Internationalization of the Nuclear Fuel Cycle

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Executive Summary

The debate over the past five years on how to limit national ownership and control of nuclear fuel-cycle facilities is largely a response to the perceived risk of a growing number of countries to acquire these sensitive technologies. This prospect is seen as a challenge to the nonproliferation regime by leading nuclear weapon states and their allies, by non-weapon states seeking both to stem proliferation and to abolish nuclear weapons, and by states and international bodies seeking to promote the peaceful uses of nuclear technology.

In June 2004, IAEA Director General M. ElBaradei appointed an international group of experts to consider "possible multilateral approaches to the civilian nuclear fuel cycle." El Baradei had previously acknowledged that the shortcomings of the nonproliferation regime were becoming more evident because nuclear-weapons technologies are more difficult to control today than they were in the past. He warned that "should a state with a fully developed [nuclear] fuel-cycle capability decide, for whatever reason, to break away from its non-proliferation commitments, most experts believe it could produce a nuclear weapon within a matter of months." To limit this possibility, ElBaradei reintroduced the idea of restricting reprocessing and enrichment exclusively to facilities that are under multinational control.

Largely in response to these initial discussions, including the report by the group of experts, many proposals have been formulated since then. The control of reprocessing or enrichment is seen as key. These represent the major technical barriers in acquiring nuclear weapons. Reprocessing and enrichment are similar in the sense that they provide the capability to produce nuclear-weapon-usable materials, i.e., the capability to separate plutonium from irradiated fuel or to produce highly enriched uranium (HEU) from uranium that is non-weapon-usable (e.g. from natural uranium). With technological barriers becoming less relevant, and weak incentives to forego research and development of these fuel cycle technologies, this is widely perceived as a problem that might only get more acute over time.

In broadest terms, two different strategies can be distinguished to discourage the development of new national nuclear fuel-cycle capabilities: ensuring fuel supply to address energy-security concerns and balancing rights and obligations under the Non-

Proliferation Treaty (NPT).

Most current proposals are targeted at the energy-security arguments for national fuel-cycle capabilities. Against this background, several proposals seek to strengthen existing market mechanisms, usually through (in one form or another) assurances of fuel supply or fuel-cycle services. These proposals are generally based on the underlying assumption that the current system of fuel and enrichment suppliers is adequately diverse, and that new suppliers are not needed.

Less visible, but equally important, are efforts to reinforce the NPT. There is currently a widely perceived dissatisfaction with the status and prospects of the treaty, in particular regarding implementation of Articles IV and VI, which define rights and obligations regarding peaceful use and disarmament. From the perspective of some non-weapon states, the current system of supplier states, which is based in the nuclear weapon states and a few closely-allied countries, is seen as one major expression of a distorted implementation of Article IV. Some proposals for multilateral approaches to the nuclear fuel cycle recognize this dilemma, and permit a more active role of non-weapon states in the supplier market, for example, through enrichment plants under multinational management or control.

In principle, most fuel-assurance proposals that envision a backup supply of fuel or enrichment services are straightforward. Some are already being implemented, others have realistic chances of moving forward if their advocates remain interested. The NTI/IAEA fuel bank proposal is a prominent candidate in this category. The strong financial support for the project and the fundamental role of the IAEA in ownership and oversight of the bank, make it a robust fuel-assurance proposal. It will have to be seen, however, how appealing it will appear to non-supplier states with emerging nuclear power programs, and how restrictive the conditions of access will be perceived by the member states of the IAEA.

In addition, most countries are already satisfied with the current situation and acknowledge working market characterized by several independent and reliable suppliers. For them, fuel assurances are largely a solution to a problem they do not face. This dilemma is exacerbated by the fact that today's main users of nuclear energy already have direct access to enrichment services: About 80% of nuclear energy is generated in countries that either possess indigenous enrichment plants or participate in one of the existing consortia. The ultimate value of these proposals is therefore unclear at present.

In the context of nuclear disarmament, proposals to internationalize the nuclear fuel cycle that inherently rely on a separation of supplier and consumer states are much less meaningful. In particular, short-term strategies to establish nuclear fuel banks and assure the supply of fuel in emergency situations may be considered less relevant because the fuel-cycle services, i.e., enrichment and possibly reprocessing capacities, have to be located somewhere. As the distinction between nuclear weapon and non-nuclear weapon states gradually becomes less relevant in a disarming world, a small number of states would retain a significant breakout capability; in fact, one can argue that only these states will have a meaningful capability to acquire or re-acquire nuclear weapons in a relatively short period of time. Proposals that envision multinational ownership and operation of plants on a basis, where all partners have equal status are most relevant in this context. They may be considered unrealistic in the short-term, but could serve as important precedents for a world preparing for nuclear disarmament.

Advocates of multinational approaches envisioning fuel cycle facilities that are not under purely national control, and possibly located outside the countries of the current supplier states, hope that such arrangements would make an important contribution to re-establishing confidence in the NPT and be sufficient to discourage additional states to develop enrichment and reprocessing technologies. Some proposals even envision a fuel cycle, in which the existence of facilities under national control has been abandoned altogether.

The German proposal for a Multilateral Enrichment Sanctuary Project (MESP) offers a precedent and model for considering future nuclear fuel-cycle facilities, if any such facilities are needed. It may be considered among the more unrealistic proposals today, but offers a normative vision of a model that could be consistent with a world preparing for nuclear disarmament. Our analysis the suggests that the so-called black-box approach, which would be needed for such projects, is a viable way of using sensitive technology without disseminating proliferation-sensitive information. The required support of the current technology holders for this or similar ideas is far from being assured, however.

Large-scale plants that are currently under construction or planned could serve not only as models for innovative multilateral arrangements but also as models for advanced safeguards approaches. Not very many new enrichment plants will be needed in the next two decades. A very significant fraction (at least 75%, and up to 100%) of the future demand of enrichment services will be covered by enrichment plants that already exist today, are currently being expanded, and under construction or planned.

Given that it is unlikely for many large new uranium enrichment plants to be required, and that proposals for fuel banks and fuel assurances do not address basic issues of the supplier/client dependency and of prevailing insecurity about the international system, the debate over multilateral approaches to the fuel cycle could more usefully focus on the conversion of existing national enrichment plants to multinational control and management. There is little incentive, however, for current enrichment providers to cede control of their existing facilities and place them in a new, and initially uncertain, institutional framework. It is hard to see how this would change. Regardless, it would be very important to place all existing plants and those planned or under construction under IAEA safeguards, in particular, because this would also facilitate the implementation of a verified fissile material cutoff treaty.

I. Introduction

The control and management of the materials, technologies and knowledge that provide the capability to make nuclear weapons has been a central aspect of international politics for at least sixty years, ever since such weapons were first built and used. At the same time, however, command of nuclear technology has been perceived by many as emblematic of being modern and, more practically, as the basis for the large-scale production of electricity, which in turn is seen as the key to economic growth and development. The nuclear weapon states, and more broadly the international community, most of which has abjured such weapons and seeks their elimination, have sought at various times to develop ways to regulate access to nuclear materials, technologies and knowledge to enable their peaceful uses while limiting their possible application to weapons. These efforts are often provoked by events that reveal the weaknesses of the prevailing nonproliferation regime. A recurring option in all these efforts, however, has been the possibility of limiting nation-state control over nuclear technologies that are most directly relevant to the capability to make fissile materials, the key ingredients in nuclear weapons, and placing these technologies in the custody and control of multinational bodies or analogous arrangement.

In this paper, we first describe briefly the sporadic efforts over the past sixty years to resolve the tension between efforts by states to gain control over nuclear technologies and to ensure these technologies will only be used for peaceful purposes. Section III outlines the current challenges and the origins of the new debate on multilateral approaches. The fundamental objective of these approaches is to discourage the development of sensitive nuclear fuel-cycle technologies by additional states, and Section IV summarizes the fundamental strategies that are pursued to achieve this objective. Before turning to a discussion of the specific proposals that are currently under consideration, Section V of this paper looks at the present demand for uranium enrichment to fuel nuclear power plants and the expected growth of nuclear power capacity over the next two decades and the enrichment capacity that will be required. This helps set the basis for discussing whether proposals for multinational control of enrichment should focus on future facilities or existing facilities and those that are currently under construction or planned. Section VI looks at important cross-cutting issues that reveal some common problems with various proposals.

We conclude by arguing that only a few currently considered forward-leaning multilateral approaches, which are at the same time the most difficult to implement, could make a meaningful difference in reframing the nuclear fuel cycle. Short-term proposals for fuel assurances with better chances of success, usually promoted by the current supplier-states and not involving ownership of facilities, are unlikely to address most of the underlying issues. An equally important effort has therefore be made to invest scarce efforts and resources on ensuring existing and under construction uranium enrichment facilities are under adequate IAEA safeguards.

II. Previous Efforts to Manage the Nuclear Fuel Cycle

The fundamental challenges of controlling nuclear technology were recognized within a very short period after the United States' Manhattan Project succeeded in building the first atomic bomb. Announcing the atomic bombing of Hiroshima, U.S. President Harry S. Truman claimed the bomb as a uniquely American achievement, because "the United States had available the large number of scientists of distinction in the many needed areas of knowledge. It had the tremendous industrial and financial resources necessary for the project. [...] It is doubtful if such another combination could be got together in the world." Recognizing the likelihood that other states would seek to match America's new found power, President Truman announced that "under present circumstances it is not intended to divulge the technical processes of production or all the military applications" of the new technology.[1]

The hope that a nuclear monopoly could be sustained by the great technological and administrative demands of making nuclear weapons, buttressed by deep secrecy about how the United States had managed this task, was challenged by the Acheson-Lilienthal report of March 1946, largely authored by Robert Oppenheimer and other leading scientists associated with the Manhattan Project. The report argued:

"*It is recognized that the basic science on which the release of atomic energy rests is essentially a world-wide science, and that in fact the principal findings required for the success of this project are well known to competent scientists throughout the world. It is recognized that the industry required and the technology developed for the realization of atomic weapons are the same industry and the same technology which play so essential a part in man's almost universal striving to improve his standard of living and his control of nature. It is further recognized that atomic energy plays so vital a part in contributing to the military power, to the possible economic welfare, and no doubt to the security of a nation, that the incentive to other nations to press their own developments is overwhelming.*" [Acheson and Lilienthal, 1946], www.ipfmlibrary.org/ach46.pdf

The report further declared that:

"*National rivalries in the development of atomic energy readily convertible to destructive purposes are the heart of the difficulty. So long as intrinsically dangerous activities may be carried on by nations, rivalries are inevitable and fears are engendered that place so great a pressure upon a system of international enforcement*

[1] Statement by the President Announcing the Use of the A-Bomb at Hiroshima, Press Release, 6 August 1945, www.trumanlibrary.org.

by police methods that no degree of ingenuity or technical competence could possibly hope to cope with them."

