

Security in a World with Expanding Nuclear Power

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Preface

Nuclear energy is a clean and relatively economical source of electricity, generating nearly one-sixth of the world's electricity today. It represents one of the few technologies that have the potential for significant scale-up to meet the growing global demand for energy without exacerbating global climate change. Yet, the power derived from splitting the nucleus can be used not only to electrify the world but to destroy it. Managing the balance between the promotion of peaceful uses of atomic energy and its destructive potential has been a major challenge since the first nuclear explosion in 1945. For the most part, this balance has been managed successfully during the growth of commercial nuclear power over the past 50 years.

The possibility for a substantial global expansion in civilian nuclear power in the coming decades, with attendant increases in uranium enrichment capacity and spent-fuel reprocessing and possibly growth in plutonium trade, gives rise to important security concerns. These expansions create both a challenge and an opportunity to strengthen the international system for monitoring and controlling the nuclear power enterprise.

To examine these concerns and opportunities more critically, and to consider options for mitigation, a workshop was held September 19–21, 2007, at Stanford University's Center for International Security and Cooperation (CISAC), involving 45 experts from the nuclear and security communities. The workshop focused on the security implications associated with expanding nuclear power worldwide.

This report is not a consensus document but rather an attempt to summarize salient issues and observations put forward at the meeting, as augmented by the authors' research. This report hopefully will contribute to a broader dialogue and help shape discussions of efforts to control, by both technical and political measures, the security risks associated with a global expansion in the use of nuclear power.

Finally, a workshop and report whose focus is specifically on the security concerns associated with nuclear power necessarily will have a negative tone, and perhaps even seem antinuclear. This was not our intention. Seen in a wider context, nuclear power may help alleviate global warming, foster development, contribute to energy security, and perhaps provide an arena for political cooperation. Finding comprehensive answers to a problem with this many dimensions was beyond the scope of both the three-day Stanford workshop and this report.

Executive Summary

The growth of energy requirements worldwide, coupled with a growing demand for energy sources that release less carbon dioxide into the atmosphere, is likely to generate a global expansion of nuclear power use, although the scale of this expansion can be debated. At the same time, the spread of nuclear power capabilities could enable the proliferation of nuclear weapons to more states and possibly to terrorists.

Threat Characterization

In the current era the proliferation threats stemming specifically from civilian power are essentially limited to misuse of uranium enrichment capacity and the diversion of plutonium from spent-fuel reprocessing. Such misuse or diversion is especially plausible if a state withdraws from the nuclear Non-Proliferation Treaty (NPT) and harnesses its civilian nuclear power facilities to produce nuclear weapons material. Terrorist threats could result from theft or seizure of reactor plutonium, but the more likely source is the large stocks of fissile materials that currently exist in states with dedicated nuclear weapon and naval reactor programs.

With the future growth and expansion of nuclear power, the increased threat resulting from that growth will not necessarily scale with the expansion in uranium enrichment capability because most of this capacity will exist in states that currently possess nuclear weapons. Non-nuclear-weapon states that acquire enrichment facilities, such as Iran, are cause for greater concern. Still, the proliferation threat will likely be confined to a few states willing to risk international condemnation and possible sanctions following NPT withdrawal to acquire a small nuclear arsenal.

The increased threat from the expansion of nuclear power may, however, scale with the use of separated plutonium, assuming closed nuclear fuel cycles become more prevalent. Even though much of the reprocessing capacity in the near term will remain in the hands of the current nuclear-weapon states, the storage and transport of this material to consumer states creates more opportunity for diversion and terrorist acquisition. Again, non-nuclear weapon states would have to weigh the benefits of acquiring a few nuclear weapons against the costs of international condemnation and possible sanctions that could cripple their civilian nuclear power efforts. It is difficult to conceive of states with substantial civil nuclear power programs taking such a risk if they were dependent on international sources for their nuclear fuel and technical support. Terrorist acquisition may be the bigger concern.

A number of projects underway internationally aim to provide systems and arrangements that reduce the proliferation risk associated with a closed fuel cycle, but the economics of these are unknown at this stage. At the same time there are plans, most notably in India, to build breeder reactors, designed to simultaneously produce power and additional fuel. Because these plants will use and produce weapon-usable plutonium, they could substantially increase the proliferation risks, especially if more states follow suit. Finally, the character of the threat in the latter part of the century is difficult to foresee, because it will depend to a large degree on the norms, system choices, and nature of the measures taken to reduce proliferation concerns in the interim.

System Trends

An analysis of technological trends in the nuclear industry and political developments in the global nonproliferation arena provides a basis for assessing the security risks of expanded nuclear power and recommending ways to minimize them. Given the time and costs of designing, developing, and licensing new systems, any expansion of nuclear power in the near term will involve more advanced versions of current reactor designs. Therefore, the systems supporting global nuclear power expansion can be viewed as covering two time frames: the next 30 years, when existing technologies will dominate the field, and succeeding years, when the next generation of significantly different systems may be ready for wide-scale adoption. In the next 30 years, the dominant proliferation concern related to expanded nuclear power is the potential for uranium enrichment capacity to expand significantly; increasing the possibility that highly enriched uranium (HEU) could be produced for nuclear weapons programs, especially if a state withdraws from the NPT. In succeeding years, the main proliferation concern is likely to shift to the possible diversion of plutonium for nuclear weapons, as next-generation systems will likely make greater use of plutonium-bearing fuels. The advent of a plutonium economy for civilian nuclear power will introduce alternate ways for states or terrorists to acquire nuclear weapons.]

The success of efforts to limit the spread of nuclear weapons in the face of substantially expanded nuclear power and technologies in either time frame will depend on the success or failure of international efforts to strengthen the nonproliferation regime, implement effective sanctions against NPT withdrawal, strengthen the International Atomic Energy Agency's ability to monitor expanded civilian nuclear power activities, and enhance the physical protection of weapon-usable material wherever it may be found to make is less accessible to non-state actors.

