Chapter 8 — Fuel Cycles and Nonproliferation

The Nuclear Non-Proliferation Treaty (NPT), which came into force in 1970, underpinned a largely successful international nonproliferation regime for several decades. It achieved this by balancing interests through three principal commitments:

- agreement by non-nuclear-weapons states to refrain from any attempt to develop or acquire nuclear weapons and to accept internationally administered safeguards on nuclear facilities;
- agreement by the nuclear weapons states to move in the direction of nuclear disarmament;
- agreement by all to cooperate on the peaceful use of nuclear technology, including global nuclear power development.

However, the last decade has proved challenging, with all three pillars of the NPT facing a new dynamic.

In regard to the first pillar, programs in Libya and North Korea and the extent of the A. Q. Khan network centered in Pakistan were revealed. While Libya renounced its program, North Korea withdrew from the NPT and tested nuclear explosives. India, a non-signatory to the NPT, received a waiver from the Nuclear Suppliers Group to engage in nuclear commerce. Iran, while claiming that its program is for peaceful purposes, has hidden uranium enrichment projects, suggesting to many a nuclear weapons motivation.

The reach of international terrorist organizations also came into sharper focus in this decade, starting with the events of 9/11. Al Qaeda has explicitly expressed its desire to acquire nuclear weapons. This has reenergized the disarmament discussion by raising the question as to whether the risks of having a nuclear weapon or weapons-usable fissile material fall into the hands of well-financed terrorists outweigh the post-Cold War security benefits of nuclear weapons and weapons-usable materials stockpiles.¹

At the same time, an expectation grew that nuclear power would, after a period of very slow growth worldwide, start on a new trajectory of major expansion, largely outside the industrialized countries that currently operate most of the nuclear fleet. For example, in the Mideast alone, Iran, UAE, Jordan, Saudi Arabia, Egypt, Turkey, and Syria have all expressed intent to pursue nuclear power. To the extent that these countries construct and operate nuclear power reactors without engaging in uranium enrichment or plutonium separation from irradiated fuel, the proliferation risks are minimal and assistance from the nuclear suppliers in line with the NPT is expected. The concern is that the nascent nuclear
power program might be used, as is being done in Iran, to justify fuel cycle development. The primary obstacle to a nuclear weapons program remains access to the needed fissile material – high enriched uranium (HEU) and separated plutonium. With enrichment or reprocessing capability, even one obtained as a legitimate activity under the NPT, the risks are for a “breakout capacity” to produce weapons material or for clandestine facilities based upon the technology and experience gained in the fuel cycle. While the Iranian situation is of the greatest concern with regard to proliferation related directly to nuclear power development, the renewed commitment to enrichment in Brazil and the commissioning of a large commercial reprocessing plant in Japan have added to a sense that fuel cycle facilities may be spreading geographically along with the anticipated “nuclear renaissance”. Such an outcome would present a fundamental challenge to U.S. nonproliferation policy, but is nevertheless interpreted by a large number of non-nuclear signatories to the NPT as consistent with the NPT so long as full scope safeguards are implemented. The question is on the table as to whether or not the NPT needs reexamination in order to address this “threshold state” concern that a country could reach the brink of a nuclear weapons program with domestic activities and fuel cycle assistance permitted under the NPT. The threshold state phenomenon can significantly impact geopolitical realities even if the country does not cross the threshold, as evidenced in the Middle East.

In this report, we focus only on the proliferation risks associated with international fuel cycle development and on their mitigation through institutional and technical means. Clearly, the issues posed by clandestine nuclear weapons programs outside the nuclear power sector are of great importance, but they are outside the scope of our fuel cycle analysis. Our discussion is framed by the conviction that, at least for the near to intermediate term, the U.S. focus should be on approaches that are within the existing NPT framework, that are based on economic incentives, that recognize the diminished role of the U.S. as nuclear supplier to the world, and that entail U.S. participation in international fuel cycle development.

**CONTEXT**

There are two issues of context that deserve some elaboration for a discussion of proliferation and the fuel cycle: the nature of weapons-usable fissionable materials in the fuel cycle, and the likely extent of nuclear power international deployment over the next several decades.