The list of "intrinsically dangerous activities" included those involving the capacity to enrich uranium in the isotope uranium-235 and to separate plutonium from spent nuclear fuel, i.e., the capability to produce those materials that can sustain an explosive chain reaction. The report made its concerns explicit: "We are convinced that if the production of fissionable materials by national governments (or by private organizations under their control) is permitted, systems of inspection cannot by themselves be made effective safeguards to protect complying states against the hazards of violations and evasions." The report proposed "if the element of rivalry between nations were removed by assignment of the intrinsically dangerous phases of the development of atomic energy to an international organization responsible to all peoples, a reliable prospect would be afforded for a system of security." The advice of the Acheson-Lilienthal report was ignored, while the Cold War began, and states sought national control over nuclear technology.

In a December 1953 speech to the United Nations, President Dwight D. Eisenhower announced what became known as the Atoms for Peace program. Eisenhower proposed sharing nuclear knowledge, technology, and materials with those countries that did not have them. One purpose was to use the promise of sharing what many saw as the most modern technology to establish and strengthen strategic ties, especially with third-world countries. Atoms for Peace also served a policy to build domestic support and foreign markets for U.S. corporations wanting to profit from what seemed to be an emerging nuclear future. The U.S. program led to a growing competition with the Soviet Union, which launched its own version of Atoms for Peace, as well as with Western industrialized countries, notably Canada, Britain, France, and later Germany who were looking for their own clients and markets for their respective nascent nuclear industries. Supplier states hoped that these would help shape political relationships as well as the choices that countries would make about what nuclear research and nuclear energy facilities to buy and where to buy them from.

As foreseen by the authors of the Acheson-Lilienthal report, national control of nuclear programs and the status, prestige and power commonly associated with them, combined with international rivalries, led to the spread of nuclear weapons. The United States has been joined by eight other states in maintaining nuclear weapons: Russia, United Kingdom, France, China, Israel, India, Pakistan and North Korea. Many other states pursued weapons capabilities but chose to abandon their programs.

The effort to widely share nuclear technology and materials meant, however, that a safeguards system had to be established. The International Atomic Energy Agency (IAEA) was made responsible for managing this system, an arrangement that was institutionalized in the 1970 nuclear Nonproliferation Treaty (NPT). There were early problems. In 1974, India carried out a nuclear weapon test using plutonium from spent fuel produced in a research reactor supplied by Canada for peaceful purposes. Other countries were seeking enrichment and/or reprocessing technology, including Argentina, Brazil, South Korea, Taiwan, Pakistan, and it appeared as if some states with these technologies, such as France and Germany, were considering their export to some of these countries. This led to the second debate about multinational or international control of key nuclear technologies, with the focus of this debate in the 1970s and 1980s centered on plutonium separation and recycling.

The concept of internationalization attracted some renewed attention when its evaluation was mandated by the first NPT Review Conference in 1975. This led to the International Nuclear Fuel Cycle Evaluation (INFCE) project, a three-year long technical study effort launched in 1977 and eventually including 66 countries, to assess future nuclear fuel cycle options and attendant proliferation risks. But, as one observer at the time noted: "What [INFCE] demonstrated in fact was that the principal issues raised by a possible relationship between civil nuclear fuel cycles and the proliferation of nuclear weapons cannot be resolved by technical ingenuity or arbitrary government intervention, but only by political negotiation and political agreement."[2] In the United States, the concept of an internationalized nuclear fuel cycle received special status in the 1978 Nuclear Non-Proliferation Act, in which the idea of an International Nuclear Fuel Authority was reiterated.[3] The United States effectively abandoned this policy objective shortly thereafter and, without support from any side, the initial weak momentum was lost again.

Finally, since 1978, the Nuclear Suppliers Group (NSG) has managed the international system to regulate nuclear trade. These states have agreed to rules for the export of critical nuclear material, equipment and technology, including the requirement of full-scope IAEA safeguards. The NSG guidelines also encourage a move away from transfers of new national enrichment and reprocessing facilities, stating that "if enrichment or reprocessing facilities, equipment or technology are to be transferred, suppliers should encourage recipients to accept, as an alternative to national plants, supplier involvement and/or other appropriate multinational participation in resulting facilities. Suppliers should also promote international (including IAEA) activities concerned with multinational regional fuel cycle centres" [INFCIRC/254, 2007].

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[2] I. Smart, "INFCE brings international agreement on nuclear fuel cycle no nearer," *Nature*, 283, 28 February 1980.

[3] From Title I of the Nuclear Non-Proliferation Act, International Undertakings, Section 104 (a): "The president shall institute prompt discussions with other nations and groups of nations, including both supplier and recipient nations, to develop international approaches for meeting future worldwide nuclear fuel needs." The text continues and introduces the idea of an International Nuclear Fuel Authority to meet nonproliferation objectives.

III. The Current Challenges and the New Debate

The weaknesses of a nonproliferation system relying on technical safeguards and export controls to restrain non-weapon states became clear with the discovery of the scale of Iraq's secret nuclear weapons program at the end of the 1991 Gulf War. The exposure of an international network trading in uranium enrichment technology that included A.Q. Khan, a key figure in Pakistan's enrichment program, raised new concerns. Khan and the network were responsible for the covert transfer of enrichment technology to Libya, Iran, North Korea, and perhaps others. The discovery of Iran's uranium enrichment program late in 2002 (first declared by Iran to the IAEA in early 2003), and North Korea's expulsion of IAEA inspectors at the end of 2002 and subsequent announcement that it was leaving the NPT, seemed further to challenge and threaten the nonproliferation regime.

The problem has taken on a new dimension with the anticipation of a nuclear renaissance. Today, some argue that a global expansion of nuclear energy is necessary to help reduce the greenhouse gas emissions that drive climate change and to meet the growing needs for electricity especially in rapidly urbanizing and industrializing developing countries. Since 2006, almost twenty countries that today have no nuclear power plants, and in many cases few nuclear scientists and engineers, have announced plans to build one or more reactors by 2020. They range from Algeria to Yemen, and include Bangladesh, Egypt, Indonesia, Israel, Jordan, Libya, Morocco, Nigeria, Qatar, Saudi Arabia, Syria, Turkey, the United Arab Emirates, and Vietnam.

The suppliers of nuclear technology have recognized the opportunity for new business after decades of stagnation. As part of its Global Nuclear Energy Partnership, the United States has signed-up 21 countries, including Ghana, Senegal, Jordan, and many former Soviet clients in Eastern Europe and the former states of the Soviet Union. The French nuclear giant AREVA has been signing contracts with former colonies across North Africa such as Algeria, Libya and Morocco for training of nuclear engineers and sharing nuclear expertise, which it hopes will lead to sales of power reactors. AREVA has also agreed to help train people for the Nuclear Energy Corporation of South Africa. Russia's nuclear industry is restructuring and seeking international clients. These developments and activities only increase the urgency to find strategies to prevent the further proliferation of nuclear weapons.

In an article published by *The Economist* in October 2003, IAEA Director General Mohammed El Baradei acknowledged that the shortcomings of the nonproliferation regime were becoming more evident because nuclear-weapons technologies are more difficult to control today than they were in the past [ElBaradei, 2003]. He warned that "should a state with a fully developed [nuclear] fuel-cycle capability decide, for whatever reason, to break away from its non-proliferation commitments, most experts believe it could produce a nuclear weapon within a matter of months." To limit this possibility, ElBaradei reintroduced the idea of restricting reprocessing and enrichment exclusively to facilities that are under multinational control.

IV. What Are Multilateral Approaches For?

As we have seen, the current discussion on multilateral approaches to the nuclear fuel cycle is not an abstract exercise. As were similar discussions in the past, it is embedded in specific, immediate concerns. On one side, advocates hope that multilateral approaches might help resolve the crisis prompted by Iran's centrifuge enrichment program. Others believe that the "nuclear renaissance" is imminent and that many more countries will—and should—use nuclear energy in the future. The main focus of the present debate is on uranium enrichment, and most proposals seek to address this particular element of the nuclear fuel cycle.[4]

In broadest terms, two different strategies can be distinguished to discourage the development of new national nuclear fuel cycle capabilities:

- ***Fuel assurances.*** Most current proposals are targeted at the energy-security arguments for national fuel cycle capabilities. The deployment of nuclear reactors for base-load electricity production is capital-intensive, and potential interruptions of operations, for example due to disrupted fuel supplies, more adversely affect the economics of nuclear energy than is the case for other energy sources. Against this background, several proposals seek to strengthen existing market mechanisms, usually through (in one form or another) assurances of fuel supply or fuel-cycle services.

  These proposals are generally based on the underlying assumption that the current system of fuel and enrichment suppliers is adequately diverse, and that new suppliers are not needed.

  Fuel assurances through multilateral arrangements are also intended to "remove the incentive and the justification for countries to develop indigenous fuel cycle capabilities" [IAEA-DG, 2005].