The Next 30 Years

In the next 30 years, worldwide nuclear power generation could double, with perhaps 20 more states joining the 30 that now use this energy source. Most nuclear power will be produced by light-water reactors fueled by low-enriched uranium, with the spent fuel being stored rather than reprocessed or recycled for future use. A few large-scale reprocessing centers (of which there are now five in operation and several more planned) can provide mixed uranium-plutonium oxide (MOX) fuel for approximately 180 reactors of 1 GWe capacity, more than the number of reactors currently licensed to burn MOX. Hence, there is no near-term need to expand commercial spent-fuel reprocessing capacity. Some long-term nuclear waste repositories may open in this time frame. A few breeder reactors, now in development and designed to maximize the energy extracted from nuclear fuel by producing excess plutonium, reprocessing and reusing it, may be fielded as well. India, for example, has very ambitious plans to build breeder reactors. These plans, if implemented, would be a significant step toward a "plutonium economy."

The single potential area for significant change in the nuclear power industry in the next 30 years—and the one posing the greatest proliferation threat—is uranium enrichment to make light-water reactor (LWR) fuel. As gas centrifuge technology spreads, more states may undertake national programs to provide reliable, independent fuel supplies—and perhaps a latent nuclear weapons option.

Challenges

The security challenges of this time frame are largely an expanded version of the current challenges: maintaining the integrity of the nonproliferation regime and accounting for and protecting fissile material. The main threats are

- NPT withdrawal by states for the purpose of developing nuclear weapons (as was the case with North Korea and might become the case with Iran);
- the undetected production of HEU in a declared enrichment facility or in an unsafeguarded centrifuge facility that has been secretly replicated; and
- clandestine diversion of plutonium from reprocessed spent fuel or fresh MOX fuel, with reprocessing possibly carried out in a small, undeclared facility (for which the technical barrier is not very high, as seen in the North Korea case);
- theft or seizure of fissile material in storage or transport by non-state actors, with or without state collusion.

The expansion of uranium enrichment capability, especially using gas centrifuges or possibly laser isotope or aerodynamic separation techniques, presents the biggest proliferation challenge to an expanded once-through light-water reactor fuel cycle. Facilities that produce low-enriched uranium (LEU) for nuclear fuel can be converted fairly easily to produce HEU. The amount of enrichment capacity needed to produce HEU for nuclear weapons is small compared to the amount of enrichment capacity needed to supply LEU fuel for even a single nuclear power reactor. And, if HEU production occurs, this material is difficult to detect in transit due to its low radiation signature and is relatively easy to fashion into a nuclear explosive. If HEU is produced, whether covertly or after a state's withdrawal from the NPT, physical protection of this material is paramount to prevent terrorists from acquiring it.

Recommendations

This era will be a test for the International Atomic Energy Agency (IAEA). Absent another organization with similar international reach and acceptance to provide global nuclear security and enforcement—which is not likely—the IAEA will have to expand its capacity and broaden its capabilities substantially. Besides having to monitor many more sites and facilities, the IAEA will need to

- require more stringent safeguards, including development and installation of new monitoring technologies;
- encourage, if not require, that safeguards be designed into new plants from the start;
- continue to improve systems for assessing countrywide material balances;
- implement continuous on-site monitoring at certain types of facilities;
- adopt new functions associated with the enforcement of the Additional Protocol;
- promulgate standards, and possibly adopt new responsibilities, for monitoring adherence to physical protection standards for sensitive materials; and

- seek new authority from the IAEA Board of Governors, perhaps backed by the UN Security Council, to act swiftly under certain preset conditions to avert the diversion of nuclear materials.

During this era NPT states should take concerted steps to strengthen the nonproliferation regime as the basis for domestic and international support for a growing commitment to nuclear power. They should

- make adherence to the Additional Protocol a prerequisite for participation in the global nuclear power enterprise;
- set enforceable standards and share best practices for physical protection of sensitive material;
- establish a norm of greater transparency to facilitate safeguards and material tracking and use this norm to guide the design of new civilian nuclear infrastructures;
- agree on a clarification or extension of the NPT to place conditions on access to sensitive nuclear technologies (beyond the only partially effective limits imposed by the Nuclear Suppliers Group);
- clearly establish the cost of NPT withdrawal, by modifying the treaty to limit a state's actions upon withdrawal, e.g., by requiring the return of any foreign equipment acquired while the state was a member of the NPT; and
- provide incentives to relieve states' concerns about access to LEU fuel, possibly through multinational fuel supply assurance programs and perhaps coupled with spent-fuel take-back options.

We recognize that above menu of desired actions will be a challenge and will not be addressed comprehensively, and the recommendations are not of equal importance, difficulty, or cost. It is our hope that the nuclear community will pursue these measures as a necessary step in supporting the global growth of nuclear power.

Other nuclear power approaches or motivations than those mentioned may develop, presenting somewhat different proliferation risks. In any event, the amount of fissile material needed to build a nuclear weapon is so small relative to the amount used in generating power, effective safeguards will be critical for every new technology.

The Later Years

The era beyond the next 30 years is likely to be defined by continuing growth in the use of nuclear power. Developments could include efforts to move beyond a once-through fuel cycle in order to maximize uranium resources and reduce spent-fuel storage requirements; adoption of next-generation technologies, some of which will incorporate proliferation-resistant features; and the maturing of political institutions for oversight and control.

New options for nuclear power are likely to emerge before mid-century. These options include fast reactors that burn actinides (the 15 chemical elements between actinium and lawrencium on the periodic table, including uranium and plutonium, most of which have long-lived radioactive isotopes that make waste disposal problematic) to

reduce the amount of accumulated plutonium in spent fuel and to ease the burden of storing radioactive waste for long periods of time; small reactors better matched to the small electricity grids in developing countries; reactor–fuel cycle collocation; and reprocessing techniques that do not produce separated plutonium. As these technologies emerge on the market, breeder reactors may replace many of the once-through LWR designs, reducing the demand for uranium enrichment but creating challenges associated with separated plutonium in the civilian nuclear fuel cycle.

The U.S.-led Global Nuclear Energy Partnership (GNEP) initiative, based on next-generation technologies to be fielded in this time frame, should test the willingness of smaller and less developed states to become part of a regime that permanently divides states into nuclear energy suppliers and users. It will also test whether supplier states can develop commercially viable advanced reactors and associated fuel cycles and make fuel supply assurances and spent-fuel take-back arrangements sufficiently attractive to user states so that the latter will forgo their sovereign right to possess national enrichment and spent-fuel reprocessing facilities. If the partnerships can be made sufficiently attractive economically and politically, especially to the consumer states, and other assurances prove effective, then many, but not all, states may join in.