It has been stated often and by many that acquisition of nuclear weapons usable fissionable material, HEU or plutonium, is the most significant challenge for developing a nuclear explosive. This is correct. Consequently, the fuel cycle facilities of concern are enrichment plants and reprocessing facilities. The former employ the same basic technology for producing low-enriched uranium (LEU) for LWR fuel (with enrichments typically in the 4-5% range) or HEU for weapons (technically defined as U235 enrichment above 20%, but in reality greater than 90% for weapons programs). The technologies in commercial use today, gaseous diffusion or centrifuges, are relatively difficult to master since they work on physical separation of isotopes with less than 1% mass difference (the separation is performed on the UF$_6$ molecule). The technologies are classified in all countries that have developed them, although leakage is known to have occurred through the Khan network tracing back to stolen early European centrifuge designs.
On the other hand, reprocessing for plutonium separation from SNF is a chemical process and, while high safety and health standards are needed for large throughput commercial operation, the basic approach is well known. There is no isotopic separation, just chemical separation of different elements. For nuclear explosive use, different plutonium isotopic mixtures have very similar critical masses. Therefore, physical safeguards and associated accounting schemes for SNF and separated plutonium are essential to the nonproliferation regime.

However, there is sometimes confusion about the quality of the fissionable material produced in the fuel cycle with respect to weapons usability. While having at least a critical mass of material is essential, other characteristics are important as well. The issues revolve around neutron background and heat generation for different isotopic mixtures. The importance of minimizing neutron background for high yield nuclear explosives is already discussed in the Los Alamos Primer that presents the original lectures delivered to the wartime Los Alamos design team. High heat levels complicate design for use of the chemical explosives used to detonate the weapon.

HEU has the best of both characteristics – low neutron background and heat - and thus poses the easier design route to a nuclear explosive. A great deal of the work needed to reach 90% enrichment has already been accomplished in reaching 5%, so high standards of control on LEU and on enrichment technology are needed.

The dominant fissile isotope of plutonium is Pu239, bred in a two step process by neutron capture on U-238 as the LWR LEU fuel is utilized. Weapons grade plutonium is predominantly made up of this isotope (over 90%). However, in a commercial reactor, the fuel remains in the core for several years and many other plutonium isotopes are produced in significant quantities through sequential neutron capture. In particular, the even isotopes (Pu-238,240,242) produce large neutron backgrounds and considerable heat, and there are significant differences for different fuel cycles.

Figure 8.1 displays the spontaneous neutron and heat levels for six materials in different fuel cycles, in each case normalized to one kilogram of plutonium. Weapons-grade plutonium has very low heat and few neutron emissions; it is produced for dedicated weapons programs in dedicated reactors with low fuel burnup to minimize production of higher isotopes. Its desirability for weapons use compared with commercial fuel is evident in the figures.

The diamond closest to the origin shows the heat and neutron emissions of a kg of plutonium separated from LWR SNF in once-through operation. Both heat and neutron backgrounds are substantially greater than those for weapons-grade. However, the result for the full TRU content, shown as “1 kg Pu plus all other actinides, discharged from a LWR” is seen in the bottom figure to be dramatically greater. Including the fission products raises the heat level substantially. The high amounts of heat and neutrons are responsible for the self-protecting nature of the SNF. Of course, this SNF cannot be used for a nuclear explosive (as opposed to “dirty bomb”) without separation of the plutonium.

MOX(Pu) corresponds to the case of once-recycled MOX. It has appreciably higher heat and neutron emissions compared to once-through LWR Pu, although not qualitatively different. The once-through fast reactor Pu result is similar. However, it is important to note that the neutron characteristics are important not only for judging weapons usability but also for evaluating fuel refabrication for closed fuel cycles. Clearly the increased background
Figure 8.1 Weapons-Usability Characteristics of Nuclear Fuels

Reactor Fuel Materials: Magnified View

Note that dotted arrows connect endpoints; they do not represent the true decay path over 100 years.

Source: Heat and spontaneous neutron emissions from weapons-grade plutonium, spent fuel from LWR (4.2% enrichment, 51 MWd/kg burnup) and spent fuel from a Fast Reactor (FR - conversion ratio 0.5, "equilibrium" fuel pass). For reference, HEU: 2.3 n/sec-kg, 5.3E-05 W/kg; WG Pu: 1.0E+05 n/sec-kg, 2.3 W/kg.

raises the cost, with the need for worker health and safety being paramount, leading to fully remote operation and maintenance. While we cannot be quantitative here in characterizing weapons usability, the MOX materials are considered to be of proliferation concern. It must be kept in mind that high yield reliable nuclear weapons are not required in many contexts: a crude lower nuclear yield device can be effective for national aims in regional contexts and for terrorist groups. This lower standard for nuclear explosives means that lower-grade fissionable materials can be used.

Keeping all the transuranics (TRU) associated with the Pu extracted from LWR irradiated fuel (i.e., including the minor actinides) appreciably increases both heat and neutron background. Perhaps of more interest, the heat and neutron emissions for an “equilibrium” full TRU recycle in a fast reactor are even larger (ten years after removal from the reactor). This would pose an extraordinary challenge for misuse in a nuclear weapon, effectively requiring further partitioning.