- ***Reinforcing Articles IV and VI of the NPT.*** There is currently a widely perceived dissatisfaction with the status and prospects of the Non-Proliferation Treaty (NPT), in particular regarding implementation of Articles IV and VI, which define rights and obligations regarding peaceful use and disarmament. From the perspective of some non-weapon states, Article IV is particularly unbalanced. Besides guaranteeing the "inalienable right" to pursue nuclear energy for peaceful purposes, Article IV also specifies that states with advanced nuclear technologies should cooperate in contributing to "the further development of the applications of nuclear energy for peaceful purposes, *especially in the territories of non-nuclear-weapon States Party to the Treaty"* (emphasis added). The current system of supplier states, which is based in the nuclear weapon states and a few closely-allied countries, is seen as one major expression of a distorted implementation of Article IV. Some proposals for multilateral approaches to the nuclear fuel cycle recognize this dilemma, and permit a more active role of non-weapon states in the

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[4] This review is no exception: for the sake of simplicity, we will often explicitly refer to supply assurances for low-enriched uranium in general and to centrifuge enrichment plants in particular.

> supplier market, for example, through enrichment plants under multinational management or control.

In principle, most fuel-assurance proposals that envision a backup supply of fuel or enrichment services are straightforward. Some are already being implemented, others have realistic chances of moving forward if their advocates remain interested. Most countries, however, are already satisfied with the current situation and acknowledge working market characterized by several independent and reliable suppliers. For them, fuel assurances are largely a solution to a problem they do not face. This dilemma is exacerbated by the fact that today's main users of nuclear energy already have direct access to enrichment services: About 80% of nuclear energy is generated in countries that either possess indigenous enrichment plants or participate in one of the existing consortia (Urenco and Eurodif).[5] The ultimate value of these proposals is therefore unclear at present.

Reinforcing Article IV and Article VI of the NPT is a more challenging and complex proposition. Advocates of multinational approaches envisioning fuel cycle facilities that are not under purely national control—and possibly located outside the countries of the current supplier states—hope that such arrangements would make an important contribution to re-establishing confidence in the NPT and be sufficient to discourage additional states to develop enrichment and reprocessing technologies. Some proposals even envision a fuel cycle, in which the existence of facilities under national control has been abandoned altogether.

Multilateral Approaches in the Context of Nuclear Disarmament

The prospects and viability of possible multilateral arrangements of the nuclear fuel cycle are typically discussed in the context of preventing further proliferation of nuclear weapons, while enabling a possible global expansion of nuclear energy. In this report, another dimension is at least equally important: What is the favored or necessary structure of the nuclear fuel cycle in a world preparing for nuclear disarmament?

In the context of nuclear disarmament, proposals to internationalize the nuclear fuel cycle that inherently rely on a separation of supplier and consumer states are much less meaningful. In particular, short-term strategies to establish nuclear fuel banks and assure the supply of fuel in emergency situations may be considered less relevant because the fuel-cycle services, i.e., enrichment and possibly reprocessing capacities, have to be located somewhere. As the distinction between nuclear weapon and non-

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[5] This estimate is based on the total capacity installed by the end of 2007 [IAEA, 2008]. Note that Canada (12.6 GWe) is not included in the quoted fraction because it primarily operates natural-uranium fueled reactors and does not necessarily require enrichment services today. The only major users of nuclear energy without an enrichment plant on their territories, and depending on the supply of low-enriched fuel, are South Korea (17.5 GWe) and Ukraine (13.1 GWe).

nuclear weapon states gradually becomes less relevant in a disarming world, a small number of states would retain a significant breakout capability; in fact, one can argue that *only* these states will have a meaningful capability to acquire or re-acquire nuclear weapons in a relatively short period of time. Proposals that envision multinational ownership and operation of plants on a basis, where all partners have equal status are most relevant in this context. They may be considered unrealistic in the short-term, but could serve as important precedents for a world preparing for nuclear disarmament.

Before turning to a discussion of the multilateral approaches currently under consideration in Section VII, we briefly review the global enrichment picture and several cross-cutting issues that, in one way or another, are relevant in this context (Sections V and VI). Appendix B summarizes the reasons for the particular relevance of centrifuge technology in the current debate on multilateral approaches.

V. The Global Enrichment Picture

For the first two decades of the post World War II era, the United States held a monopoly on fuel-cycle services for customers in the Western world. Starting in the late 1960s, and intensified by a series of events in the early 1970s, several Western European countries and Japan developed independent enrichment capabilities in order to secure a non-U.S. enrichment supply for their growing light-water reactor fleets. From these efforts, two enrichment suppliers ultimately emerged, Urenco and Eurodif, each involving a different set of Western-European countries. As illustrated in Figure 1, many other countries have also pursued enrichment or reprocessing capabilities, sometimes to support nuclear weapons programs. In all cases, the nuclear weapon states opposed the development of these capabilities in NPT non-nuclear weapon states, even when there were no immediate concerns about a country proliferating. Iran is the subject of the current debate.

Ultimately, a large oversupply of installed enrichment capacity resulted in the 1980s and 1990s, because additional reactor capacities had not been added at the expected rate due to technical difficulties, first major accidents, and political and public opposition to nuclear energy. In addition, a major fraction of the required SWU demand has been temporarily suppressed since the mid-1990s by LEU originating from down-blended Russian HEU.[6]

[6] The 500 MT of the original HEU deal are sufficient to fuel a reactor-capacity of 50 GWe for about ten years when diluted with natural uranium, or for about 15 years when diluted with 1.5%-enriched blend-stock. Although significant, this material, and even potential additional stocks of military HEU that could become available in the longer-term future, both combined are not sufficient for a lasting impact on the enrichment-services market. Down-blended military stocks could defer, but ultimately not avoid construction of additional enrichment plants to support a given total reactor capacity.

Figure 1. Reprocessing and Enrichment: Activities and Capabilities, 2009.
See also Table 2 in Appendix A for a list of enrichment plants

Looking Ahead: Demand for Enrichment by 2030

As of January 2009, the IAEA reports a net installed capacity of 372 GWe (gigawatt electric) produced by 438 nuclear power plants worldwide. In its latest nuclear-energy forecast, the agency estimates that the share of nuclear-generated electricity will remain at its current level throughout the next two decades [IAEA, 2008]. By 2030, this would correspond to an installed nuclear capacity of 470–750 GWe or to 7–9% of the total electric capacity, for a low and high estimate, compared to 8% today. We also note, however, that throughout most of the nuclear era, projections of future nuclear growth have been consistently too optimistic.[7]

[7] Many of the factors that constrained nuclear power in the past—high capital costs, slower-than-projected growth in demand for electricity, scarcity of capital in developing countries, and problems with public acceptability—are likely to continue to dampen its growth. For a discussion, see Chapter 7 in [GFMR, 2007].

Reactors fueled with low-enriched uranium, either light-water or gas-cooled, are likely to dominate the nuclear-power generation in the mid-term future. Assuming that natural-uranium-fueled reactors will continue to provide about 10% of the total nuclear capacity and that fast breeder reactor will not play a significant role by 2030, then 420–680 GWe will require enrichment services. As shown in Table 2 in Appendix A, the enrichment capacity already available or planned today is sufficient to fuel about 520 GWe of light-water reactor technology.[8]

A very significant fraction (at least 75%, and up to 100%) of the future demand of enrichment services will be covered by enrichment plants that *already* exist today, are currently being expanded, and under construction or planned. If multinational arrangements beyond simple fuel assurances were to play an increased role in the next 10–20 years, the conversion of additional national plants to multinational control would have to be seriously considered.

VI. Cross-cutting Issues

In the following, we briefly review several cross-cutting issues, mostly technical in nature, that are relevant for all proposals approaches and their potential to address the problem of proliferation of fuel-cycle technologies.

VI.1. Sustainability of Supplier/Client-State Systems

The technical capability to develop sophisticated nuclear fuel cycle technologies is not a privilege of a few highly developed industrialized countries. As an important example, Figure 2 illustrates the timelines of selected centrifuge programs, from the beginning of the R&D phase through successful operation of a pilot-scale facility. The figure suggests that the time required to go through the phases of a centrifuge program has not significantly decreased in the last few decades: it takes about 15–20 years to develop the technology, and even outside assistance can apparently reduce the R&D period by only a few years. More important though is the recognition that countries may have begun R&D on enrichment technologies sooner or later, depending on when they felt sufficiently confident to be able to carry out such a project, assuming that they had previously concluded that a need for this capability exists.[9]

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[8] For the estimate of the total enrichment capacity shown in Appendix A (Table 2), we assume that the laser-enrichment facility in the United States will in fact be built. We do not assume, however, that any new capacities in existing facilities will be added beyond those already planned—a very conservative assumption.

[9] Availability of outside assistance may, of course, encourage a country to embark on a research and development program earlier than it would otherwise do.

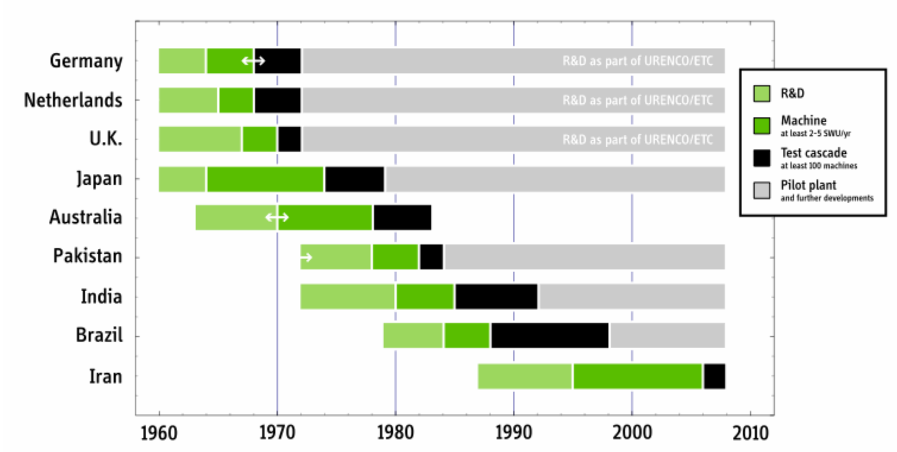

Figure 2. Timelines of selected centrifuge programs.