The risk that plutonium might be diverted for weapons will grow in this era, as separated plutonium plays a larger role in the international fuel cycle with the next-generation systems. Proliferation-resistant designs, if they can be made economically feasible, could mitigate some of this risk. Uranium enrichment will remain an issue, though hard to quantify, because so much depends on the actions taken in the current era and their effect. The most significant question for controlling the risk of proliferation in these out-years is whether most of the nuclear-power states, and the international community, can or will be persuaded to give full consideration to proliferation risks in making their technical, economic, and political decisions about nuclear power, from the current era forward.

A variety of costs are connected with controlling the threats that may accompany the global growth of nuclear power. System and operational costs that affect the industrial participants will ultimately be borne by the utility owners; there are costs to states to provide development support, to regulate and protect the domestic program, and to support the international control apparatus; and there are less direct costs to states' foreign relations (note the major impact on Iran and North Korea of their nuclear programs), which may well grow as the developed states undertake to shape the civil nuclear policies of new entrants. Even from a very high-level perspective, this list can be expanded. Our workshop was limited by time and the expertise of the participants, so the question of cost details and their impact on the willingness of the community to move forward was simply noted as requiring further study.

Although the effectiveness of the IAEA in this future world cannot be estimated, there are those who, doubting the institution can overcome structural and cultural obstacles, suggest that other organizations might have to be created and empowered to augment the IAEA. Given the difficulty that has been encountered in creating strong international organizations in general, this path seems problematic. Strengthening and transforming the IAEA in the next 30 years to address changes in the nuclear world, then building on that transformation in the succeeding era, seems a more viable path.

Chapter 1: Introduction

This report is divided into the major elements of the nuclear power cycle: the “front” end of the nuclear fuel cycle, largely focusing on uranium enrichment; the reactors; the “back” end of the fuel cycle, which concerns the use and disposition of spent reactor fuel; and the transportation and storage that interconnect stages of the fuel cycle. Each chapter undertakes to present current and future system characteristics, accompanying security risks, and options for their reduction, and to note some of the financial and political factors that will shape responses. Each chapter also considers two main time frames: the next 30 years, during which much of the overall system will rely on advanced versions of extant technology and techniques, and a later time, in which new systems with, inter alia, greater proliferation resistance and more robust physical protection will have matured and perhaps be commercialized.

The report concludes with observations focused on the primary security issues and some important factors, such as the challenge to the national and international institutions responsible for effective safeguards and the need for alternatives to national enrichment and reprocessing, particularly for those states whose nuclear programs do not justify having such facilities on economic grounds.

Some Defining Factors

Nuclear power will grow in the future, driven mainly by expanding energy needs in developing countries, particularly in South and East Asia, and by the need to reduce future carbon dioxide emissions in all countries. If global nuclear power were to continue to be only 16% of the world’s electric power, as it is now, the nuclear generating capacity would have to double over the next 25 years to 700 GWe—and this estimate may be conservative in light of the prospective Kyoto follow-on agreements and accelerating demand in China and India. Even in the United States, the factors that have slowed nuclear power—cost, safety, waste management, regulatory and political uncertainty, public resistance, and investor wariness—are not being seen as insuperable problems as before. The growth, however, will not be universal. Cost and infrastructure requirements are likely to limit new nuclear power entrants from the present 30 to perhaps 50 over the next 25 years.

The future expansion of nuclear power worldwide will be defined largely by economic considerations, while public acceptance of nuclear power, particularly in the United States, will be conditioned by perceptions of reactor safety and environmental concerns associated with waste disposal. Concern over global warming may make nuclear power more politically acceptable to some, but it is too early to tell how this concern will affect general public acceptance of nuclear power. In the United States, the excellent safety record of the nuclear industry since the 1979 Three Mile Island accident and the apparently effective options for interim waste storage in dry casks at reactor sites and long-term geologic disposal at Yucca Mountain have not fully renewed public faith in nuclear power. Whether concern with carbon dioxide emissions or rising fuel prices will tip the balance in favor of nuclear power remains to be seen. Finally, security concerns involving the proliferation of nuclear weapons to states or non-state actors will be a significant part of the political dialogue and will affect acceptance of nuclear power. A full public discussion over a major nuclear energy revival in the United States has not

yet emerged, but polling suggests public support does exist as it does among a number of leading figures.

As the late Wolfgang Panofsky cautioned at the workshop, nuclear power will never be simply a commercial enterprise for which one can make projections based on economic factors alone. Events will happen that will dramatically affect the acceptability of nuclear power. (Prof. Panofsky used the term Black Swans, popularized by Nassim Nicholas Taleb to denote hard-to-predict events that have a major negative impact and much faultfinding in the aftermath.) Examples could include a failed state in which fissile material control is problematic, inventory differences that are perceived as (and may be) diversions, a successful attack and seizure of fissile material, interception of illegal commerce in fissile material, theft in a weak state in which guards and others are unreliable, and the detonation of a nuclear weapon in anger by a state or non-state actor. The public and political reaction to such events would be directed at nuclear energy and probably result in brakes being applied. Just as a nuclear accident anywhere is perceived to be a nuclear accident everywhere, so too will a security breach anywhere be perceived as a security breach everywhere. Anticipating such events, the advocates of expanded nuclear power should focus on mitigating measures, such as reducing stockpiles of plutonium; strengthening and internationalizing nuclear emergency search teams to respond to nuclear emergencies, including searching for missing material; and instituting much more effective technical means to monitor gateways for fissile material movement.

There is considerable effort being made by the countries in the Generation IV International Forum to design new reactor systems, mainly fast reactors and high-temperature reactors, which provide improvements in safety, proliferation resistance, waste generation, resource utilization, and cost of construction and operation. However, these will not reach the stage of commercial construction for 25 to 30 years. In the meantime, the global growth in nuclear power will be provided largely by more modern versions of the light-water reactor (LWR).