Another important issue is the fuel characteristic after a considerable storage time. The vectors on Figure 8.1 show what happens after one hundred years. Clearly the once through LWR fuel loses a considerable part of its radiation barrier, emphasizing the need for continuing safeguards. The fast reactor “equilibrium” TRU fuel still retains a very substantial neutron emissions background even after a hundred years.

The conclusion from this venture into plutonium isotopes is that separation of plutonium from SNF provides material that is clearly not as desirable as weapons grade but that nevertheless represents a major risk unless safeguards, accountability, and security are all at the highest standards at all locations where such material is stored. This has taken on additional gravity in the context of increasingly sophisticated terrorist groups with international reach and ambitions. The characteristics of separated TRU on the other hand, particularly that under discussion for closed fast reactor fuel cycles, is far less desirable and usable for explosives. However, for the same reasons, it will pose a major challenge for safe and economic fuel cycle operations.

Another contextual issue is the anticipated spread of nuclear power and its attendant proliferation concerns. These concerns are centered mostly on countries that are just beginning or just thinking about building nuclear power programs. The programs will be small for quite some time, relative to the scale at which investments in fuel cycle facilities make economic sense. Of course, the growth trajectory for nuclear power is unknown: a commitment to mitigating CO2 emissions could still spur a major expansion, but the high capital costs or a serious nuclear accident could dampen such prospects substantially. The 2003 MIT Future of Nuclear Power report constructed a scenario of what a one terawatt global nuclear deployment might look like in 2050. Even in such a growth scenario, the result was that about 80% of the deployed nuclear power would still be in the major nuclear states in that time frame. It is important to keep this in mind in contemplating the scale of the proliferation challenge associated with fuel cycle development: the challenges are substantial, but are likely to be relatively few in number. Today, the trajectory for nuclear power growth is below the terawatt path.
INSTITUTIONAL APPROACHES TO FUEL CYCLE PROLIFERATION CHALLENGES

The principal objective of international fuel cycle nonproliferation policy is limitation of the spread of enrichment and reprocessing facilities and technology, most especially in regions of geopolitical concern. For the last quarter of the 20th century, these objectives were largely met. The Nuclear Suppliers Group (NSG), formed after the Indian nuclear explosive test in 1974, grew to treat such facilities differently from reactors and fuel supply. This has stemmed from an interpretation of the NPT by the NSG that there is not a requirement to assist with such technologies and, to a very large degree, a lack of interest by non-NSG members to acquire them.6 In the early years of the NSG, agreements such as that for German supply of end-to-end fuel cycle capability to Brazil were not implemented.

During this period, the United States played a dominant role. Among many factors underpinning this role was the leading U.S. position in the global nuclear technology business. The nearly forty year hiatus in ordering new nuclear plants in the U.S. has taken its toll on national capacity, and many other countries now have effective and competitive nuclear industries. The days of a near monopoly by U.S. companies on nuclear technology will not return. Indeed, it will be a challenge to reestablish a major position as even more players emerge on the international market, such as Russia, South Korea, and China. Nonproliferation policies with regard to the fuel cycle need to evolve in step with these commercial realities.

Instead, the United States has, in recent years, given increased emphasis to limiting the spread of enrichment and reprocessing through its bilateral agreements on the Peaceful Uses of Atomic Energy (the so-called 123 agreements). It is a very bad idea to adopt this as a universal approach. The UAE included a binding commitment to abstain from enrichment and reprocessing in its 123 agreement with the United States; this is a welcome statement of leadership by the UAE. Nevertheless, it is unrealistic and unproductive to expect that this can be extended universally. First the United States already has executed many 123 agreements without this condition, including in the Middle East (Egypt and Turkey), and it cannot be expected that the condition would be negotiated into renewals. Second, the Department of State has suggested that the condition would be applicable in the Middle East, with different regions treated differently. Yet Jordan and Saudi Arabia, for example, have already signed nuclear cooperation agreements with major supplier countries without such a condition. While the U.S. negotiated the UAE agreement with the fuel cycle restrictions, South Korea successfully won the bid for construction of the first nuclear power reactors in the UAE and indeed in the region. The other members of the NSG show no indication of formalizing restrictions that go beyond the NPT in their cooperative nuclear agreements. The U.S. approach is ad hoc and does not add up to a strong policy.