There are several reasons to conjecture that the technological challenge of developing centrifuge technology may be easing, however. Key technologies that were previously used specifically for centrifuge-component manufacturing are expanding into additional sectors of modern industry and/or require less experience or expertise to be operated. As technology develops, even relatively advanced scientific and engineering skills or capabilities are being integrated into hard- and software, which are in turn produced and traded in the global market. More countries therefore are likely to move into a position, where indigenous development of centrifuge technology becomes feasible in principle.

This trend is, of course, sometimes recognized in the current debate on multilateral approaches to the nuclear fuel cycle—and one of the reasons to pursue new approaches in the first place. Nevertheless, lower technological barriers, and the resulting increased difficulty of effectively controlling sensitive nuclear technologies, also mean that supplier/client-state systems can only be maintained over time if they are broadly supported by those states qualifying as clients in such system.[10] If, on the other hand, incentives to acquire national enrichment capabilities—for either peaceful or military purposes—continue to exist, we can indeed expect successful independent development and deployment of centrifuge technology in more states over time. Multilateral approaches can play a relevant role to reduce these incentives, but they have to address not only the energy-security dimensions, but ultimately also the NPT rights and obligations of both weapon and non-weapon states.

[10] In particular, attempts to maintain a supplier/client-state system without the support of some key non-supplier countries with ambitious nuclear programs do also not address the clandestine problem, which is particularly relevant for centrifuge technology because clandestine enrichment plants based on this technology are extremely difficult to detect. They do not produce significant signatures normally used to detect hidden nuclear facilities, and special signatures specific to centrifuges are probably too weak to be useful for detection at significant distances [Kemp and Glaser, 2007].

VI.2. The Competitive Disadvantage of Newcomers

Efforts have been made to counter the energy-security argument by pointing out that it is often cheaper to purchase enrichment services on the international market than to build a national plant at home. Although that is technically true, the economic penalty is not severe.

Newcomers will not be able to compete with established enrichment providers on the international market, but for a small-sized enrichment program for domestic fuel supply, first-generation technology may be entirely sufficient and satisfactory. Fuel and enrichment costs are only a few percent of the cost of nuclear energy, which is dominated by the costs of constructing, operating, and maintaining nuclear power plants. If a country had to pay four times the market-price for domestic enrichment services (i.e., $500 instead of $125 per SWU), the overall cost of electricity would increase by less than 10%—a small insurance premium for energy security. In short, economics alone are not a significant basis for foregoing an indigenous enrichment capability when it simultaneously offers a measure of energy security.

Again, fuel-assurance proposals are explicitly designed to counter the energy-security argument—but economic considerations may not be as strong as they are sometimes perceived. Even if a state has no intentions to acquire nuclear weapons or a nuclear-weapon option, and even if it recognizes that indigenous development of enrichment capabilities (or re-activation of a former enrichment program) will be more expensive than purchasing the fuel on the international market, it may still decide to pursue this path if the alternative is to de-facto give up certain rights irrevocably.

VI.3. Viability of Black-Box Approaches

Most proposals for multinationally owned and operated plants depend on a “black box” approach, in which the sensitive technology (e.g. centrifuge equipment) is supplied to a country or project on a pre-fabricated basis, and the operators—or even the owners of the plant—do not have access to any proprietary or proliferation-sensitive information.

Today, there are only a few states and companies holding enrichment technologies that are able to compete on the international market. These are *Enrichment Technology Company* (ETC), a joint venture between Urenco and Areva, in which only the Urenco countries however have access to the technology itself, the *United States Enrichment Corporation* (USEC), and Russia's Rosatom. Both ETC/Urenco and Rosatom have decades of experience in designing and fabricating centrifuges and operating large-scale plants on a commercial basis. It is therefore extremely unlikely that any other provider can enter the market of enrichment technologies in the foreseeable future. If new plants are to be built—and we have seen that this may not be necessary over the next two decades—one or more of these providers will have to be involved, and without their active support any attempt to establish new enrichment plants under multinational control supplying a sizable regional market is likely to fail.

Both ETC/Urenco and Rosatom have supplied technology on a black-box basis in the past: Russia has exported small facilities to China since the 1990s, while ETC is providing the technology for two new plants in the United States (one operated by Urenco, one by Areva) and for one plant in France—all based on the black-box approach.[11] So far, these transfers have only occurred between suppliers and recipients that "trusted" each other. In all these cases, the recipients were weapon states, and proliferation concerns mattered little.

There are different types of proprietary or proliferation-sensitive information that could be involuntarily disseminated through poorly implemented or due to fundamental limitations of black-box approaches.

The most sensitive parts of a gas centrifuge for uranium enrichment are enclosed in an outer casing and includes the centrifuge rotor, bearings, baffles, scoops, and other components of the machine. Since the final assembly of the centrifuges at the enrichment plant would be carried out by the company providing the technology, this information might be considered well protected, also because maintenance of the machines is unnecessary.[12]

In contrast, certain features of a modern enrichment plant, including some characteristics of the centrifuges themselves, cannot be captured with black-box approaches and would be accessible to the plant operator even if the centrifuge technology itself were provided on a black-box basis. With respect to the machines, the operator could easily determine some operational characteristics of the centrifuges, including rotor-frequency, feed rate, separation factor, SWU capacity, or the uranium inventory per machine—*all considered proprietary information by the technology holders today.* In addition, the operator has access to most cascade-design principles and would, over time, acquire the skills to operate a modern enrichment plant effectively.

At present, it is unclear if the available technology providers would support any black-box approach involving partners with whom they do not already have strong business relations given that a significant fraction of their intellectual property would

[11] In many respects, since ETC was formed in 2003, even the existing Urenco plants in Germany, the Netherlands, and the United Kingdom are black-box plants similar to those now under construction outside the original Urenco countries.

[12] If, for whatever reason, the plant operators *could* visually access parts of the centrifuge, some elements of the design would be compromised. Key to fabricating reliable advanced machines, however, are the specific manufacturing techniques and tolerances, which would still be "invisible" through visual access to the machine or its components.

be at risk of being compromised. The situation is made more complex given that the existing technology holders and enrichment companies are usually closely tied to each other.[13] These enrichment companies, whose consent would be needed to provide the technology for a black-box project, may be reluctant, however, to create new competitors or over-capacities in the enrichment market. In contrast, if they saw indeed the need for new enrichment capacities, they would most likely prefer an expansion of their own capacities to cover this market themselves.

VI.4. Safeguarding Existing and New Plants

One argument often made for multilateral approaches is that they would favor the construction of large-scale enrichment plants and therefore reduce the total number of plants worldwide. These fewer facilities could then be safeguarded at even higher standards because the IAEA would be able to focus its resources more effectively. Unfortunately, the current trend points in a different direction: *average capacities are growing, but the fraction of centrifuge plants under safeguards is likely to decline.*

This is important because those plants that are currently under construction could serve not only as models for innovative multilateral arrangements but also as models for advanced safeguards approaches.

Brazil and Iran are the only non-weapon states building entirely new plants, but their capacities are small and for domestic use only. More importantly, they are presently not good candidates for multilateral approaches involving foreign investment because the technology used in these plants may not be considered competitive by potential partners.[14]

In contrast, all large-scale plants currently planned or under construction and using state-of-the art enrichment technology are located in NPT weapon states: Two centrifuge plants are under construction in the United States (Urenco Eunice, NM and USEC Piketon, Ohio). In addition, Areva recently applied for a license to build a third U.S. centrifuge plant (Eagle Rock, Idaho). Finally, Areva is also replacing the existing gaseous diffusion plant in France with a new centrifuge plant (George Besse II), which will be the largest one built using ETC/Urenco technology.

All these new plants will be offered for IAEA safeguards. In fact, the United States in particular seems to be interested having these facilities under IAEA safeguards and is

[13] For example, Urenco and Areva jointly own ETC and are, at the same time, the main customers of ETC, www.enritec.com.

[14] [Forden and Thomson, 2007] have proposed a detailed plan for converting Iran's enrichment plant in Natanz to a project involving multinational ownership and management. This plan envisions that modern centrifuge technology, supplied by one of the existing technology providers, could be phased in over time.

exploring advanced safeguards methods and instruments to support this process. Specific approaches for how these advanced methods could be applied to the U.S. plants have been proposed [Durst, 2008].

Nevertheless, very few if any of these new large-scale plants in the weapon states will be selected for safeguards due to IAEA budget constraints. The IAEA is also not officially involved in discussions with the future operators of these plants, which could facilitate implementation of safeguards at a later stage.[15] In any event, it appears unlikely that the operators of the new U.S. plants would encourage and actively support advanced safeguards approaches, even if their regulators or the IAEA asked for it. From the operator's perspective, this could create a perceived "double standard" where the safeguards on existing plants in Europe would be inferior to those in the new plants located in nuclear weapon states (France and the United States). There could then be pressure to modernize the older plants, something to be avoided from the perspective of the operators for economic reasons.

In sum, there is currently a serious deadlock with regards to implementing modern safeguards in new enrichment facilities. Advanced approaches are available and yet those facilities, where these methods could be implemented to set a new "gold standard," will not even be selected for safeguards or, if they were, safeguards would be modeled on an old approach that is considered inadequate by many. This is a detrimental situation for the viability of multilateral approaches that involve ownership and operation of facilities because those would have to be safeguarded, preferably, to highest standards available.

VII. Twelve Proposals

In June 2004, IAEA Director General M. ElBaradei appointed an international group of experts to consider "possible multilateral approaches to the civilian nuclear fuel cycle." The final report, released in February 2005, discusses three types of multilateral options [INFCIRC/640, 2005]: Assurances of services not involving ownership of facilities, conversion of existing national facilities to multinational facilities, and construction of new joint facilities. Based on these three types of basic options, the report suggested five different multilateral approaches (MNAs) that should be considered:

[15] In the case of the NPT nuclear weapon states, the design information questionnaire (DIQ) is only submitted to the IAEA once the facility has been selected for safeguards. In contrast, a non-weapon state has to provide this document already when it is considering the construction of a new plant that would have to come under IAEA safeguards. As a result, for example, the layout and design of the new plants based on ETC/Urenco technology will be both patterned on the existing ones in Europe—despite recent discussions of the desirability of incorporating "safeguards-by-design" features in new sensitive nuclear fuel cycle facilities.