As the nuclear enterprise grows, a major question remains as to whether and how best to close the fuel cycle securely. (A single recycle of plutonium and uranium from LWR spent fuel increases the energy extracted from the original uranium by approximately 20%, and this number can be increased by repeated reprocessing—and with new reactor types, with breeding ratios greater than one.) In the United States, the policy for the last 30 years has been not to recycle and to attempt to persuade others of the proliferation risk of commerce in separated plutonium. Elsewhere, a number of countries have moved ahead with a closed cycle—Japan being a primary example among non-weapon states. Those who focus on the proliferation risk attending reprocessing call for restraint, because they see no pressing need to reprocess now, thus suggesting there is time to strengthen the controls of the nonproliferation regime.

One factor that affects the timing of future recycling is the availability of natural uranium. The 5 million tons in known uranium sources (figures from the International Atomic Energy Agency and the Organization for Economic Cooperation and Development's Nuclear Energy Agency) will satisfy the current consumption rate for at least 70 years, perhaps at an increasing extraction cost. But cost will not be a limiting factor for some time, because the cost of nuclear fuel itself is a small part of the sale price of electricity generated by nuclear power. Moreover, extraction costs for many minerals decrease with time, due to the adoption of new technologies. Based on the experience of

price-production elasticity from other metal minerals, the World Nuclear Association suggests that number could reach 200 years for all conventional uranium sources. These duration estimates will be offset by the projected rise in demand. For example, if nuclear power were to triple over 50 years and then plateau, the 70 years for known uranium sources would decrease to 50 years and the 200-year estimate would become approximately 100 years. Nevertheless, the point remains that uranium reserves at acceptable extraction costs are poorly known and, hence, should not be used to justify a premature commitment to reprocessing. If reprocessing is broadly adopted in the future—for example, to reduce the volume of high-level waste—and breeder reactors are brought on line, then the reserves of fissile material would last for many centuries.

Security-Related Issues

Security concerns arise because the amount of fissile material involved in the operation of a single nuclear power reactor is much larger than that required to produce a nuclear bomb. For example, a single 1 GWe light-water reactor burning low-enriched uranium (LEU) fuel enriched to 4% U-235 requires an annual enrichment capacity of approximately 140,000 SWU (separative work units) to provide fuel for the reactor. This amount of separative work, if diverted to highly enriched uranium (HEU) production alone, could produce approximately 600 kg of 95% U-235 HEU each year, enough for approximately 30 weapons. Similarly, this same 1 GWe LWR produces enough reactor-grade plutonium for approximately 30 crude fission bombs each year, once the plutonium is separated from the spent fuel. Obviously, a state would have to develop the reprocessing capacity to separate this plutonium; however, the material is there, and reprocessing has been demonstrated to be within the capability of many states (e.g., North Korea). Moreover, if operated at lower burn-up, the reactor could produce weapon-grade plutonium, albeit in smaller quantities due to the lower duty cycle of the reactor. Therefore, a country that acquires 1 GWe of nuclear capacity—the approximate size of one standard plant—and also has or acquires an indigenous uranium enrichment or spent-fuel reprocessing capacity—has the wherewithal to build nuclear weapons and is held back only by self restraint, treaty commitments, and potential political costs. It is appropriate to note, however, there is no evidence that any national nuclear weapons program to date has used spent fuel from commercial power reactors in its weapons program.

A more recent security concern centers on the greater accessibility of gas centrifuge enrichment technology. As countries come to rely on nuclear power, they may, in spite of cost, undertake to build indigenous facilities for uranium enrichment and fuel fabrication to provide a secure fuel supply. This capability necessarily provides a route to nuclear weapons material, should they choose it. To counter a move toward national enrichment, several concepts are being studied to provide a firm guarantee of fuel supply by an international entity—an issue elaborated upon in chapter 2.

Civil Nuclear Power as a Source of Plutonium for Nuclear Weapons

There has been a long running debate over the utility of plutonium produced in civil power reactors as a weapon material. The plutonium produced in efficiently operated light-water reactors has a number of disadvantages: the heat produced by the material itself would require some form of cooling of the pit in an assembled device without adversely affecting the implosion symmetry; its radioactivity would require more

sophisticated handling, particularly during manufacturing; the higher isotopes of plutonium have some effect on the nucleonics during a chain reaction; and most importantly, the higher ambient neutron flux due to spontaneous fission of Pu-240 makes pre-initiation more likely, resulting in a “fizzle” (an explosive yield in the range of 500 to 1000 tons).

These technical barriers have led some commentators to question whether a state intent on building nuclear weapons would consider using reactor-grade plutonium, and whether these hurdles would also frustrate a non-state actor’s efforts to successfully detonate a high-yield weapon. Others, however, have noted that the obstacles are not insurmountable and that as a terrorist threat even a fizzle in a population center would be a major catastrophe in terms of death, destruction, and contamination, compounded by the fear that the event may not be limited to a single occurrence.

Most scientists who are involved in the U.S. nuclear weapons program or who have had access to the requisite sensitive information have concluded that reactor-grade plutonium can be made into a workable weapon and should be considered as a security risk associated with the global nuclear power enterprise.

The U.S. government has been notably silent regarding the specifics of this debate, but it has (1) strongly supported international measures to safeguard and secure reactor-grade plutonium so it does not find its way into military programs and into the hands of terrorists and (2) prohibited the reprocessing of spent fuel under its control to produce separated reactor-grade plutonium. Further, a 1997 Department of Energy report addressing the pre-initiation issue noted that advanced nuclear-weapon states have developed techniques that would allow reactor-grade plutonium to be used in a weapon without significant performance degradation, and less advanced states using earlier technology should be able to construct a weapon using reactor-grade plutonium that has a yield significantly higher than a kiloton.

To conserve time, the organizers of the CISAC workshop decided not to review this history and instead made the working assumption that reactor-grade plutonium is second only to highly enriched uranium and weapon-grade plutonium (>90% Pu-239) in terms of the need for careful safeguards and physical protection in a world with expanded civilian nuclear power.

