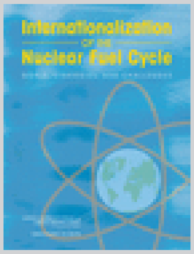

Internationalization of the Nuclear Fuel Cycle: Goals, Strategies, and Challenges

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SUMMARY

Following the proposals for nuclear fuel assurance of International Atomic Energy Agency (IAEA) Director General Mohamed ElBaradei, former Russian President Vladimir V. Putin, and U.S. President George W. Bush, joint committees of the Russian Academy of Sciences (RAS) and the U.S. National Academies (NAS) were formed to address these and other fuel assurance concepts and their links to nonproliferation goals. The joint committees also addressed many technology issues relating to the fuel assurance concepts. This report provides background information and support for the following consensus findings and recommendations of the joint committees:

Finding 1a

By 2020, many countries that currently do not have a nuclear power plant are likely to initiate national programs for the construction of nuclear power stations.[1] These countries do not now have facilities for uranium enrichment for nuclear fuel production or spent nuclear fuel reprocessing.

Finding 1b

Uranium enrichment and spent fuel reprocessing are the key technologies that enable countries to produce direct-use materials for nuclear weapons.[2] The more countries to which either technology (enrichment or reprocessing) spreads, the greater the proliferation risks. Currently it appears that more countries that have not already deployed these technologies are interested in establishing uranium enrichment programs than in pursuing spent fuel reprocessing technologies, making the spread of enrichment technology a greater near-term concern for nuclear proliferation. But the intention to acquire spent nuclear fuel reprocessing capabilities was the main focus of proliferation concerns in the 1970s and could become so again.

Finding 1c

Requirements of the nuclear security environment, the difficulty of providing safeguards and security, and the demand for nuclear fuel cycle services change over time, and technology advances with time. Any approach for enhancing the nonproliferation features of international fuel cycles must be staged to respond to the nonproliferation needs of the time period. Today this suggests a focus on convincing countries that they do not need to establish their own enrichment facilities, which has motivated efforts by several countries and international organizations to address the enrichment issue. Similar efforts are needed to convince countries that they do not need their own reprocessing facilities. Also needed are strengthened efforts to prevent the spread of these technologies through illicit or inadequately regulated exports and black-market nuclear networks, and improved safeguards for both uranium enrichment and spent

[1] Until and unless construction begins, estimates of nuclear growth are based upon expressions of interest and should be considered as having substantial uncertainty.

[2] The main nuclear weapons materials are highly enriched uranium, obtained by enriching naturally occurring uranium, and plutonium, primarily obtained by reprocessing irradiated reactor fuel.

fuel reprocessing facilities, designed both to increase international confidence that significant diversions from declared facilities would be detected and to strengthen the ability to provide timely warning concerning covert facilities and activities.

Recommendation 1a
The countries that currently provide nuclear fuel services should redouble efforts, with other countries and the IAEA, to establish mechanisms for increasing reliability of supply of nuclear fuel, so that countries that do not now have enrichment technology would have reduced incentives to build their own uranium enrichment facilities.

Recommendation 1b
The international community should help countries provide adequate capacity for safely storing spent fuel (on their own territory or elsewhere), or reliable reprocessing services from existing providers, to reduce countries' incentives to establish their own reprocessing facilities. Separated plutonium or fabricated plutonium fuel should not be sent to countries that have not previously received such material and do not have reprocessing capabilities. The spread of separated plutonium to additional countries poses many of the same proliferation risks posed by the spread of reprocessing capabilities.

Recommendation 1c
For similar reasons the United States and other nations should reduce and seek to minimize commerce in and the transfer of highly enriched uranium (which poses proliferation risks) except if sealed in a reactor core.

Second-level findings:

a. To ensure a reliable supply of nuclear fuel, a country needs reliable fuel fabrication services as much as it needs reliable sources of uranium and enrichment services.
b. To assist in the international fuel assurance programs, it would be helpful if nations with fuel fabrication facilities made those available.
c. Fuel fabrication technology for uranium oxide fuel with low-enriched uranium is not sensitive from a proliferation perspective. Hence, if countries choose to establish their own fabrication capabilities to produce fuel assemblies for their own nuclear power stations, without establishing uranium enrichment or spent fuel reprocessing capabilities—as South Korea has done, for example—this should not pose significant international concerns.