1. “Reinforcing **existing commercial market mechanisms** on a case-by-case basis through long-term contracts and transparent suppliers' arrangements with governments. [...]

2. Developing and implementing **international supply guarantees** with IAEA participation. Different models should be investigated, notably with **IAEA as guarantor** of service supplies, e.g. as administrator of a fuel bank.

3. Promoting voluntary conversion of **existing facilities to MNAs,** and pursuing them as **confidence-building measures,** with the participation of NPT non-nuclear weapon States and nuclear weapon States, and non-NPT States.

4. Creating, through voluntary agreements and contracts, **multinational, and in particular regional, MNAs for new facilities** based on joint ownership [...]

5. The scenario of a further expansion of nuclear energy around the world might call for the development of a **nuclear fuel cycle with stronger multilateral arrangements**—by region or continent**—and broader corporation,** involving the IAEA and the international community.

   (all emphases in the original)

As many advocates of multilateral approaches emphasize, these five options are viewed as complementary strategies. They become more and more difficult to implement, however, as they depart from established practices or as they require new legal and institutional frameworks (Options 3–5). Accordingly, the group of experts emphasized that these options would have to be introduced gradually and incrementally. More recently, the IAEA Director General more explicitly outlined his vision for a three-step approach to create a global non-discriminatory framework for the nuclear fuel cycle [IAEA-DG, 2008]:

> “The ideal scenario, in my opinion, would be to start with a nuclear fuel bank under IAEA auspices. Then we should agree that all *new* enrichment and reprocessing activities should be placed exclusively under multilateral control. Ultimately, all *existing* facilities should also be converted from national to multilateral control.”

These general considerations about possible multilateral approaches to the nuclear fuel cycle have led a series of governments, industry groups, and nongovernmental organizations to make specific proposals that they would actively support. These are briefly summarized below.

Since 2005, twelve[16] proposals have been put forward by various countries, industry groups, or nongovernmental organizations (Table1). The original documents, in which the proposals were first presented (all referenced in the table), define to varying degrees the instruments, decision-making bodies and procedures, participants, financing, location, rights and obligations of the parties, enforcement, and operational questions. Table 1 lists the most basic features of these proposals and, when applicable, also assigns one of the five potential approaches that were originally suggested in [INFCIRC/640, 2005]

		Original reference	Approach	Fundamental Mechanism and Conditions
1	U.S reserve of nuclear fuel	INFCIRC/659 (Sep 2005)	2	Fuel assurances (fuel reserve) For states that forego enrichment and reprocessing
2	Peaceful use of nuclear energy, Russia	INFCIRC/667 (Feb 2006)	(3)	Create system of international centers providing nuclear fuel cycle services IUEC Angarsk (see below) as an example
3	Global Nuclear Energy Partnership (GNEP)	USA, Feb 2006	(1)	Fuel supply, possibly spent fuel take-back Existing supplier states provide services for recipient states
4	Ensuring Security of Supply	WNA Report (May 2006)	2	Fuel assurances (enrichment services, fuel reserve)
5	Six Country Proposal (RANF)	GOV/INF/2006/10 (June 2006, restr.)	2	Fuel assurances (enrichment services)
6	IAEA Standby Arrangements, Japan	INFCIRC/683 (Sep 2006)	2	Fuel assurances provided by existing supplies Reduce incentives for additional states to develop national capabilities
7	NTI fuel reserve	NTI Letter (Sep 2006)	2	Fuel assurances (fuel reserve for at least one full core, under IAEA auspices)
8	Enrichment bonds, United Kingdom	INFCIRC/707 (June 2007)	2	Fuel assurances (enrichment services)
9	International enrichment center (IUEC), Angarsk	INFCIRC/708 (June 2007)	(3)	Share in multinational enrichment plant (in Russia, no technology transfer) Oriented chiefly to states not developing indigenous capabilities
10	Multilateral Enrichment Sanctuary Project (MESP), Germany	INFCIRC/704 (May 2007)	4	Establish multilateral extraterritorial enrichment plant States retain right to establish fuel cycle facilities under national control
11	Multilateralization of the fuel cycle, Austria	INFCIRC/706 (May 2007)	(5)	Establish a new authority to ensure "fair" distribution of nuclear fuels Eventually all facilities multinational and operated through this authority
12	Nuclear Fuel Cycle, European Union	EU non-paper (June 2006)	n/a	Criteria to evaluate multilateral arrangements and fuel assurances Not meant to "impinge on national choices and arrangements"

Table 1. Fundamental objectives and conditions of the current proposals.

The numbering of the proposals (1–12) has been adopted from [Rauf and Vovchok 2008]. The options refer to the five suggested approaches defined in [INFCIRC/640, 2005] see also main text.

Several excellent reports and review articles have discussed the existing proposals in detail, namely [Simpson, 2008], [NAS, 2008], and [Yudin, 2009]. Below, we will not go through every single proposal again. Instead, we group them according to the five

[16] This number is somewhat arbitrary. Whereas some proposals have been refined continuously and gathered momentum over time, others have remained rather abstract, making it difficult to predict what future activities might result from them. On the other hand, several independent groups and analysts have made further proposals that could also be included in the list.

general options defined in [INFCIRC/640, 2005], briefly discuss similarities and differences, and highlight important examples.

Approach 2: Fuel Assurances with IAEA Participation

Six out of the twelve proposals envision fuel assurance mechanism without involving new multilateral ownership or operation of facilities, i.e., they are fundamentally based on the existing set of enrichment suppliers. Most proposals do require that recipient states would have to forego indigenous enrichment (or reprocessing) activities in order to be eligible for supply in an emergency situation. Similarly, most proposals envision that the criteria for access have to be clearly defined in advance and that the decision to authorize the release has to be taken quickly, for example, by the IAEA Director General. Full compliance with NPT obligations is usually considered the central criterion for release.

Fuel assurances that are contingent on the small set of existing suppliers, with most plants located in nuclear weapon states, are unlikely to play a central role in a world preparing for nuclear disarmament unless they are coupled with strong multilateral ownership and management of the enrichment facilities themselves. In the following, we discuss one particular, forward-leaning example of a nuclear fuel bank.

The NTI/IAEA Fuel Bank. In September 2006, the Nuclear Threat Initiative committed $50 million to the IAEA for the creation of a fuel bank containing a stockpile of low-enriched uranium to be owned and managed by the IAEA, provided that the "IAEA takes the necessary actions to approve establishment of this reserve" and that "one or more member states contribute an additional $100 million in funding or an equivalent value of low enriched uranium to jump-start the reserve" [Nunn, 2006]. NTI required these conditions to be met within two years of the announcement, but this deadline has since been extended to September 2009. As of the time of this writing, only $3 million are missing to meet the target fund of $150 million.[17] This amount is considered to be sufficient to acquire enough low-enriched uranium for one full core of a standard light-water reactor (about 60 metric tons), or sufficient to fuel such a plant for about three years.

The strong financial support for the NTI/IAEA fuel bank proposal, and the fundamental role of the IAEA in ownership and oversight of the bank, make it a robust fuel-assurance proposal. It will have to be seen, however, how appealing it will appear to non-supplier states with emerging nuclear power programs, and how restrictive the conditions of access will be perceived by the member states of the

[17] As of January 2009, contributions were made by the United States ($50 million), the European Union ($32 million), the United Arab Emirates ($10 million), and Norway ($5 million), "Sam Nunn Applauds EU Contribution to IAEA Fuel Bank," NTI Press Release, 10 December 2008.

IAEA.[18] In terms of eligibility of access, NTI envisions that "this stockpile will be available as a last-resort fuel reserve for nations that have made the sovereign choice to develop their nuclear energy based on foreign sources of fuel supply services—and therefore have no indigenous enrichment facilities" [Nunn, 2006]. In other words, the proposal does not require a country to waive its right to pursue enrichment in principle, but the country only has access to the bank if it is not enriching uranium at the time of the request.[19] Finally, the NTI/IAEA fuel bank proposal may appeal to countries with a single power reactor, where it could provide a relevant assurance of supply; for other countries with larger nuclear capacities, such as South Korea or Ukraine, the limited size of the fuel bank might be a serious constraint.

Approach 3: Conversion of Existing Facilities

[INFCIRC/640, 2005] listed the *voluntary* conversion of existing enrichment facilities as another possible multilateral approach to the nuclear fuel cycle. Only Russia has since made a proposal oriented along these lines and has begun implementing the architecture of an International Uranium Enrichment Center (IUEC), *co-located with but separate from the Angarsk enrichment plant,* at great speed. Russia has also proposed to create an independent fuel reserve of low-enriched uranium at the Angarsk site, an additional element that is not explicitly discussed below.

The International Uranium Enrichment Center at Angarsk. In September 2006, Rosatom announced establishment of the IUEC on the site of the Angarsk enrichment plant (Angarsk Electrolysis Chemical Complex, AECC). The proposal was formally communicated to the IAEA in June 2007 [INFCIRC/708, 2007] and described as a pilot project for a previously introduced more comprehensive "system of international centres providing nuclear fuel cycle services" [INFCIRC/667, 2006].

To provide the basis for its proposed framework, Russia established four new joint stock companies (JSC): Atomenergoprom is a 100% state-owned (Rosatom) company, which owns and operates the Angarsk enrichment plant, AECC. Atomenergoprom also owns TENEX, which co-founded the International Uranium Enrichment Center (IUEC)[20] and owns 51% of that company (IUEC). Authorized companies of new member countries can join the IUEC on the basis of separate

[18] Once the complete funding is pledged, the IAEA Director General is likely to take the proposal to the Board of Governors, which would have to agree to proceed with the development of a detailed proposal, which would be carried out in consultation with the member states. Such a detailed plan would have to specify the reserve contents (chemical form, enrichment level, etc.), location, access, pricing, and various other technical and legal issues [Holgate, 2008]. Ultimately, the Board of Governors would have to vote favorably on the proposal before the deadline expires.