Controlling Proliferation

The main bulwarks against weapons acquisition by non-weapon states are the states’ commitment not to do so embodied in the nuclear Non-Proliferation Treaty (NPT) and their acceptance of International Atomic Energy Agency (IAEA) monitoring of their civilian nuclear programs, the control of sensitive nuclear technology exports by the nuclear suppliers acting in concert, and the potential enforcement of coercive action by the UN Security Council or by individual states or state coalitions. The main defense against theft or seizure within each state’s nuclear facilities is the adequacy and integrity of its physical security system and of its material control and accounting system. The safeguards implemented by the IAEA have been strengthened by the Additional Protocol, which allows the agency to conduct verification more broadly than previously. However, 70 countries have yet to accept the protocol. A latent proliferation risk that has little in the way of a technical solution relates to the NPT withdrawal right. A long-term political solution would involve constraints on, if not the negation of, that right.

Safeguarding a substantially growing nuclear enterprise will be a major challenge for the IAEA, and doing so while taking on new tasks as part of the Additional Protocol will compound the challenge. The agency's current funding is inadequate, and its structure and governance will need to be revised. It is far from clear that the political support necessary for these steps can be found.

Assessing Proliferation Resistance and Physical Protection

A working group of the Generation IV International Forum (GIF), which is guiding development of innovative future nuclear energy systems, has devised a qualitative and quantitative methodology for evaluating the proliferation resistance and physical protection (PR&PP) characteristics of nuclear energy systems (NES). Since a major goal for Generation IV systems is to make diversion, theft, or sabotage more difficult, having a means of assessing relative difficulty is an important analytical tool not only to judge acceptability but also to guide design and deployment. The structure of this methodology allows evaluations to be performed at the earliest stages of system design and to become more detailed and more representative as designs progress.

For a proposed NES design, the methodology defines a set of challenges, analyzes system response, and assesses outcomes, much as has been done in the past for reactor safety but with the great difference that the challenges involve human will. The challenges are various threats by proliferant states or non-state actors, from which a standard reference threat set has been defined. The proliferation threats include

- covert diversion of declared materials;
- covert misuse of declared facilities, including secretly operating part of an enrichment facility to produce HEU;
- clandestine dedicated facilities, including a small reprocessing facility to reprocess diverted spent fuel or diverted fresh MOX fuel; and
- overt misuse of facilities or diversion of declared materials, which has a different political character than the other challenges and a different class of possible responses.

The physical protection threats posed by non-state actors or agents of proliferant states include

- radiological sabotage,
- material theft or seizure, and
- information theft.

The technical and institutional characteristics of nuclear energy systems are separated into subsystems and targets. Pathways—sequences of events and actions taken by the malefactor—are identified by expert judgment, the system's response along these pathways is qualitatively analyzed by experts, and the results are aggregated into six measures for proliferation resistance and three measures for physical protection. (The uncertainties that accompany these detailed estimates also can be aggregated.)

The measures for proliferation resistance are

- technical difficulty (e.g. materials handling capability, ability to overcome multiple barriers, general sophistication),
- cost and human resources required,
- time required,
- attractiveness of material type (weapon utility),

- detection probability, and
- detection resource efficiency (e.g. the resources required to apply safeguards).

The measures for physical protection are

- probability of success,
- consequences (contribution to malefactor's strategic goals and cost to the host), and
- physical protection resources (comprehensive cost of protection and of enhanced protection).

The final steps in PR&PP evaluation integrate the findings and interpret the results. The evaluation will include best estimates of numerical and narrative descriptors, along with their uncertainties, in the most useful form for a particular audience. It should be noted, however, that this integration process does not attempt to aggregate the measures into a single number, because too much information is lost in that process.

This methodology is compelling and ought not to be limited to use by the Generation IV developers, who are looking out 30 years. It should be provided to the Nuclear Regulatory Commission (NRC) and Generation III reactor builders. This report follows the Stanford workshop in using this PR&PP evaluation methodology as a qualitative guide to help frame security concerns associated with the possible global expansion of civilian nuclear power and to develop insights into system improvements that could provide greater proliferation resistance and physical protection against theft by non-state actors.

Chapter 2: Front End of the Nuclear Fuel Cycle

Introduction

A substantial growth in nuclear power would most certainly lead to an expansion of uranium enrichment capacity, although not necessarily in the near term (next decade or two) due to the excess enrichment capacity that currently exists in Russia and the additional capacity that will come on line in other countries with current plans to build modern enrichment facilities (e.g., China, France, Japan, the United States, and possibly Canada, Australia, and South Africa). Reactors that require uranium enrichment services, which are mostly light-water reactors, account for about 350 GWe of capacity. This is more than 90% of the total nuclear-power-generating capacity available worldwide today.

The total uranium enrichment capacity today is approximately 44 million SWU (separative work units) per year. Many of the existing facilities were built to enrich uranium for nuclear weapon programs, especially in Russia and the United States. The enrichment complex is undergoing transformation, with a number of new projects underway that will replace facilities based on gaseous diffusion technology with new ones that will employ gas centrifuges.

The enrichment capacity that would be required to supply fuel for a power reactor depends on a number of factors, in particular, the cost of natural uranium. However, a standard 1 GWe light-water reactor requires approximately 120,000 SWU of enrichment capacity annually to supply it with LEU fuel. This means that in the far term, a five-fold expansion of nuclear power (to 1500 GWe) would require a comparable increase in enrichment capacity to about 220 million SWU/year.

From a nuclear nonproliferation point of view, the expansion of uranium enrichment capacity represents a substantial risk. Enrichment facilities can produce highly enriched uranium, which is a directly usable weapon material. Moreover, producing enough material for a nuclear weapon would require only a fraction of the enrichment work that is needed to support operations of a nuclear power plant—as little as about 5000 SWU in some circumstances. This means that a country that operates enrichment facilities as part of its civilian fuel cycle almost automatically has access to the capability to produce weapon-usable material.

The current nonproliferation regime does not prohibit any non-nuclear-weapon state from acquiring uranium enrichment capability for use in its civilian programs, as long as the facilities are properly declared and placed under IAEA safeguards. Nuclear-weapon states are not normally constrained by these requirements, but their enrichment facilities could be placed under safeguards under various voluntary arrangements. Overall, the growth of civilian nuclear power and the corresponding increase in enrichment capacity will present a serious challenge for the nuclear nonproliferation regime as well as for the efforts to stop production of new weapon-usable fissile material.