A broad-based attempt to impose abstention through bilateral cooperative agreements will have at least two negative impacts. It raises the temperature on how Article IV of the NPT is interpreted, and it will serve to further diminish the U.S. role in international nuclear commerce if it blocks entry into additional 123 agreements or impedes agreement renewals. This will serve neither security nor economic interests. And the ability of the U.S. to improve its position in that global market, as already stated, faces enormous challenges of rebuilding both a domestic market and a nuclear industrial capacity as a platform for international sales and influence.
At least for the near term, economic incentives should be aligned with security goals, and a focus on a multilateral NSG approach based on fuel cycle economic realities has a higher probability of success. We have seen that the economically most sensible fuel cycle approach for “green field” nuclear power programs is, and will remain for some time, LWRs for electricity with long term storage of first-pass irradiated fuel. This supports an approach based on economic incentive for limiting the spread of reprocessing, at least for several decades. For fresh LWR fuel, limiting the spread of enrichment will require an economic and secure supply. For small nuclear power deployments, as is the case for green field programs, the economic choice is clearly purchase of fuel on the international competitive market.

The SNF will eventually require geological isolation of some or all of its constituents, depending on whether SNF partitioning and/or recycling of plutonium/TRU is implemented in the long term. Experience suggests that establishing national geological isolation programs requires substantial resources and a political process that can be sustained over a very long period. Avoiding this challenge carries substantial incentive for small nuclear programs. This suggests a fuel leasing approach: the nuclear fuel supplier retains ownership of the fuel and removes the SNF after a short cooling period back to the country of origin or possibly to a third country that establishes an international geological repository. Clearly the challenge that faces such an approach today is the willingness of the fuel supplier (or third party country) to accept the SNF without requiring return of the constituents: in other words, to lease the fuel rather than sell the fuel and provide storage/reprocessing services. The fuel supplier would of course treat the returned SNF as it does its own, ideally long term storage for many decades until the optimum fuel cycle path is determined. Without minimizing the difficulty of SNF return, for this is indeed a major challenge, we stress that the nuclear growth scenario described above suggests that the returned SNF in question would likely be a small fraction of the SNF handled in the fuel supplier’s domestic program. In the U.S., irradiated fuel from research reactors has already been returned for nonproliferation reasons.

One specific approach along these lines has been termed the Assured Nuclear Fuel Services Initiative (ANFSI). It specifically suggests that the leasing scheme be implemented between commercial entities negotiating commercial contracts for fuel-service transactions. Importantly, the contracts should, as is customary, have a fixed term, say ten years, during which time the country leasing the fuel would agree to abstain from developing either enrichment or reprocessing capability. There is a commercial logic to this abstention in that the leasing country is not developing the capacity to compete against the supplier during the contract period, in return for the benefits of economic supply of fresh fuel and elimination of the waste challenge. The IAEA would apply safeguards to such transactions, ideally in the framework of the Additional Protocol (see box). Of course the contracts can be renewed for another period. The benefits of securing the nonproliferation advantages of fuel leasing for a material period such as ten years should not be underestimated, rather than chasing the illusion that countries will by treaty or long term binding agreement give up “rights” that they insist are part and parcel of the NPT deal. Frankly, this will not happen except perhaps in isolated cases, as should be evident from the experience of the last decade. ANFSI does
not contemplate reopening the NPT for a contentious negotiation that is unlikely to succeed, especially in the absence of a consistent position even among the Nuclear Suppliers Group (NSG). It is a voluntary approach based on economic incentive and the notion that a spotlight will be placed on countries that decline an obviously good deal. The recent international approach to Iran provides some hope that a spotlight can be effective in turning up the heat when proliferation concerns are evident.

ANFSI contemplates going further in terms of economic incentive for fresh fuel purchase on the international market. Enrichment services are a small part of nuclear power costs, a fraction of a cent per kWh of electricity. Even if the enrichment costs were fully subsidized for early stage nuclear power programs as part of a non-proliferation-motivated incentive to avoid enrichment development during the contract period, the total costs would be less than a billion dollars per year for the next couple of decades. We are not advocating such a direct subsidy of the full enrichment costs, but it is useful to see that the scale is small, so there can be many attractive ways to encourage participation in the leasing approach through economic incentive in fuel supply (in addition to the benefit on the waste management side). In addition to direct approaches (credits, price discounts, insurance and export financing), indirect approaches such as a link to carbon credits for avoided emissions could be pursued.9

There has been much discussion about internationalizing fuel cycle facilities, going back over sixty years and given some renewed impetus in 2005 by the IAEA (see Table 8.1 for a selective history). Of course, such proposals have made little progress in the face of national prerogatives, with the possible exception of the recent attempt to establish a fuel bank for security of supply for those without enrichment capacity. This is not in conflict with ANFSI. For example, enrichment plants with international shared ownership and IAEA safeguards could be the entity entering into the commercial contracts, possibly in competition with private companies. URENCO, originally a German, Dutch, British consortium, was established through a limited form of international ownership. This would be a plus in regards to security of fresh fuel supply and far preferable to a profusion of national enrichment facilities, especially if combined with a robust international fuel bank. However, it would not address the most challenging aspect of fuel leasing, return of the SNF and eventual geological isolation of HLW, and indeed could even complicate it. The repositories still need to be in sovereign countries, and a commercial attraction of fuel leasing is revenue enhancement in supplier countries.
Clearly ANFSI and other fuel leasing approaches face some core challenges: security of supply, technological leadership, and political asymmetry.