Finding 2
Several messages are clear from the NAS-RAS workshop and other recent discussions in Vienna about assurance of supply:

a. Few countries have declared a willingness to forgo forever a right to develop their own uranium enrichment or spent fuel reprocessing nuclear technology in the future.[3]

[3] The charter of the International Uranium Enrichment Center in Angarsk, Russia, requires members other than the host country to commit to not develop their own uranium enrichment capabilities. As of June 2008, Kazakhstan and Armenia have made that commitment and become members.

Some countries have expressed adamant opposition to requiring a country to forgo the development of its own enrichment and reprocessing technologies as a condition of assurance of supply of nuclear fuel or low-enriched uranium.

b. To be successful, uranium enrichment, fuel assembly production for nuclear power stations, and spent fuel storage/reprocessing technologies continue to operate in the international market.
c. No single mechanism or strategy for assurance of nuclear fuel supply is likely to address every country's legitimate needs and desires. Each country's or region's needs and requirements may be different.
d. New mechanisms for assured nuclear fuel supply may only modestly change countries' incentives to establish enrichment facilities, as the existing international market provides strong assurance of supply, and countries have a variety of other reasons for establishing their own enrichment plants, including a desire to participate in the profits of enrichment, national pride, and a desire to establish a nuclear weapons option for the future.

Recommendation 2a

The governments of the United States and Russia should continue to support a broad menu of approaches to increasing assurance of nuclear fuel supply.

An array of mechanisms for assurance of nuclear fuel supply has been proposed, from diversified long-term contracts through the existing market, enrichment bonds,[4] and international fuel centers to creating a virtual or actual fuel bank. Some of these are already in place. The Russian and U.S. governments should support a broad menu of these approaches, ensuring that these do not undermine each other.

Recommendation 2b

The governments of the United States and Russia should seek to establish additional benefits and incentives for countries that choose not to establish their own uranium enrichment and spent fuel reprocessing facilities. Possibilities could include assistance in establishing the necessary infrastructure for safe and secure use of nuclear energy.

Recommendation 2c

To support nonproliferation goals, the nations that currently supply nuclear fuel should work expeditiously with other countries and the IAEA to make assured fuel supplies available before there is a major commitment to new nuclear power plants by countries that do not have them today.

Finding 3a

It is feasible to establish a multinational center to provide enrichment services without sharing enrichment technology for countries willing to refrain from developing their own enrichment

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[4] Enrichment bonds: A guarantee by a state that supplies enrichment services that enrichment providers will not be prevented from supplying the recipient state with uranium enrichment services if the guarantee is invoked (adapted from a proposal by the United Kingdom).

facility as long as they participate in the center.[5] The International Uranium Enrichment Center (IUEC) in Angarsk, Russia, is one such center. There have been proposals to establish centers under international organizations, although their feasibility has yet to be established. An international dialog, in which concerned countries evaluate the pros and cons of supplementing multinational centers with a center under international control, is needed. Two European multinational consortia have provided enrichment services for two decades: Eurodif, like the IUEC, does not share its technology among its members, but participants need not forgo development of enrichment technology as a condition of participation. Urenco has only three partners, all of which have access to its technology.

Finding 3b

If global usage of nuclear energy increases, it may become increasingly difficult to maintain a system in which nationally controlled facilities in only a few countries provide all enrichment and reprocessing services, as desirable as that might be from a nonproliferation perspective. Offering the opportunity to profit from these technologies may reduce the likelihood that countries would perceive efforts to inhibit expansion of access to the technology as unfair.

Recommendation 3

Over time, Russia, the United States, and other nations should work to create a global system featuring a small number of centers for the sensitive steps of the fuel cycle (especially enrichment and spent fuel management, possibly including storage, reprocessing, or disposal), owned, operated, and controlled by consortia of states or international organizations (but without spreading the relevant technologies beyond existing technology holders). Such a global system, offering many countries the opportunity to participate and share in the profits, would provide a somewhat more equitable and sustainable long-term basis for limiting enrichment and reprocessing facilities to a small number of countries. There has been some criticism that the proposed mechanisms are unfair. The preliminary arrangements should be improved over time.

Finding 4

As use of nuclear power grows, there is a need worldwide for well-educated personnel to support the whole nuclear fuel cycle.

Recommendation 4

Countries with large nuclear power programs, such as the United States and Russia, should encourage young people to enter nuclear engineering and related fields and programs that give the breadth of perspective needed.