In general, the proliferation risks associated with uranium enrichment are easier to control if the number of countries and facilities remain limited and all facilities are placed under IAEA safeguards. However, it will be very difficult to reach universal agreement on a policy that limits the number of facilities. Attempts to restrict countries' ability to develop their own enrichment capability would violate their right to access to civilian nuclear technologies guaranteed by the Non-Proliferation Treaty. The discriminatory nature of the NPT—dividing countries into nuclear-weapon states that have the right to

possess nuclear weapons, although presumably not indefinitely, and non-nuclear-weapon states that forgo indefinitely their right to such weapons—has been a source of tension within the NPT for many decades. To expand this exclusionary principle to include certain aspects of the civilian nuclear fuel cycle, uranium enrichment plants in this instance, would likely meet with little international support. It is therefore very important to develop economic and political arrangements that will ensure that the spread of enrichment technology remains limited.

Enrichment Technologies and Economics

Enrichment is a process that is used to increase the concentration of the fissile uranium isotope, U-235, from the level of about 0.7% in natural uranium to the level of 3.5–5% required to fuel modern light-water reactors. Some research and naval reactors use uranium with higher enrichment levels. Uranium that can be directly used in nuclear weapons normally contains more than 80% U-235. However, any material with more than 20% U-235 is considered highly enriched uranium (HEU).

Several technologies have been applied on an industrial scale to enrich uranium. The first was electromagnetic separation, used in the Manhattan Project to produce enriched uranium for the nuclear bomb dropped on Hiroshima. This technology was quickly abandoned after World War II as inefficient and too energy intensive.

Until the 1970s, gaseous diffusion plants that were built as part of the U.S. weapons program supplied virtually all commercial enrichment services. In the early 1970s, the projected growing demand for enrichment resulted in the creation of two dedicated commercial projects—the EURODIF consortium led by Belgium, France, Italy, and Spain, and URENCO, which includes Germany, the Netherlands, and the United Kingdom. EURODIF started full-scale operation of its gaseous diffusion plant in France in 1980. URENCO gas centrifuge plants started providing commercial enrichment services in 1975. In addition, in 1973 the Soviet Union started supplying enrichment services to the Western market using centrifuge facilities that were part of its nuclear weapons program.

In the 1980s, the United States, France, and other countries initiated full-scale development of laser-based separation technologies to replace gaseous diffusion enrichment plants. The proposed technologies used either atomic (AVLIS, SILVA) or molecular (MLIS) processes and appeared to offer significant advantages over gaseous diffusion, primarily in terms of power consumption and low capital cost. However, by the time these development programs reached their final stage in the 1990s, centrifuges emerged as the most efficient and commercially competitive technology. Virtually all laser-separation projects were terminated in the 1990s or early 2000s. The only laser-based separation technology currently under consideration is a molecular process called SILEX, which may reach the pilot-plant stage in the next few years. It is, however, unclear whether this process will be commercially competitive. While legacy gaseous diffusion plants still operate in the United States and France, most countries that have access to uranium enrichment technology use gas centrifuge plants.

Nevertheless, laser technologies are used for other types of isotope enrichment and may be very attractive for clandestine uranium enrichment programs due to their small size (which derives from their very high separation factor per stage), which makes them difficult to detect. Economic efficiency is not the primary desideratum for

clandestine programs, as Iraq's reliance on electromagnetic separation prior to 1990 clearly demonstrates, but rather technology access and low visibility (to avoid detection) are priorities.

The current uranium enrichment market is dominated by a small number of suppliers in Russia, Europe, and the United States. The capacity that exists in Russia is estimated to be about 20 million SWU/year, URENCO has about 9 million SWU/year, EURODIF about 8 million SWU/year, and the U.S. Enrichment Corporation (USEC) in the United States about 5.5 million SWU/year. Smaller producers include Japan and China, with about 1 million SWU/year each, Pakistan with 5000 SWU/year, and India with 10,000 SWU/year. Brazil has built a new facility with the capacity of 120,000 SWU/year. The enrichment plant that is being built in Iran is estimated to have the capacity of about 10,000 SWU/year; a size that clearly is insufficient to supply LEU fuel for a single light-water reactor but that could produce one or two bombs' worth of HEU per year.

Both the United States and France are planning to replace their gaseous diffusion plants with centrifuge facilities. The United States is building three new enrichment facilities that will together have the capacity of about 10 million SWU/year and will replace the current U.S. gaseous diffusion enrichment plants. One—built by USEC—will use centrifuges of indigenous U.S. design, and two—built by URENCO-owned Louisiana Energy Services (LES) and by AREVA—will use URENCO centrifuges. AREVA is also building a centrifuge enrichment facility in France that will have a capacity of about 8 million SWU/year and will replace the country's gaseous diffusion plant. Other significant changes in the market of enrichment services will probably involve expansion of the capacity of plants in Europe and construction of new facilities in Russia. Other countries that have enrichment facilities are also expected to expand, although on a smaller scale.

From the economic point of view, there is every reason to believe that in a free and unregulated marketplace a few key suppliers that have access to advanced technology—URENCO, Russia, and to some extent France and the United States—would be able to satisfy the increased demand in enrichment services even in the case of a substantial expansion of nuclear power. However, the market in enrichment services is not free from regulations and restrictions. And experience shows that countries rarely base enrichment capability decisions solely on cost considerations, because these technologies have security benefits either in the form of enhanced military power (i.e., nuclear weapons) or improved energy independence. Moreover, fuel costs are a small fraction of the total cost of nuclear-generated electricity; thus, the economics of enrichment is less consequential than, say, the economics of nuclear power plant construction.

One of the arguments used to justify the development of enrichment capability is the need to provide a guaranteed fuel supply for nuclear reactors that a country operates. Given the extremely high capital cost of a nuclear power plant, it is understandable that a country might want to protect that investment by making sure that the plant will be supplied with fuel throughout its life cycle (i.e., 60 years). In most circumstances a country would be willing to bear the additional cost of the enrichment plant.