Security of supply: As already noted, international enrichment facilities would provide a degree of security of supply, but other approaches do so as well. Government-to-government assurances that fuel services will not be withheld for any reason other than a material violation of international non-proliferation commitments under the NPT and IAEA safeguards agreements would backstop commercial contracts. Even this will still need to be backed by a firm multilateral guarantee. In particular, the IAEA, with assistance from the Nuclear Threat Initiative and several countries, has established a fuel bank to address this. The IAEA should be authorized by the United Nations Security Council to assume a guarantor role through the fuel bank or fuel reserve, ensuring access to the contracted fuel services so long as nonproliferation commitments are observed. The Additional Protocol is important in this regard. The IAEA role could be extended with respect to nuclear fuel supply to a coordinating role analogous to that of the International Energy Agency in cases of supply disruption in the oil markets. Further, the long term contracts with fixed prices dispel price volatility concerns during the contract term.

Technological leadership: Some countries argue that a fuel leasing arrangement combined with the commitment to abstain from enrichment and reprocessing will prevent development of indigenous technological leadership. These arguments are not compelling for a ten year contract period – and probably not for periods beyond that. First, the technologies in question are not likely to form the basis of a major contribution to the national economy, especially given that fuel cycle evolution is not clear at the moment and fuel services represent a small part of the cost of nuclear power. The spillover effects of national investments

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Table 8.1 A Selective History of International Nonproliferation Initiatives

<table>
<thead>
<tr>
<th>DATE</th>
<th>INITIATIVE</th>
<th>OBJECTIVES</th>
<th>RESULT</th>
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<tbody>
<tr>
<td>1946</td>
<td>Baruch Plan</td>
<td>U.S. proposal for intense oversight/international management of the civilian nuclear fuel cycle</td>
<td>Vetted by Soviets, who oppose facility inspections and giving up a U.N. veto on atomic matters</td>
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<td>1977</td>
<td>Regional Nuclear Fuel Cycle Centers Study</td>
<td>Study initiated by the IAEA to assess feasibility of establishing multinational fuel cycle facilities</td>
<td>Study finds that facilities are technically feasible, but too many challenges exist with tech transfer and providing security of supply</td>
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<tr>
<td>1975-1980</td>
<td>International Nuclear Fuel Cycle Evaluation</td>
<td>Study initiated by the U.S., conducted by the IAEA and other countries and orgs - intended to address the technical connections between fuel cycles and weapons</td>
<td>Study finds that no technical solution is adequate; process contributes to rollback of nuclear supplier intentions to provide enrichment/reprocessing technology (e.g., Germany to Brazil)</td>
</tr>
<tr>
<td>1980–1987</td>
<td>Committee on Assurance of Supply</td>
<td>IAEA group addresses fuel banks and other supply strategies</td>
<td>–</td>
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<tr>
<td>2005</td>
<td>Multilateral Approaches to the Fuel Cycle</td>
<td>IAEA Director General requests a report describing options and outlooks for MNAs</td>
<td>Impact includes some increased interest in multinational fuel cycle arrangements</td>
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<tr>
<td>2006</td>
<td>NTI commits $50M for bank</td>
<td>Drum up interest and matching funds for an LEU bank</td>
<td>Total $150M goal reached with Kuwait’s donation in March 2009</td>
</tr>
<tr>
<td>March 2010</td>
<td>IAEA and Russia sign fuel bank agreement</td>
<td>Establish a 120-MT LEU stockpile in Angarsk, Russian; IAEA will control sales from the stockpile</td>
<td>Russian authorities declare fuel bank operational in Dec. 2010</td>
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in technology innovation are likely to be much greater in other sectors. Further, there is no permanent rejection in ANFSI of the “birthright” to develop enrichment and reprocessing technology, just a decision to abstain for a fixed contract period as a judgment of net economic and political benefit, during a period in which the future of nuclear power and fuel cycle development become clearer. Finally, those agreeing to the leasing conditions should be admitted, without additional political tests, to an international R&D program on advanced reactors that could be central to future fuel cycles. This cooperation would not extend to enrichment or reprocessing technologies and would require participation in the Additional Protocol. The R&D program should have a period of laboratory research, conceptual design, and modeling and simulation rather than near-term large-scale demonstration facilities.