[19] The authors of the NTI/IAEA fuel bank proposal realize that this will be a controversial proposition. In particular, there could be hard cases, where it would be difficult to decide upon eligibility to access the bank (e.g. countries pursuing enrichment for military but not for civilian purposes).

[20] Kazakhstan's JSC NAC Kazatomprom is the second co-founder of the IUEC.

government-to-government agreements and, together, acquire up to 49% of the center. The simplified structure of the arrangement is illustrated in Figure 3. [Grigoryev, 2008] discusses the concept in more detail.

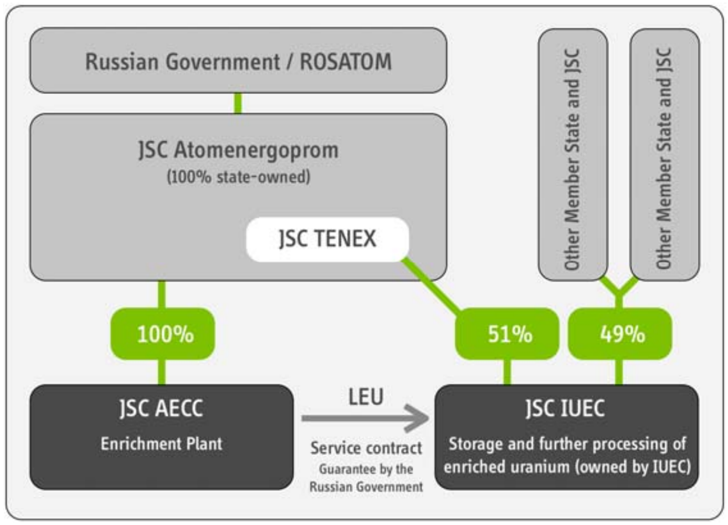

Figure 3. Simplified structure of the Russian proposal of an international nuclear fuel cycle center at Angarsk.

Note that two separate facilities are involved in this proposal: an enrichment plant (AECC) and a storage and processing plant for low-enriched uranium (IUEC).

According to the basic principles of the IUEC, the terms of the membership are equal for all parties and access to enriched uranium, or indirectly to an equivalent enrichment capacity, is assured for all members. The Russian company TENEX, however, controls the majority of the company and can therefore take all strategic decisions about the IUEC without support of the other partners.

A Russian company also controls the enrichment plant itself, in which no foreign participation is currently envisioned. The enrichment plant delivers the enriched product to the IUEC through a negotiated service contract guaranteed by the Russian Government [Grigoryev, 2008]. It will have to be seen how robust this critical arrangement will be considered by potential new IUEC partners, but it appears that AECC has no interest in disrupting operation of IUEC, where the product is prepared for off-site shipping and fuel fabrication, because Russia would presumably cover domestic requirements for low-enriched uranium with the Angarsk complex as well.

There is no concern about access to proprietary or proliferation-sensitive information by one of the non-Russian member states of the IUEC because the relevant technology is located in another facility, which does not form part of the multilateral arrangement.

In January 2007, the AECC enrichment plant was added to Russia's list of eligible facilities for IAEA safeguards. The AECC has not been selected for safeguards so far, and, given the IAEA's budget constraints, it is unlikely that this will happen any time soon. Similarly, in January 2008, Russia added the multinational part of the Angarsk site to the list of eligible facilities. Since the ownership (and possibly operation) of the IUEC will involve NPT non-weapon states, the IUEC can be expected to be selected for safeguards, which would place the nuclear material held and processed at the plant under IAEA safeguards.

[INFCIRC/708, 2007] specifies that the IUEC is “oriented chiefly to States not developing uranium enrichment capabilities on their territory.” An earlier description of the plan appeared more restrictive, when specifying that membership is open to “all interested countries not envisaging the development of indigenous sensitive nuclear technologies and meeting the established nonproliferation requirements” [Ruchkin and Loginov, 2006].

Approach 4: New Multinational Facilities

As discussed in Section V, there is currently more than enough enrichment capacity available to supply today's global reactor fleet. Furthermore, the present or presently planned capacity could prove large enough to support a significant expansion of nuclear energy, e.g. to more than 500 GWe of light-water-reactor capacity, consistent with medium-range IAEA estimates for the year 2030. Unsurprisingly therefore, with the one exception discussed next, there has not been great interest in pursuing the idea of new enrichment facilities as a test bed for innovative multinational approaches.

The Multilateral Enrichment Sanctuary Project. Since 2007,[21] Germany has been actively advocating a proposal for an extraterritorial and multinationally-owned enrichment facility under IAEA supervision—the so-called Multilateral Enrichment Sanctuary Project (MESP), formally introduced in [INFCIRC/704, 2007], and later refined and amended in two additional documents.[22]

The key elements of the proposal are as follows: The enrichment plant would be situated in an extraterritorial area donated by a host county. The IAEA would obtain sovereign rights over this territory, formalized in an agreement between the host state and the agency (Host State Agreement). In particular, the IAEA would obtain the necessary rights permitting construction of an enrichment plant on this territory. Preferably, the host country itself would not have enrichment capability.

[21] Prior to that, the possibility of building an extraterritorial enrichment plant under IAEA supervision was mentioned in an interview with German Foreign Minister F.-W. Steinmeier in the German newspaper *Handelsblatt*, published on September 18, 2006.

[22] [INFCIRC/727, 2008] and [INFCIRC/735, 2008].

At the same time,[23] a group of interested states, which does not include the host country itself, would set up a joint commercial company to finance, construct, and operate an enrichment plant on this special territory. No single state would be allowed to hold a majority share in this company. The group of states would sign an agreement with the IAEA (MESP Agreement), specifying important framework conditions for the plant. The enrichment technology, i.e., most likely centrifuge technology, would be supplied by one of the existing technology providers on a black-box basis. The IAEA would supervise (regulate) and safeguard the plant. The IAEA would also control a revolving buffer stock of low-enriched uranium that it could distribute when requested by a state, as long as a set of predefined criteria is met.

All participating states would retain the right to develop, construct and run their own enrichment plants.

The geographical location of the plant itself "must be acceptable to the broad majority of the international community." In addition, the country should be characterized, for example, by a reliable infrastructure, good accessibility, and political stability. Additional elements of the proposal are designed to guarantee market neutrality of the arrangement.

The combination of some explicitly defined positive boundary conditions, e.g. the retention of the right to pursue enrichment indigenously, and joint ownership in an enrichment plant, with no single party having a majority in it, could effectively resolve the concerns of some states that fuel-assurance proposals seek to further restrict the rights under Article IV of the NPT or reinforce the current supplier/client-state system. Specifically, if the MESP proposal were successful in bringing together a host country and a group of interested states that would be widely perceived as a genuinely new enrichment supplier, adding diversity to the current system dominated by the United States, Western Europe, and Russia, the project could have a high normative impact—even for third countries not involved in the project.

Establishing a new enrichment plant embedded in a fundamentally new institutional context is necessarily a complex process. In the case of the MESP proposal, several independent parties with fundamentally different roles and interests have to identify themselves and agree to collaborate on such a project. It will be an enormous challenge to coordinate this effort and to align the interests of all project participants, i.e., of the host state, whose participation would be based primarily on the perceived political reward of supporting this project, but which is not directly involved in the enrichment project at all; the group of interested states and their designated new enrichment company, which may or may not have previous experience in operating

[23] Depending on the circumstances, of course, the group of interested states could form first, announce its intention to build a new enrichment plant, and encourage potential host states to signal their interest in participating in a project modeled on the MESP proposal.

fuel cycle facilities; the technology provider, whose interest in the project might be particularly difficult to assure; and, finally, possibly even the IAEA, which is generally supportive of the project but would have to take on a major new task and responsibility.

The MESP proposal, by design, faces a multifaceted "chicken-or-egg" problem because none of the participants can easily take a leading role on its own. One scenario that could move the project forward would be that a country expresses interest in participating in an MESP as the host state. It could then serve as a moderator for further discussions with the IAEA and its member states, during which a group of interested states might form. At this stage, the set of participants might be sufficiently well defined to work out, over time, the detailed framework agreements necessary for the project.

IX. The Way Forward

The debate over the past five years on how to limit national ownership and control of sensitive nuclear fuel-cycle facilities is largely a response to the capability of a growing number of countries to develop uranium enrichment gas centrifuge technology. Even a relatively small enrichment plant with the capacity to enrich uranium to fuel a single standard nuclear power reactor provides the capability to produce annually enough highly enriched uranium for a significant number of weapons. In the case of centrifuge facilities, and in contrast to other enrichment processes, conversion to military use can be done rather quickly. The fact that such plants are also easy to conceal, and thus could be built clandestinely, adds to the concern. This prospect is seen as a challenge to the nonproliferation regime by leading nuclear weapon states and their allies, by non-weapon states seeking both to stem proliferation and to abolish nuclear weapons, and by states and international bodies seeking to promote the peaceful uses of nuclear technology.

This is not the first time that efforts have been made to consider ways to constrain national access to critical nuclear technologies that provide the capability to make fissile materials, the key ingredients in nuclear weapons. The United States sought to retain a complete monopoly on nuclear-weapon-related technologies after World War II. As other states have acquired these weapons, they too have sought to prevent its further spread. Efforts to prevent nuclear proliferation have, however, been made more difficult by the strategic interests of nuclear weapon states in keeping their weapons, and in some cases sharing nuclear technology, materials and knowledge with their allies, by additional states seeking nuclear-weapon capability, and by the application of some of these technologies in producing nuclear electricity. The 1970 nuclear Non-Proliferation Treaty sought to resolve this basic dichotomy by establishing obligations both to negotiate nuclear disarmament and to support the peaceful use of nuclear technology. However, this too has failed to resolve the fundamental problem highlighted in the 1946 Acheson-Lilienthal report of “intrinsically dangerous activities” under national control in an international system characterized by state rivalry, insecurity, and lacking fair, equitable and just collective security mechanisms.