This approach is demonstrated by recent choices by the United States and China. The United States chose to build new enrichment facilities on its territory instead of

relying on supplies from Europe or Russia, even though some of these facilities will use technology imported from Europe. In a similar development, China has indicated that it would prefer to build new enrichment facilities on its territory rather than to participate in a multinational arrangement that would rely on facilities located in Russia, despite the fact that the new enrichment plants built in China will use older Russian technology. It should be expected that the countries building new nuclear power plants would make decisions similar to those of the United States and China.

Most new national enrichment facilities in states with less developed civilian nuclear infrastructures will not use the latest technology, whether constructed with outside help or not and therefore might not be economically competitive. This aspect, however, is unlikely to be a serious problem for the host country. Since the cost of enrichment is a relatively small part of the overall cost of electricity generated by a nuclear power plant (which is dominated by capital cost), even an inefficient enrichment facility would be unlikely to raise significantly the cost of electricity and therefore can be presented as economically justifiable.

Moreover, the overall economic effectiveness of a centrifuge enrichment plant is determined not only by the capacity of individual centrifuges but also by their reliability and their manufacturing and operating costs. Different approaches have proven viable. Russia currently operates a very efficient enrichment operation that uses a large number of reliable and inexpensive low-capacity subcritical centrifuges. URENCO has been using higher capacity supercritical centrifuges to build its successful commercial operation.

At the same time, neither costs nor centrifuge capacity would matter to a country that is developing its enrichment capability with the specific goal of providing a guaranteed supply of enrichment services or building nuclear weapons. Low-performance centrifuges would be adequate for these tasks, as long as they are not prohibitively unreliable and the country is willing to bear the costs associated with their production and operation. While the effort might require a substantial subsidy to the enrichment industry, some countries might be willing to provide one, justifying the expenditure by the need to support innovation and advanced technologies in metallurgy, composite materials production, and precision machining, which are required for development of centrifuge capability. A country could also make a deliberate decision to invest in the development of an indigenous uranium enrichment program as a way of building up latent nuclear weapon capability or even acquiring nuclear weapons.

These considerations make it difficult to argue against new national enrichment programs based on technological or economic grounds or to make a strong case that pursuit of an independent enrichment capability is an unambiguous sign of nuclear weapon ambitions, though failure to build associated fuel fabrication capability would be a strong warning sign. It is likely that some countries with new nuclear generation capacity will choose to build their own uranium enrichment facilities. The risks associated with these facilities are considered in the next section.

Proliferation Risks Associated with Civilian Enrichment Facilities

Although many technologies have been used in the past and, as just discussed, some countries may opt for less-than optimum systems, gas centrifuges have emerged as the most efficient and competitive commercial technology. More than two-thirds of the

enrichment capacity that exists today is based on gas centrifuges. This share will grow in the future, since virtually all new facilities planned or under construction today use gas centrifuges.

Centrifuge-based enrichment facilities present a very difficult challenge from the nonproliferation point of view. A centrifuge facility that can produce sizable amounts of HEU can have a very small “footprint”—i.e., it can be made very small in size, does not consume inordinate amounts of electricity, and does not produce detectable emissions or signals. Civilian fuel cycle facilities that produce low-enriched uranium can be relatively easily and quickly reconfigured to yield highly enriched product. The technology that is required for development and mass production of centrifuges, e.g. precision machining, is increasingly available commercially, and it is unclear whether export control efforts can prevent its further proliferation, because the basic technologies are inherently dual-use with many peaceful commercial applications. Export controls may slow proliferation, but substitution (e.g., aerodynamic or laser isotope separation instead of gas centrifuge techniques, or carbon composite instead of maraging steel rotors) and indigenous production will undermine their effectiveness.

Other enrichment technologies, in particular, aerodynamic separation (Becker nozzles) or laser isotope separation, are unlikely to be competitive with centrifuges, so it is somewhat less likely that they will be developed for civilian nuclear power programs. Again, though, cost may not be the driving factor for some national decisions, especially if access to the more cost-effective technologies is denied via export controls. Iraq was pursuing electromagnetic isotope separation prior to the 1991 Gulf War as part of its clandestine nuclear weapons program, and the South African nuclear weapons program used aerodynamic separation to produce HEU for its weapons. These or other technologies may present a nonproliferation challenge similar to that of centrifuges.

Terrorist Threats

The nature of the uranium enrichment process makes physical protection of facilities against terrorist threats relatively easy. As long as the facility operates at low enrichment levels, the material is not an attractive target for theft. Moreover, regardless of enrichment levels, the material normally exists in the form of uranium hexafluoride, which makes theft highly impractical. (Diversion of material by the state would still be possible, and it is considered in the section devoted to proliferation resistance.)

While low-enriched uranium itself requires almost no special physical protection, centrifuge facilities may present a vulnerability of a different kind. Information about centrifuges—such as blueprints, parts, samples, or information about design and technological processes involved in production—may be of considerable value to a state that is trying to develop its own technology. This information may be an attractive target for theft and therefore should be adequately protected. In most cases this protection does not present any significant challenge and would include normal measures applied by the industry to protect its proprietary information. The insider threat (i.e., the problem presented by A.Q. Khan), while difficult to guard against, can be mitigated by internal security measures that should become standards not only for security reasons but also to protect proprietary information.

Proliferation Threats

Ensuring proliferation resistance of enrichment facilities against state-level diversion or clandestine use is a more challenging task. The main issues that should be considered here are the possibility of breakout, i.e., the use of a declared facility to produce HEU after withdrawal from the NPT; the use of legitimate facilities to support and conceal separate clandestine activities, including the construction of clandestine facilities based on knowledge and material acquired for legitimate activities; and the undetected diversion of material and enrichment work from a declared facility.

Breakout

Breakout is the most difficult issue to deal with. If a country that has an enrichment facility on its territory decides to convert it to the production of HEU, it could probably begin producing weapon-grade material in a matter of days. This step, of course, would involve a very consequential political decision. In the case of non-nuclear-weapon states, it would require withdrawal from the Non-Proliferation Treaty. In the case of nuclear-weapon states with enrichment facilities, it would require suspension of any promises made not to produce HEU and removal of the facilities from voluntary safeguards, if they exist. These decisions would certainly carry substantial political cost as well as the risk of international sanctions or military conflict—the main deterrents to breakout.