Finding 5

Arrangements that would provide assured return of spent nuclear fuel could provide a much more powerful incentive for countries to rely on international nuclear fuel supply than would assured supply of fresh fuel, because assured take-back could mean that countries would not need to incur the cost and uncertainty of trying to establish their own repositories for spent

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[5] By a *multinational* center, the joint committees mean a facility whose ownership and management involves an arrangement among several countries. Eurodif, Urenco, and the International Uranium Enrichment Center at Angarsk are examples. By an *international* facility, the joint committees mean a facility whose ownership and management are centered in a fully international organization such as the IAEA.

nuclear fuel or nuclear waste. Further, it would reduce the number of countries where plutonium-bearing material is stored around the world. Fuel leasing, reactor leasing, and similar approaches could have this benefit, if managed appropriately. For many countries, however, the political barriers to taking back other countries' spent nuclear fuel or nuclear waste are substantial.

Recommendation 5
The United States, Russia, and other suppliers should increase their emphasis on establishing mechanisms for assured fuel-leasing or reactor-leasing services,[6] including take-back of all irradiated fuel. Russia already has legislation and arrangements in place to offer fuel leasing and has such a contract in place with Iran. In both international fuel supply approaches and in take-back of spent fuel, Russia is farther along in offering services to other countries. The United States and Russia should work together on cooperative approaches that would make it possible to enter into fuel-leasing arrangements in which they would guarantee to supply, and to take back, fuel for the lifetime of reactors built in "newcomer" states, with the fuel taken back to Russia for now, or to the United States, as well, if circumstances someday make that possible.

Finding 6
A hidden danger of creating such centers is the potential for leakage of sensitive technology. The most damaging leakage of sensitive technology occurred when A. Q. Khan, working as a contractor for Urenco, was able to acquire enough information and contacts to build the supply line for Pakistan's nuclear weapons program. Khan went on to form a supply network that fed into weapons programs in Libya, North Korea, and Iran. An event like this puts the nonproliferation regime in great danger.

Recommendation 6a
The United States and Russia should work diligently with other nations to ensure that all efforts to establish international centers for enrichment, reprocessing, or other sensitive activities include specific, stringent plans to prevent leakage of sensitive information and technology. Plants with staff from countries that do not have technology of the type used at that plant should maintain the sensitive technology in "black boxes" so that the international staff does not have access to the technologies themselves. Plans to prevent technology leakage should be subject to review by a small group of international experts familiar with such technology controls before the centers are established.

Recommendation 6b
Russia the United States and other countries working to develop centers should have criteria for participation. Two major criteria for participation by countries beyond the technology holders who provide the technology for the center should be that they not have or be developing an enrichment facility, and that they should be in compliance with IAEA safeguards and nonproliferation obligations.

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[6] Today the only discussions of reactor leasing are those on the floating power plants being built by Russia and the nuclear battery being proposed by Toshiba. There will be many legal issues to work out in both cases.

Finding 7
Safeguard arrangements, fuel transfer processes, and return of spent fuel provisions are only a few of the complex legal issues that must be resolved if fuel assurance, fuel take-back, and multinational or international fuel center programs are to be effective.

Recommendation 7
The IAEA should lead an international effort to identify these legal questions and options to be considered. The IAEA should also convene countries to reach agreement on preferred solutions.

Finding 8
Both Russia and the United States are working on new technologies for processing spent fuel, intended to reduce the economic costs and proliferation risks of traditional reprocessing approaches and improve waste management. The technologies being proposed would still pose significant proliferation concerns if deployed in countries that did not previously have reprocessing capabilities. The new technologies under development will take significant time before being ready for demonstration at commercial scale.

Recommendation 8
Developers of nuclear fuel cycle technologies should assess the technologies' proliferation risks and projected economic costs and benefits as critical elements of design.

Finding 9a
In most cases, reprocessing is not economic under current conditions. When the world's economically recoverable uranium resources diminish compared to demand or there is widespread deployment of fast reactors, then reprocessing may become economically attractive.

Finding 9b
Excess stocks of plutonium separated from spent fuel, beyond plutonium that would be needed for making MOX fuel for use in the near term, pose security risks.

Recommendation 9
States should end the accumulation of stockpiles of plutonium separated from spent fuel as soon as practicable, and begin to reduce existing stocks. Spent fuel should only be reprocessed when its constituents are needed for fuel, or when reprocessing is necessary for safety reasons.