Asymmetry and incentives: The criticism of creating another set of “haves” and “have-nots” layered on top of the NPT distinction of nuclear weapons states has been leveled at fuel leasing approaches. However, ANFSI calls for voluntary entry into fixed-term contracts with both economic and political incentives. The nonproliferation benefits include lock-in for the contract period of commitments to abstain from enrichment and reprocessing technology development and a spotlight on countries with nascent nuclear power programs that choose not to gain the economic and political benefits offered.

Indeed, the biggest asymmetry in ANFSI is really in the other direction: the suppliers take full responsibility for waste management, with the evident domestic political challenges of winning public support in the interests of nonproliferation policy. The saving grace here may be the relatively small increment in waste management responsibilities in most cases. As a second-best option, the supplier state should agree to retrieve the SNF for long term storage and to return no more than the fission products (within reasonable specifications for TRU), no earlier than one century later; Russia is moving in this direction. If the supplier state is pursuing a closed fuel cycle within that period, there is no issue. If not, the choice would be SNF disposal or partitioning of the fission products and disposal of the TRU through transmutation, mixing with HLW, deep boreholes, or some other secure means; with a functioning repository program at that time, the direct SNF disposal is likely to be the choice in the absence of a closed fuel cycle. Of course, if the supplier states cannot bring themselves to take back the SNF in the context of publicly accepted waste management systems, the path will be open to a multiplicity of reprocessing operations some time in the future, with its attendant proliferation risks.

Clearly, ANFSI and other fuel leasing approaches face considerable challenges for implementation. Indeed, the recent history with regard to Iran and Brazil highlights this fact. Both situations, for very different reasons, would logically be amenable to an ANFSI-like approach, but the U.S. and international responses have not been shaped by the economic arguments in concert with declared nonproliferation objectives of all parties. Instead, the very different perception about national intentions in these two cases has led to diametrically opposite responses that weaken the prospect for a consistent international regime.

In summary, we recommend that the United States pursue its fuel cycle nonproliferation agenda by continuing to emphasize cohesion within the NSG and by providing economic and political incentives for commitments to abstention from enrichment and reprocessing technology development and deployment in nascent nuclear power programs. The flip side of the incentives coin is a focus on those countries that reject an attractive offer and the resulting enhanced opportunity for targeted multilateral approaches towards the fuel cycle activities of these countries.
TECHNICAL APPROACHES TO FUEL CYCLE PROLIFERATION CHALLENGES

Any end-to-end nuclear fuel cycle can contribute to proliferation in that it requires enrichment capacity and/or produces plutonium. The principal barriers to proliferation are institutional: most important are the commitments of most sovereign nations to not acquire or develop nuclear weapons based upon self-interest, and negotiated international agreements and implementing agencies, such as the NPT and the IAEA, respectively. Nevertheless, technical means can contribute significantly to the implementation of nonproliferation norms, enhancing transparency for the international community, confirming security of nuclear materials for operators, and raising the bar against diversion. We shall touch on a few topics directly relevant to nuclear fuel cycle development: technology choices guided by proliferation resistance criteria, and technical safeguards.

Fuel cycle choices

Plutonium is the weapons usable material produced in the current fuel cycle, since it is created from the dominant uranium isotope in LEU fuel, U-238, in the neutron environment of the reactor core. Figure 8.1 spells out the technical dimensions of the materials issue. One proliferation-resistant choice is the LWR once-through fuel cycle since the plutonium remains in a very high radiation environment. The least attractive cycle for proliferation resistance is the MOX/PUREX cycle in which plutonium is extracted from irradiated fuel for recycling. We saw in Chapter 6 that this fuel cycle does not have economic or waste management benefits, but it has nevertheless been practiced for decades by some countries with sunk costs in large reprocessing facilities (sometimes constructed for dual military-civilian purposes). Unfortunately more than 250 metric tons of separated plutonium has accumulated in storage. While the security standards have generally been very good in the western countries with these stocks, this accumulation of plutonium is very unappealing and sets an unfortunate example for nascent nuclear power programs elsewhere. Strong safeguards and security of the stockpiles are essential.

