operates mainly with fast neutrons (neutrons in the energy range above 0.1 MeV) and does not need a moderator. Fast reactors are generally designed to use plutonium fuels and can be designed to burn actinides.

**Fissionable material**
In general, an isotope or a mixture of isotopes capable of nuclear fission. Isotopes U-233, U-235, Pu-239, and Pu-241 are referred to as both fissionable and fissile, while U-238 and Pu-240 are fissionable but not fissile.

**Fuel element** (fuel assembly, fuel bundle)
A grouping of fuel rods, pins, plates, or other fuel components held together by spacer grids and other structural components to form a complete fuel unit that is maintained intact during fuel transfer and irradiation operations in a reactor.

**Fuel fabrication plant**
An installation for manufacturing fuel elements.

**Geological repository**
Underground installation for the disposal of nuclear material, such as used fuel and/or high-level and transuranic nuclear waste.

111. These definitions are taken primarily from the *IAEA Safeguards Glossary*, 2001 edition.

**High enriched uranium (HEU)**
Uranium containing 19.8 percent or more of the isotope U-235.

**High-level radioactive waste (HLW)**
Highly radioactive materials produced as a by-product of the reactions that occur inside nuclear reactors. HLW takes one of two forms: used reactor fuel when it is accepted for disposal; or second cycle aqueous rafinnate or other radioactive materials remaining after used fuel is reprocessed.

**Isotope**
One of two or more atoms of the same element that has the same number of protons in its nucleus but different numbers of neutrons. Isotopes have the same atomic number but different mass numbers.

**Lanthanides**
A series of chemical elements with atomic numbers from 57 to 71.

**Light water reactor (LWR)**
A power reactor that is both moderated and cooled by ordinary (light) water. LWR fuel assemblies usually consist of clad fuel rods containing uranium oxide pellets of low enrichment, generally less than 5 percent U-235, or MOX having low plutonium content, generally less than 5 percent. There are two types of LWR: boiling water reactors (BWRs) and pressurized water reactors (PWRs).

**Low enriched uranium (LEU)**
Enriched uranium containing less than 19.8 percent of the isotope U-235.

**Mixed oxide (MOX)**
A mixture of the oxides of uranium and plutonium used as reactor fuel for the recycling of plutonium in thermal nuclear reactors (thermal recycling) and for fast reactors.

**Natural uranium**
Uranium as it occurs in nature, having an atomic weight of approximately 238 and containing minute quantities of U-234, about 0.7 percent U-235, and 99.3 percent U-238. Natural uranium is usually supplied in raw form by uranium mines and concentration (ore processing) plants as uranium ore concentrate, most commonly the concentrated crude oxide U3O8, often called yellow cake.

**Nuclear fuel cycle**
The nuclear fuel cycle is a system of nuclear installations and activities interconnected by streams of nuclear material. The characteristics of the fuel cycle may vary widely from state to state, from a single reactor supplied from abroad with fuel to a fully developed system. Such a system may consist of uranium mines and concentration (ore processing) plants, thorium concentration plants, conversion plants, enrichment (isotope separation) plants, fuel fabrication plants, reactors, used fuel conventional reprocessing or more advanced chemical partitioning plants, and associated storage installations. The fuel cycle can be "open" by direct disposal of used nuclear fuel or "closed" in various ways: for example,

by the recycling of enriched uranium and plutonium through thermal reactors (thermal recycle), by the reenrichment of the uranium recovered as a result of used fuel dissolution and partitioning, or by the burning of actinides in fast reactors.

**Plutonium**
A radioactive element that occurs only in trace amounts in nature, with atomic number 94 and symbol Pu.

**Reactor**
Any device in which a controlled, self-sustaining fission chain reaction can be maintained. Depending on their power level and purpose, reactors are subdivided into power reactors, research reactors, and critical assemblies.

**Reprocessing (conventional)—PUREX**
An installation for the chemical partition of nuclear material from fission products following dissolution of used fuel. The installation may also include the associated storage, head-end (cutting and dissolution) operations, conversion and analytical sections, a waste treatment facility, and liquid and solid waste storage. Conventional reprocessing involves the following steps: fuel receipt and storage; fuel decladding and dissolution; partition of uranium, plutonium, and possibly other actinides (for example, americium and neptunium) from fission products; partition of uranium from plutonium; and purification of uranium and plutonium. Once purified, uranium nitrate and plutonium nitrate may be converted, respectively, to $UO_2$ and $PuO_2$ powder at an adjoining plant. Depending on the economics, these powders may be either indefinitely stored or recycled as MOX fuel into an LWR or advanced burner or breeder reactor. More advanced chemical partitioning involves separation of the actinides and some fission products that could simultaneously provide a fuel stream that is burnable in advanced reactors and is proliferation-resistant.