Finding 10
Many of the technologies for improved nuclear fuel cycles are not areas that will advance without directed research specifically focused on the nuclear fuel cycle; advances in other areas of science and engineering will help, but are not sufficiently linked to nuclear fuel cycles to solve the technical challenges described here, by themselves. Research is needed in the areas of processing of irradiated nuclear fuel and nuclear fuel design (beyond the incremental improvements in uranium oxide fuel for light water reactors), as well as in improved approaches to disposal of wastes or spent fuel, and reduced-cost recovery of uranium from low-grade sources. Additional research and development is also needed to develop advanced safeguards and security technologies that can provide increased capabilities to detect covert nuclear

facilities; highly accurate near-real-time monitoring of material flows in bulk processing plants with reduced intrusiveness, increasing confidence that any diversion would be detected; low-cost real-time monitoring that would set off an immediate alarm if stored nuclear material were tampered with or removed; effective protection against sophisticated outsider and insider theft and sabotage threats at reduced cost; and design of facilities to simplify and increase the effectiveness of safeguards.

Recommendation 10
The U.S., Russian, and other governments should take the lead in a cooperative international effort to make additional research and development investment in advanced safeguards and security technologies. A focused effort should be made to make the results of this research and development available to the international community to ensure that new facilities are more secure and readily safeguarded. The international community also should adopt the philosophy of designing high levels of security and safeguards into new nuclear systems and facilities from the outset, including both the inherent technical characteristics of the process and the institutional measures to be taken.

Finding 11
It is not possible today to construct an entire, operational international fuel cycle program.[7] Such a program will have to be built incrementally. However, elements of that program currently exist and the groundwork for other elements has been laid.

Recommendation 11
The U.S., Russian, and other governments should

- continue to invest in research and development on advanced approaches to once-through and closed fuel cycles that offer the potential to improve proliferation resistance, safety, security, economics, resource utilization, and waste management
- utilize a systems approach to developing and assessing these technologies, with clear objectives and technically justifiable criteria for decision making. Use systems analysis to identify potentially promising approaches before proceeding to build pilot or larger facilities.
- take all relevant proliferation risks into account when assessing proliferation resistance, including how the availability of the materials, facilities, and expertise associated with a particular fuel cycle approach would affect the time, cost, uncertainty, and detectability of a nuclear weapons program

The implementation of those elements that are feasible today, for example, assurance of fuel supply, should not be delayed while other options are being refined or explored both institutionally and technically.

[7] One run internationally and including all elements of the fuel cycle.

Finding 12
The United States and the Russian Federation have signed an agreement on peaceful nuclear cooperation, but it must still be allowed to come into force. The lack of a U.S.-Russian agreement in force is interfering with joint efforts to reduce proliferation. The expanded cooperation in nuclear energy research and development and commercial implementation that such a bilateral cooperation could make possible could serve both countries' interests in expanding the use of nuclear energy while meeting safety, security, and nonproliferation objectives. Article 2 of the signed agreement lists possible areas of cooperation, including, among other areas, scientific research and development on nuclear power reactors and their fuel cycles; nuclear fuel cycle services; radioactive waste handling; and nuclear safety, regulation, nonproliferation, and safeguards.

The joint committees recognize that it is unlikely that the U.S. government will bring the agreement into force in an environment of worsening relations between the United States and Russia. It is the joint committees' hope that current disagreements that have recently emerged will not interfere with the United States and Russia working together toward their common goal of inhibiting nuclear weapons proliferation as nuclear energy use grows across the world.

Internationalization OF THE Nuclear Fuel Cycle

GOALS, STRATEGIES, AND CHALLENGES

U. S. Committee on the
Internationalization of the Civilian Nuclear Fuel Cycle

Committee on International Security and Arms Control,
Policy and Global Affairs

Nuclear and Radiation Studies Board
Division on Earth and Life Sciences

NATIONAL ACADEMY OF SCIENCES *AND*
NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

Russian Committee on the
Internationalization of the Civilian Nuclear Fuel Cycle

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PREFACE AND ACKNOWLEDGMENTS

The so-called nuclear renaissance has increased worldwide interest in nuclear power. This potential growth also has increased, in some quarters, concern that nonproliferation considerations are not being given sufficient attention. In particular, since the introduction of many new power reactors will lead to requiring an increase in uranium enrichment services to provide the reactor fuel, the proliferation risk of adding enrichment facilities in countries that do not have them now led to proposals to provide the needed fuel without requiring new indigenous enrichment facilities. Similar concerns exist for reprocessing facilities.

In 2006, International Atomic Energy Agency (IAEA) Director General Mohamed ElBaradei, Russian President Vladimir V. Putin, and U.S. President George W. Bush each announced plans to assure the provision of fuel to countries that want to develop nuclear power. The proposals were aimed at dissuading these countries from building uranium enrichment plants because such plants could be used to produce weapons-usable highly enriched uranium. In the spring of 2006, members of the Committees on International Security and Arms Control of the U.S. National Academy of Sciences (NAS) and the Russian Academy of Sciences (RAS), which have had a productive partnership for more than 25 years, met with each other, with senior officials in their respective governments, and with Director General ElBaradei to identify issues of national and international importance on which independent advice from the two academies would be useful.