The choice of full recycle of TRU in fast reactors leads to material that is clearly unattractive for nuclear weapons purposes (see Figure 8.1). This is, in principle, beneficial for the nonproliferation regime. However, by the same token, the fuel cycle will be more challenging to operate, and possibly too expensive. It would seem impractical that such a fuel cycle would operate in countries with small programs. On the other hand, fuel cycle “parks” (either international or nationally operated as part of a large nuclear enterprise) with such reactors could accept LWR SNF from countries with small programs and process the fuel to supply the fast reactors – in effect, acting as a waste management program for the LWR TRU. Such a choice would mimic the leasing approach of spent fuel takeback. Theoretically, this fuel cycle (including the waste management “service” for LWRs in small programs) possesses a high degree of proliferation resistance. However, the technical challenges of realizing such a fuel cycle economically are formidable and will require decades of research and development. The intermediate risk is that evolving nuclear power programs could adopt the argument that the MOX/PUREX cycle will be a bridge to full TRU recycle in the long term. This quite possibly could be a bridge to nowhere other than enhanced proliferation risk or worse.
Reprocessing choices

Commercial reprocessing of LWR SNF has used the aqueous solvent extraction PUREX process. It produces three streams: very pure plutonium; uranium; fission products and minor actinides. Other aqueous approaches have been developed that avoid separation of pure plutonium (e.g., UREX, see Appendix E). However, there is a view that the process chemistry can be changed easily to separate out the plutonium, so the degree of nonproliferation advantage gained by these alternatives is debated.

Pyroprocessing has been developed as an alternative approach, especially well-suited to metallic rather than oxide fuels. The plutonium extracted through pyroprocessing is mixed with some rare earth elements, uranium, and other actinides. The Idaho National Laboratory has worked on pyroprocessing in order to handle metallic fuel from the Experimental Breeder Reactor II. Extensive work is going on in South Korea to develop this technology, under the argument that pyroprocessing is more proliferation resistant.

The major pyroprocessing proliferation advantage is that all operations take place behind considerable shielding with robotic manipulators and consequently the facility may be easier to safeguard. Further, since they are more compact and modular than large scale aqueous facilities, they could reasonably be co-located with one or two fast reactors and integrated into an effective safeguards system. On the other hand, material accounting becomes more challenging and pyroprocessed materials are in metallic form, potentially providing important experience for weaponization. All in all, pyroprocessing may improve on PUREX with respect to proliferation resistance, but not sufficiently so as to drive the fuel cycle and reactor choice or policy choices of the U.S. on the disposition of U.S.-origin fuel. And the reality is that countries entering into reprocessing in the relatively near term are much more likely to choose the well understood, relatively straightforward aqueous process.

Enrichment choices

A key nonproliferation issue is detection of enrichment facilities that could be used to make HEU. The first generation of large scale commercial (or dual use) enrichment technologies was that of gaseous diffusion. Its footprint and power requirements are very considerable for a scale relevant to a weapons program (and certainly for the larger scale needed for a commercial plant), meaning that it is a difficult technology to hide from modern surveillance capabilities.

Centrifuges, the second generation technology, offer a much smaller footprint in terms of space and power. The associated difficulty in detecting such plants was played out with the belated discovery of Iran’s hidden centrifuges. This technology does require special materials to withstand the centrifuge operating conditions, and these can be monitored to a degree, but the success in evading detection in Iran for quite some time suggests the limits of these approaches. A major complication is that even special materials and critical components for centrifuges increasingly have multiple civilian applications; examples are carbon fiber for centrifuge rotors, golf clubs, commercial aircraft, and myriad other uses, and precision motor controllers. Safeguarding and materials accounting in declared enrichment plants is challenging; detecting clandestine facilities in which the centrifuge technology has been replicated is even more so. The Additional Protocol is aimed at addressing such problems, but it is not in effect in a number of countries of interest (such as Iran).
We may now be on the threshold of third generation technology with a further significant reduction in footprint and power requirement (and therefore cost of enrichment services, providing the commercial imperative for development and deployment). In particular, laser advances over the last several decades have led to numerous efforts at developing isotope separation (equivalently enrichment in a specific isotope) technologies based on selective atomic or molecular excitations. A specific Australian-origin technology called SILEX (Separation of Isotopes by Laser Excitation) has been advanced to the Nuclear Regulatory Commission (NRC) for licensing by the Global Laser Enrichment (GLE) consortium (GE-Hitachi-Cameco). The cost advantages proclaimed by GLE are exactly those associated with a very small signature for surveillance. Further, the technology is promoted as having other important isotope separation applications, such as silicon, carbon and oxygen, meaning that its development for uranium enrichment in other countries could be “covered” by a need for other useful isotopes. This has led to an active discussion of a fundamental question: does the Nuclear Regulatory Commission need to make a judgment on proliferation risk in considering the license to operate? Slakey and Cohen argue this case, stating that the Atomic Energy Act requires that the NRC judge whether a technology is "inimical to the common defense and security" of the United States, while the applicants note that a proliferation judgment was not rendered in approving a license for a centrifuge plant. The distinction is in the maturity of the technologies, with the laser technology never operated commercially and the centrifuge plant replicating a European design already operated at large commercial scale. There is no question that the technology will remain classified and that high levels of compliance will be sought if the license is issued. The concern is over leakage, as has occurred with the centrifuge technology. But the reality is that the basic technology was developed outside the United States over many years. Many other countervailing factors would need to be considered as well, including the importance for United States nonproliferation policy to regain footing as a global nuclear supplier. The need to consider proliferation issues in NRC deliberations seems obvious, but the conclusions of such deliberations seem much less so and will need to take into account classified specifics of the technology and its history as well as overall United States economic and security factors. Input to the NRC from DOE, State, and the intelligence community is important for any such deliberation.