The current debate over internationalization of the nuclear fuel cycle has generated many approaches and proposals. It is important, however, to recognize that the “easy” solutions, which seem feasible in the shorter term and have attracted most of the attention, largely fail to address critical problems, while more far-reaching proposals will be difficult even partially to implement because most countries are satisfied with their existing arrangements. The more visionary proposals have not received much traction because they challenge key aspects of the present international system of states’ rights and privileges.

The twelve specific proposals made so far for moving towards more explicit and formal multinational control and management of the nuclear fuel cycle are mostly supplier-state or nuclear-industry proposals. Some envision a management role for the IAEA. But there is a notable absence of interest among countries that would currently qualify as clients. It is clear that there is not a long list of countries currently asking for uranium enrichment plants or even new enrichment services. This simply reflects the fact that almost all states with a significant reliance on nuclear energy, e.g. states with a significant of domestic nuclear capacity (10 GW or more), already have indigenous enrichment capabilities. Existing or planned enrichment capacities are sufficient to supply fuel for nuclear reactors for at least another two decades, even if total installed nuclear capacity almost doubles by 2030.

Moreover, for most states without uranium enrichment capacity the current market for enriched uranium works, and there is little reason for them to expect these market mechanisms to fail. These states have strong relationships with their suppliers of enriched uranium. New fuel assurance mechanisms would be potentially relevant only to countries that begin to lose trust in the current system or are newcomers to the market. These would be states that are worried about being denied access to enrichment services for political reasons by powerful actors in the international system. These states would also be the most hesitant to rely on fuel assurances, since these assurances would also rely on political guarantees by the same great powers in the international system.

Some of the proposals that seek to strengthen market mechanisms, namely fuel assurances and banks, have a good chance to go forward. As pointed out, however, they may prove to be largely irrelevant because most the main buyers of enriched uranium are satisfied with the current supplier market, or have their own supply, and are therefore unlikely to ever use the services now being developed.

A similar problem limits the utility of proposed fuel assurances that do not confer to the client ownership rights on the enrichment process. Most such fuel-assurance schemes require the client to forego a domestic enrichment capacity and thus explicitly reinforce dependency on the supplier and reinforce the two-tier supplier/client system. Russia's initiative to add additional state-partners to the management of LEU produced by a national plant is a proposal involving ownership rights for recipients of fuel assurances. But this proposal limits clients to a minority stake in the enriched uranium storage facility while Russia retains a majority stake and sole control of the associated enrichment plant. Again, such proposals are likely to move forward, but will be of little long-term value in easing concerns among the very states they seek to target.

Fuel banks and fuel assurances also do not address a second more fundamental problem of the existing structure of the nuclear fuel cycle, the issue of entitlement. Non-weapon states have an internationally recognized legal right to national uranium enrichment and reprocessing capacity. Attempts to push through more formal restrictions on national fuel-cycles while nuclear weapon states keep such facilities and keep their weapons may in fact spur national enrichment projects, rather than preventing them.

Arguments that developing new national fuel cycle capabilities would be expensive compared to relying on the existing international fuel cycle services market may carry little weight. If economics mattered, many countries would not pursue new nuclear programs or continue existing ones. Deploying non-competitive enrichment technology may be seen as a transitional phase before a nation's technology matures, as an issue of investing in building national scientific and technological capacity, and even as the cost of mastering a complex and prestigious technology. Developing this technology also provides a nuclear-weapon option, but, even if it raises suspicions, does not necessarily prove the intent to acquire nuclear weapons.

The German proposal for a MESP offers a model for multinational arrangements for future nuclear fuel-cycle facilities, if any such facilities are needed. It may be considered among the more unrealistic proposals today, but offers a normative vision of a model that might be consistent with a world preparing for nuclear disarmament.

Given that it is unlikely for many large new uranium enrichment plants to be required or constructed over at least the next two decades, and that proposals for fuel banks and fuel assurances do not address basic issues of the supplier/client dependency and of prevailing insecurity about the international system, the debate over multilateral approaches to the fuel cycle could more usefully focus on the conversion of existing national enrichment plants to multinational control and management. There is little incentive, however, for current enrichment providers to cede control of their existing facilities and place them in a new, and initially uncertain, institutional framework. It is hard to see how this could change. Regardless, it would be very important to place all existing plants and those planned or under construction under IAEA safeguards because this would facilitate the implementation of a verified fissile material cutoff treaty (FMCT).

Proposals to place existing enrichment plants under multinational control also avoid a key problem. The plants are on the territory of a nation-state and nothing would prevent nationalization of a multinational facility by the host state. This is an issue of state sovereignty. There are twelve states with enrichment plants, only three of them (Germany, the Netherlands, and Japan) do not have nuclear weapons, and these three are in military alliances with the United States. It is hard to see the international community responding forcibly against a nuclear weapon state or its close allies. The problem of international action is made more difficult still in the case of the five NPT nuclear weapon states, which are permanent members of the Security Council and have veto power.

The challenge for all proposals for internationalization of the nuclear fuel cycle is to recognize and address that the basic problem lies in an unequal international system dominated by nuclear weapon states, enduring national rivalries, state sovereignty, and the uneven but seemingly inevitable technological development of all societies. To be feasible and of enduring value, proposals should not fundamentally rely on reinforcing supplier/client-state distinctions and dependency, limit the exercise of a state’s right to act on its territory, or technology controls. They should seek instead to be based on principles of promoting equity, sharing sovereignty, and furthering nuclear disarmament.

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APPENDIX A

Country	Name/Location	Status	Safeguards	Capacity
Brazil	Resende	und. con.	yes	120
China	Shaanxi	operat.	(yes)	1000*
	Lanzhou 2	operat.	(offered)	500
France	George Besse II	und. con.	(yes)	7500
Germany	Gronau	operat.	yes	4500*
India	Rattehalli	operat.	no	(military)
Iran	Natanz	und. con.	yes	250
Japan	Rokkasho	operat.	yes	1050
Netherlands	Almelo	operat.	yes	3500
Pakistan	Kahuta	operat.	no	(military)
	Chak Jhumra	planned	(offered)	150
Russia	Angarsk	operat.	no	2200†
	Novouralsk	operat.	no	13300†
	Zelenogorsk	operat.	no	7900†
	Seversk	operat.	no	3800†
United Kingdom	Capenhurst	operat.	yes	4000
United States	Piketon, USEC	und. con.	(offered)	3800
	Eunice, Urenco	und. con.	(offered)	3000–5900
	Eagle Rock, Areva	planned	(offered)	3000
	Wilmington, Laser	planned	?	3500–6000

Total enrichment capacity, expected for 2015:	up to 68000
Total light-water-reactor capacity supported:	$\sim$ 520 GWe

Table 2. Enrichment Plants, 2009–2015. Asterisks mark capacities after ongoing or planned expansions are complete. For the end of 2008, we assume a total enrichment capacity in Russia of 27200 tSWU/yr, which is based on the most recent official information quoting 26200 tSWU/yr for the end of 2007 and an annual growth-rate of about 4% [IBR, 2008]. The distribution of capacities among these plants is based on scaling the previously quoted fractional contributions.

APPENDIX B

Why Centrifuges Are Different

It is generally understood that, in the whole process of building nuclear weapons, the step of acquiring significant amounts of weapon-usable fissile material is the most difficult one. For this reason, nonproliferation efforts have focused here as the point of control. The gas centrifuge provides a way of acquiring fissile material while reducing many of the existing implementation costs associated with other routes. As we will briefly discuss below, centrifuges offer a rapid breakout capability compared to other enrichment technologies. In other words, the state can easily convert its peaceful facility to weapon purposes, leaving little or no time for the international community to react. At the same time, clandestine centrifuge plants are difficult to detect. They do not produce significant signatures normally used to detect hidden nuclear facilities, and special signatures specific to centrifuges are probably too weak to be useful for detection at significant distances.

These two characteristics of the modern gas centrifuge, the rapid breakout and the clandestine operation, are difficult to address by safeguards and highlight why centrifuge technology may require fundamentally new approaches to the nuclear fuel cycle.

The Rapid-Breakout Problem

The use of nuclear technologies under national control in a breakout-scenario can never be excluded once the decision has been taken to violate international treaties banning proliferation. The key factor here is the speed with which this can be done, in order to minimize penalties and negative repercussions. Some enrichment technologies are easier and quicker to use for this purpose than others. The breakout potential of centrifuges is a well-known characteristic of the technology and was, in fact, explicitly considered when the original safeguards concept for centrifuge facilities was developed in the early 1980s.[24]

The time required to convert the facility from the production of low-enriched uranium to the production of HEU depends on the particular approach taken. A cascade designed to produce low-enriched uranium for fuel can be re-fed its low-enriched product and begin converting it to highly enriched uranium (HEU) suitable for weapons use in a matter of days—a procedure called batch recycling. Alternatively, the machines can be reconfigured into a narrower but longer cascade with more

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[24] Centrifuges have a small inventory hold-up and, therefore, a short equilibrium time. In order to address the specific safeguards challenges of centrifuge technology, the limited-frequency unannounced access (LFUA) concept was developed.

stages, a process which requires additional time before HEU production can begin (possibly several weeks), but which is more efficient than batch recycling. Simulations of centrifuge-cascade performance demonstrate the credibility of these options in a breakout scenario using centrifuge technology [Glaser, 2008]. In other words, if the available enrichment capacity is sufficient, a country has also a good chance to produce weapon-quantities of material before there is sufficient time to respond politically. Even a small enrichment plant, such as the ones that Iran proposes to build at Natanz, which is sized to fuel only a single power reactor, could make enough HEU for tens of bombs a year—or if pre-enriched feed material (LEU) is available, could produce enough weapon-grade uranium for four bombs in a little more than a week.

The Clandestine Problem

A country could try to build a clandestine centrifuge plant hoping to escape detection altogether. Classically, there are a number of ways to detect clandestine nuclear activities,[25] but the publicly available information suggests that there is no practical method of detecting clandestine centrifuge plants or their supporting fuel-cycle facilities. This makes centrifuges the only mainstream fuel-cycle technology capable of producing weapon-usable fissile material without a significant possibility (or risk) for detection. The clandestine option, and to a lesser extent the rapid-breakout option, are already concerns—but they would be even more so, were a rapid expansion in the use of nuclear energy to occur in the coming decades.