With funding from the John D. and Catherine T. MacArthur Foundation and the Carnegie Corporation of New York, two committees with members appointed by the NAS and the RAS, working jointly, produced this report analyzing the proposals and options for future international nuclear fuel cycles, including the incentives that might be required for countries to accept fuel assurance guarantees and not develop enrichment or reprocessing facilities, as well as technical fuel-cycle issues. The statement of task for this study can be found in Appendix A. The task notes that this report is not intended to cover the policy and technical aspects of international fuel cycles comprehensively. Rather, the joint committees summarize key issues and analyses, offer some criteria for evaluating options, and make findings and recommendations to help the United States, the Russian Federation, and the international community reduce proliferation and other risks as nuclear power is used more widely.

This report is intended for all those who are concerned about the need for assuring fuel for new reactors and at the same time limiting the spread of nuclear weapons. This audience includes the United States and Russia, other nations that currently supply nuclear material and technology, many other countries contemplating starting or growing nuclear power programs, and the international organizations that support the safe, secure functioning of the international nuclear fuel cycle, most prominently the International Atomic Energy Agency.

Fuel assurance proposals have been discussed in conferences and journal articles. However, to receive input from the countries that might use the fuel assurance program, the joint committees held a workshop at the IAEA in April 2007, where people from eight countries presented their opinions or comments on the fuel assurance programs. While not officially representing their governments, these experts provided valuable insights into the issues that must be addressed for the fuel assurance programs to succeed. Appendix B of the report contains a summary of the workshop. The joint committees also addressed technologies being developed for new approaches to reprocessing (also called recycling and regeneration) and possible advanced reactors. While these discussions are necessarily limited due to the technologies being in the early stages of development or existing only as concepts, some advantages and disadvantages are discussed.

The joint committees addressed the different elements of the statement of task at different levels. Much of Part B of the task calls for comparisons of technologies in Russia with those envisaged in the United States. The Global Nuclear Energy Partnership (GNEP) comprises two initiatives from President George W. Bush. One is an international initiative beginning with an accord expressing the signatories' guiding principles for expansion of nuclear power. The other is a domestic nuclear energy and fuel cycle technology initiative with seven different goals. The international initiative has garnered dozens of partners. The domestic technology initiative has shifted its focus, emphasis, and timeline several times over the course of the study. These changes were significant, from switches among advanced fuel processing technologies that are mostly in the research phase and evolutionary commercial fuel-processing technologies to different fuels manufactured with as-yet-to-be-developed technologies. For these reasons, the joint committees were unable to compare the concrete Russian technological options with the multitude under consideration in GNEP. Because the Russian approaches have been developed more fully and in many cases the Russian government has selected particular approaches for deployment, these approaches are described in more detail in this report than the early-stage concepts being considered in the U.S. Technologies in related areas being pursued in other countries were beyond the joint committees' charge, and are considered only in passing here.

We wish to thank the IAEA, especially Director General Mohamed ElBaradei, Deputy Director General Yuri Sokolov, and Tariq Rauf for their support of our international workshop held in Vienna. We also thank Alan MacDonald of the IAEA for his substantial assistance in arranging the workshop. We thank the workshop attendees and the presenters at the joint committee meetings in the United States and Russia who provided us with their expert knowledge (see Appendix E).

We especially thank Yuri Shiyan of the RAS, Micah Lowenthal, NAS Study Director, and Rita Guenther of the NAS. Without the tireless work of these three individuals, the report would not have been completed.

This joint study addresses some of the serious international issues connecting the spread of nuclear power and nonproliferation concerns. The NAS and RAS have met and worked together for many decades on issues related to science and technology, including decades of dialogues and, more recently, joint studies on international security problems. We strongly believe that inhibiting the spread of nuclear weapons capabilities while promoting better access to safe, clean energy is in the interests of Russia, the United States, and the larger world community. It is precisely at times like these, then, that cooperation is needed between our scientific communities to help focus on those common interests and promote efforts toward common goals. The need for such cooperation grows under the conditions we see today.

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Academies' Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the process.

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Christopher Whipple, ENVIRON, and Harold Forsen, Bechtel Corporation. Appointed by the National Academies, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring joint committees and the institution.

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