An important lesson from this unresolved discussion is that we can expect isotope separation technology to advance. This heightens the importance of moving with more urgency to update the global nonproliferation regime, rather than inevitably being reactive to a yet unknown breakthrough technology.

Safeguards

Next generation safeguards are an important part of the response to these challenges. Technology-based safeguards have had a principal focus on timely detection of fissile material theft or diversion from nuclear fuel cycle facilities, complementing physical security and facility inspections. The goal is a sufficiently accurate inventory of fissile materials at each stage of the fuel cycle to enable governments to account for and protect nuclear materials within their borders and to assist the IAEA in its monitoring of international commitments under the NPT. A summary table of technical objectives at various stages of the fuel cycle, taken from a 2005 American Physical Society (APS) report, is shown in Table 8.2.
The safeguards technologies resulting from the first generation of robust R&D have now been deployed widely and effectively. However, the array of recent and future challenges has not been addressed with a commensurate response. An important factor is the sheer increase in the IAEA safeguards responsibilities, with many more facilities under safeguards likely in the future and, in the last several years, an order of magnitude increase in the number of Additional Protocol agreements implemented. These are good developments, but technologies are needed that can safely limit the burden of inspections. Introduction of new reactor, reprocessing, and/or enrichment technologies and new large scale fuel cycle facilities, including long term storage sites, will add complexity and new protocols to the IAEA effort. As already noted, the Iran situation has highlighted the importance of detection of undeclared fuel cycle facilities, and the concern about terrorism has heightened the importance of integrated safeguards and security. Yet, modern enabling technologies, such as modeling and simulation and integrated sensor, information, and communications systems, are employed minimally today.

A few of the areas that call for a renewed commitment to safeguards technology R&D include:

- **Safeguards-by-design:** This entails integration of facility-specific safeguards systems into the early stages of nuclear facility design, for both physical and process configuration, while respecting the imperatives of efficient safe commercial operation. Modeling and simulation will be an essential tool. The Japanese Rokkasho Reprocessing Facility provided a good model for advancing safeguards-by-design.

- **Real-time process monitoring:** New, faster, and more accurate non-destructive assay in operating plant conditions is a technological challenge. Advanced detection algorithms, such as Bayesian statistics, and diversion pathway modeling (part of safeguards-by-design for new plants) will complement current safeguards for keeping track of fissile materials. For example, at an enrichment plant, enrichment and mass flows will be needed simultaneously for feed, product, and tails streams.

- **Data integration:** An overall safeguards system will require integration of authenticated heterogeneous data, potentially from hundreds of sources, as the basis for remote facility monitoring. An automated system will alert inspectors to anomalies and potentially initiate physical containment measures autonomously.
Environmental monitoring: Environmental samples (ground, water, air, surfaces) taken outside the facilities, together with very sensitive analysis of elemental and isotopic composition, are a crucial system element for detection of undeclared facilities. This is technologically challenging, particularly if a large area is to be covered and the host country is not cooperative. Novel communicating sensor networks and small energy sources may be key enablers.

Until recently, the DOE safeguards technology program operated with only a few million dollars per year, incommensurate with the scope and urgency of the challenges and opportunities. The Next Generation Safeguards Initiative (NGSI), begun in 2008, has program plans approaching $50M/year. This is a more appropriate level, although it must be pointed out that not all of this is directed at next generation technology since NGSI has additional responsibilities (human capital development, international engagement,…). The technology program needs to be built and sustained with the highest priority.

There are considerable technical challenges in development of next generation safeguards for the real world operating environment of fuel cycle facilities. A dedicated and coordinated program of field testing in representative facilities will be required. A variety of commercial and national laboratory facilities can be employed in the United States for demonstrating and refining many of these technologies. Collaboration with international partners for meaningful demonstration projects will also be essential, given the limited number of domestic modern nuclear facilities. The DOE should develop an open and transparent stakeholder process to provide a safeguards technology roadmap aligned with the challenges of global fuel cycle development.

CITATIONS AND NOTES

4. A dirty bomb consists of a radioactive source and a conventional explosive where the goal is to disperse radioactivity. It is not a nuclear weapon and there is no nuclear yield. The radioactive material does not have to be fissionable (e.g., cobalt-60, used widely for industrial gamma ray sources).