Traditional safeguards were not designed for the detection of clandestine plants. They may be able to infer the existence of such plants by tracking material flows (namely uranium-hexafluoride, UF_6) upstream of the facility, provided there is no covert production in parallel. However, the agency has no way of detecting the existence of a completely parallel, undeclared "fuel-cycle" dedicated to the production of nuclear weapons. Because of this, safeguards do not protect against the replication of centrifuge technology from declared to undeclared facilities. As long as states can replicate their technology in this way, they are able to reduce or remove the political cost associated with early detection. This aspect, of course, is one relevant consideration in the effort to discourage additional states to develop enrichment technologies because these capabilities could then also raise concerns about the existence of clandestine programs besides declared ones.

[25] These include: optical imaging (using satellites), thermal-infrared imaging, and effluent monitoring. For centrifuges, one can also consider electromagnetic emanations generated by the centrifuge electronics. All of these seek to detect centrifuges directly by their signatures.

REFERENCES

[Acheson and Lilienthal, 1946] C. I. Barnard, J. R. Oppenheimer, C. A. Thomas, H. A. Winne, and D. E. Lilienthal (Chairman of the Board of Consultants), A Report on the International Control of Atomic Energy; Prepared for the Secretary of State's Committee on Atomic Energy (known as: The Acheson-Lilienthal Report), Washington, DC, 1946, www.ipfmlibrary.org/ach46.pdf.

[Braun, 2007] C. Braun, *Nuclear Fuel Assurances: Proposals and Prospects,* Presentation at the 4th Plenary Meeting of the International Panel on Fissile Materials, London, October 12, 2007.

[Chayes and Lewis, 1980] A. Chayes and W. B. Lewis (eds.), *International Arrangements for Nuclear Fuel Reprocessing*, Ballinger, Cambridge, MA, 1977.

[Durst, 2008] P. C. Durst, "An Analysis of Advanced Safeguards Approaches for New Large-scale Uranium Enrichment Plants," *49th INMM Annual Meeting, Institute of Nuclear Materials Management*, Nashville, TN, 13–17 July 2008.

[ElBaradei, 2003] M. ElBaradei, "Towards a safer world," *The Economist*, 16 October 2003.

[Forden and Thomson, 2007] G. Forden and J. Thomson, *Iran as a Pioneer Case for Multilateral Arrangements,* Massachusetts Institute of Technology, September 2006 (revised May 2007).

[GFMR, 2006] *Global Fissile Material Report 2006,* International Panel on Fissile Materials, Princeton, NJ, www.ipfmlibrary.org/gfmr06.pdf.

[GFMR, 2007] *Global Fissile Material Report 2007,* International Panel on Fissile Materials, Princeton, NJ, www.ipfmlibrary.org/gfmr07.pdf.

[GFMR, 2008] *Global Fissile Material Report 2008,* International Panel on Fissile Materials, Princeton, NJ, www.ipfmlibrary.org/gfmr08.pdf.

[Glaser, 2008] A. Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation," *Science & Global Security,* 16(1–2), 2008, pp. 1-25.

[Grigoryev, 2008] A. Grigoryev (General Director, JSC IUEC), "International Uranium Enrichment Center (JSC IUEC)," *Technical Meeting: Expanding Nuclear Power to New States: Defining Needs and Exploring Means to Facilitate Success,* International Working Group, Landau Network Centro Volta (IWG-LNCV), Lago di Como, Italy, 10–14 June 2008.

[Holgate, 2008] L. Holgate, "Fuel Assurances: IAEA Fuel Bank," *49th INMM Annual Meeting, Institute of Nuclear Materials Management*, Nashville, TN, 13–17 July 2008.

[IAEA, 2008] International Atomic Energy Agency, *Energy, Electricity and Nuclear Power Estimates for the Period up to 2030,* Reference, Data Series No. 1, 2008 Edition, August 2008.

[IAEA-DG, 2005] Statement of the IAEA Director General M. ElBaradei, *Reflections On Nuclear Challenges Today,* International Institute for Strategic Studies, Alistair Buchan Lecture, London, 6 December 2005.

[IAEA-DG, 2007] Statement of the IAEA Director General M. ElBaradei to the Board of Governors, Vienna, Austria, 11 June 2007.

[IAEA-DG, 2008] Statement of the IAEA Director General M. ElBaradei to the Sixty-Third Regular Session of the United Nations General Assembly, New York, 28 October 2008.

[IBR, 2008] *Russian Enrichment Industry State & Prospects of Development, Annual Report 2007,* International Business Relations Corporation (IBR), Department of Nuclear Power Engineering & Nuclear Fuel Cycle, Moscow, 2008, www.ibr.ru.

[INFCIRC/254, 2007] *Communication Received from the Permanent Mission of Brazil regarding Certain Member States' Guidelines for the Export of Nuclear Material, Equipment and Technology,* INFCIRC/254, Rev. 9, Part 1, International Atomic Energy Agency, Vienna, Austria, 7 November 2007.

[INFCIRC/640, 2005] *Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report submitted to the Director General of the International Atomic Energy Agency,* INFCIRC/640, International Atomic Energy Agency, Vienna, Austria, 22 February 2005.

[INFCIRC/659, 2006] *Communication dated 28 September 2005 from the Permanent Mission of the United States of America to the Agency,* INFCIRC/659, International Atomic Energy Agency, Vienna, Austria, 29 September 2005.

[INFCIRC/667, 2006] *Communication received from the Resident Representative of the Russian Federation to the Agency transmitting the text of the Statement of the President of the Russian Federation on the Peaceful Use of Nuclear Energy,* INFCIRC/667, International Atomic Energy Agency, Vienna, Austria, 8 February 2006.

[INFCIRC/704, 2007] *Communication received from the Resident Representative of Germany to the IAEA with regard to the German proposal on the Multilateralization of the Nuclear Fuel Cycle,* INFCIRC/704, International Atomic Energy Agency, Vienna, Austria, 4 May 2007.

[INFCIRC/708, 2007] *Communication received from the Resident Representative of the Russian Federation to the IAEA on the Establishment, Structure and Operation of the International Uranium Enrichment Centre,* INFCIRC/708, International Atomic Energy Agency, Vienna, Austria, 8 June 2007.

[INFCIRC/727, 2008] *Communication dated 30 May 2008 received from the Permanent Mission of the Federal Republic of Germany to the Agency with regard to the German proposal for a Multilateral Enrichment Sanctuary Project,* INFCIRC/727, International Atomic Energy Agency, Vienna, Austria, 30 May 2008.

[INFCIRC/735, 2008] *Communication dated 22 September 2008 received from the Permanent Mission of Germany to the Agency regarding the German proposal on a Multilateral Enrichment Sanctuary Project,* INFCIRC/735, International Atomic Energy Agency, Vienna, Austria, 25 September 2008.

[Joseph, 2005] L. Joseph, *Multilateral Approaches to the Nuclear Fuel Cycle,* Issues Brief, Lowy Institute for International Policy, Sydney, Australia, August 2005.

[Kemp and Glaser, 2007] R. S. Kemp and A. Glaser, "The Gas Centrifuge and the Nonproliferation of Nuclear Weapons," pp. 88–95 in Shi Zeng (ed.), *Proceedings of the Ninth International Workshop on Separation Phenomena in Liquids and Gases (SPLG),* 18–21 September 2006, Beijing, China, Tshinghua University Press, 2007.

[Krass et al., 1983] A. Krass, P. Boskma, B. Elzen, and W. A. Smit, *Uranium Enrichment and Nuclear Weapon Proliferation,* Stockholm International Peace Research Institute (SIPRI). Taylor & Francis Ltd, London and New York, 1983, available at books.sipri.org.

[NAS, 2008] U.S. and Russian Committees on the Internationalization of the Civilian Nuclear Fuel Cycle, *Internationalization of the Nuclear Fuel Cycle: Goals, Strategies, and Challenges*, U.S. and Russian Academies of Sciences, Washington, D.C., 2008.

[Nunn, 2006] Statement by S. Nunn at the 50th IAEA General Conference Special Event, *New Framework for the Utilization of Nuclear Energy in the 21st Century: Assurances of Supply and Nonproliferation,* Vienna, Austria, September 19, 2006.

[Oppenheimer, 1946] J. R. Oppenheimer, "The International Control of Atomic Energy," *Bulletin of the Atomic Scientists,* 1(12), June 1946, www.ipfmlibrary.org/opp46.pdf.

[Rauf and Simpson, 2004] T. Rauf and F. Simpson, "The Nuclear Fuel Cycle: Is it Time for a Multilateral Approach," *Arms Control Today,* 38(7), December 2004, pp. 17–21.

[Rauf and Vovchok 2008] T. Rauf and Z. Vovchock, "Fuel for Thought," *IAEA Bulletin,* 49(2), March 2008, pp. 59–63.

[Ruchkin and Loginov, 2006] S. V. Ruchkin and V. Y. Loginov, "Securing the Nuclear Fuel Cycle," *IAEA Information Bulletin,* 48(1), September 2006, pp. 24–26.

[Simpson, 2008] F. Simpson, "Reforming the Nuclear Fuel Cycle: Time is Running Out," *Arms Control Today*, 38(7), September 2008, pp. 12–19.

[SIPRI, 1980] Stockholm International Peace Research Institute, *Internationalization to Prevent the Spread of Nuclear Weapons,* Taylor & Francis, London, 1980.

[Squassoni, 2008] S. Squassoni, "Looking Back: The 1978 Nuclear Nonproliferation Act," *Arms Control Today,* 38(10), December 2008, pp. 64–67.

[Yudin, 2009] Y. Yudin, *Multilateralization of the Nuclear Fuel Cycle: Assessing the Existing Proposals*, United Nations Institute for Disarmament Research (UNIDIR), forthcoming.