**Thorium**
A radioactive element with atomic number 90.

**Transmutation**
The conversion of one nuclide into another through one or more nuclear reactions, and more specifically, the conversion of an isotope of one element into an isotope of another element through one or more nuclear reactions.

**Transuranic elements**
Transuranic elements are the chemical elements with atomic numbers greater than 92.

**Uranium**
A naturally occurring radioactive element with atomic number 92.

**Used nuclear fuel**
Fuel from a reactor that is no longer efficient in power production because its fission process has slowed.

# List of Acronyms

| | |
|---|---|
| AIROX | Atomics International Reduction Oxidation |
| ASEAN | Association of Southeast Asian Nations |
| BWR | boiling water reactor |
| CGNPC | China Guangdong Nuclear Power Company |
| CIAE | China Institute for Atomic Energy |
| CNNC | China National Nuclear Corporation |
| COEX | coextraction |
| CPIC | China Power Investment Corporation |
| ERDO | European Repository Development Organization |
| EU | European Union |
| GNEP | Global Nuclear Energy Partnership |
| GW-day | gigawatt day |
| GWe | gigawatt electric |
| HEU | high enriched uranium |
| HLW | high-level radioactive waste |
| IAEA | International Atomic Energy Agency |
| IFNEC | International Framework for Nuclear Energy Cooperation |
| IUEC | International Uranium Enrichment Center |
| KAERI | Korean Atomic Energy Research Institute |
| kWe | kilowatt electric |
| kWh | kilowatt hour |
| LEU | low enriched uranium |
| LWR | light water reactor |
| MOX | mixed oxide |
| MT | metric ton |
| MTHM | metric ton of heavy metal |
| MW | megawatt |
| MWe | megawatt electric |
| Myrrha | Multipurpose Hybrid Research Reactor for High-tech Applications |
| NPT | Nuclear Non-Proliferation Treaty |
| NTI | Nuclear Threat Initiative |
| PUREX | plutonium-uranium extraction |
| PWR | pressurized water reactor |
| RDO | Repository Development Organization |
| RFS | reliable fuel supply |
| SNPTC | State Nuclear Power Technology Company |
| SPE | special purpose entity |
| UREX | uranium extraction |
| WER | water energetic reactor |

# Contributors

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**James P. Malone** is Chief Nuclear Fuel Development Officer at Lightbridge. In 2009, he retired after a decade with Exelon Generation Company, where as Vice President of Nuclear Fuels he oversaw procurement for seventeen operating nuclear reactors and guided management of used fuel. Before joining Exelon, he served for ten years as Vice President and Senior Consultant at NAC International, advising on fuel reliability and the front- and back-ends of the nuclear fuel cycle. While at NAC, he worked on the international safeguards system for the Rokkasho Mura reprocessing plant in Japan. Previously, he worked at SWUCO, Inc., as a nuclear fuel broker, a manager of technical services, and finally as Vice President; he also served as manager of economic analysis at Yankee Atomic. He began his career in 1968 as an engineer in the utility reactor core analysis section of the Nuclear Engineering Department of United Nuclear Corporation. He is a member of the American Nuclear Society and past Chairman of its Fuel Cycle Waste Management Division.

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Visiting Professor at the Newton Institute for Mathematical Sciences at the University of Cambridge. His research is in the areas of plasma astrophysics and astrophysical fluid dynamics and magnetohydrodynamics (solar and stellar magnetic fields, in particular); high energy density physics; boundary mixing instabilities; combustion modeling; applications of stochastic differential equations and optimization problems; and inverse methods. He is a Fellow of the American Physical Society and a Foreign Member of the Norwegian Academy of Science and Letters. He is a Fellow of the American Academy and serves as a member of the Academy's Council. He is Senior Advisor to the Academy's Global Nuclear Future Initiative.

# The Global Nuclear Future Initiative of the American Academy

There is growing interest worldwide in civilian nuclear power based on the recognition of its potential for meeting increased energy demands. But the spread of nuclear technology, in the absence of rigorous safety regimes, presents unique security risks, including the potential proliferation of weapons capabilities to new states and to subnational and terrorist groups.

The Academy's Global Nuclear Future Initiative is working to prevent this dangerous outcome by identifying and promoting measures that will limit the security and proliferation risks raised by the apparent growing global appetite for nuclear energy. The Initiative has created an interdisciplinary and international network of experts working together to devise and implement nuclear policy for the twenty-first century.

To help reduce the risks that could result from the global expansion of nuclear energy, the Initiative addresses a number of key policy areas, including the international dimension of the nonproliferation regime, the entirety of the fuel cycle, the physical protection of nuclear facilities and materials, and the interaction of the nuclear industry with the nonproliferation community. Each of these areas has specific challenges and opportunities, but informed and thoughtful policies for all of them are required for a comprehensive solution. We also recognize that "game changers," developments that could have a tremendous impact but cannot be extrapolated from current trends, could influence the course of events and should be identified and included in our deliberations.

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