Some arrangements that regulate operations of enrichment facilities may provide additional deterrence against breakout or at least delay production of HEU. It has been argued, for example, that countries that receive outside assistance with the construction of civilian nuclear facilities under the terms of the Non-Proliferation Treaty should not be allowed to keep these facilities if they withdraw from the NPT. However, even if this interpretation of the NPT were universally accepted and enforced, it would not affect enrichment and other facilities that have been designed and built indigenously. Another potential constraint on a country's ability to convert an enrichment facility to HEU production would be obligations it might have assumed if the facility was built as part of a multinational arrangement. Ultimately, however, if a country is willing to bear the political costs of withdrawing from its obligations, there is very little that can be done, short of sanctions or military intervention, to prevent conversion of a facility on its soil to HEU production. In some cases, when the enrichment plant is built with outside assistance, it might be possible to design the facility in a way that would allow its permanent (or temporary) disablement, although proposals of this sort suffer from the difficulty in getting countries to agree upon self-destruct mechanisms that, in the event of a failure, might inadvertently destroy the enrichment facility. Using military force to destroy a facility that has been removed from IAEA safeguards remains an option, albeit one with its own political costs.

Clandestine Facilities

If a country is determined to acquire nuclear weapon material, it may use its civilian enrichment program as a source of expertise, equipment, and materials for a clandestine weapon-related effort. Although a decision to start a clandestine weapon program would clearly carry substantial political risks, it cannot be ruled out.

In a country that develops and manufactures its own enrichment equipment (e.g., centrifuges); this equipment could be diverted to set up a clandestine facility. One way to

prevent such diversion would be to establish controls over the production of centrifuges or their key components, e.g., centrifuge rotors, magnets, and bearings. It is not clear, however, whether countries would agree to such controls or whether the controls could be made sufficiently effective. In any event, at this time there is no legal framework that would allow international control over centrifuge production.

Detection of a clandestine facility, once it has been built, is a challenging task, especially if it uses gas centrifuges. Inspections instituted under the Additional Protocol would help verify whether such facilities are engaged in HEU production, but it is generally agreed that inspectors would have to learn of the facility location from other sources.

The prospects for detecting other activity that accompanies uranium enrichment are somewhat better. In particular, conversion plants that produce uranium hexafluoride feedstock for enrichment have a larger footprint and, therefore, are easier to detect. However, in the presence of a legitimate civilian enrichment program, a country might not need to build a separate conversion facility, instead diverting material from the legitimate one. Preventing this diversion would require establishing safeguards on the natural uranium conversion process and maintaining material balances of uranium feedstock in the country. Some measures in this direction have been taken already. In 2003 the IAEA began extending safeguards at uranium conversion facilities to the bulk material located at such plants, rather than to just output, as traditionally has been the case. At the same time, since IAEA safeguards can be applied only to material that is "suitable for fuel fabrication or for being isotopically enriched," it is not yet clear whether these safeguards can adequately protect material from diversion.

Even civilian conversion facilities placed under comprehensive safeguards could be used to mask clandestine conversion facilities. In addition, the circulation of large amounts of material in bulk form that would be required to support enrichment activities associated with a civilian nuclear power program would generally make it difficult to reliably prevent diversion of the relatively small amount of material required for a nuclear weapons program. It would probably require periodic material balance assessments for the entire country, which could prove to be extremely difficult, if at all practical.

Diversion

Finally, enriched uranium can be diverted directly from civilian enrichment facilities. One way of doing so would be to divert some low-enriched uranium to use it later as feedstock in production of HEU (at a clandestine facility or after a breakout). Another possibility is to use some of the plant enrichment capacity to produce highly enriched uranium during otherwise normal operations of the facility. Both types of diversion may use undeclared feed to avoid affecting the material balance of the enrichment plant.

Preventing diversion of material at gas centrifuge facilities is a particularly challenging task. Centrifuges are characterized by a relatively high separation factor achieved at one stage, small in-process inventory, very short cascade equilibrium time, and modular plant design. All these factors contribute to the possibility of easy and quick reconfiguration of cascades and diversion of some enrichment capacity during normal plant operation. Verification of enrichment capacity is further complicated by the fact

that the actual capacity of centrifuges has generally been protected as commercially sensitive information.

Despite these problems, the IAEA, in cooperation with enrichment plant operators, has developed some safeguards for gas centrifuge facilities. Safeguards are currently applied to URENCO centrifuge facilities in Europe, centrifuge plants in Brazil, China, and Japan, and to a vortex facility in South Africa. Details of safeguards vary from one facility to another, but key components are common to all enrichment plants.

The goals of IAEA safeguards include detection of the production of significant quantities of undeclared HEU (defined as material containing 25 kg or more of HEU) or detection of the diversion of significant quantities of low-enriched uranium (defined as 75kg of U-235 in the form of LEU or approximately 2 metric tons of LEU) that could be used as feed for HEU production in a clandestine facility (or after breakout). To achieve these aims, safeguards rely on periodic material balance assessments, plant surveillance, verification of the plant configuration during periodic inspections known as Limited Frequency Unannounced Access (LFUA), and, in some cases, on techniques to continuously monitor the level of enrichment at various points in an enrichment plant.

Material balance assessments, conducted annually, include an analysis of facility records and reports, as well as direct measurements to determine the amount of material present at the facility. Material flows and balances are also verified during more frequent random material balance inspections that involve the so-called mailbox system, in which facility operators deposit constantly updated reports on material flows to a secure mailbox. During an inspection these records are verified against the actual amount of materials present at the plant. The frequency of these inspections depends on the size of the facility, with a large enrichment plant requiring perhaps 15 visits a year.

LFUA inspections are the primary means for verifying that no part of a facility was modified to produce highly enriched uranium. During these inspections, which are conducted on very short notice (within about two hours in the case of European facilities), inspectors have access to the facility halls and can visually verify that cascade arrangements correspond to the plant design specifications. IAEA inspectors are also allowed to take swipe samples in the facility to determine the presence of HEU. As is the case with other inspections, the frequency of LFUA visits depends on the size of a facility. Normally, these visits are conducted from four to twelve times a year. It should be noted that the effectiveness of these inspections depends on the facility's design. Some plants, e.g. those of Russian origin, are designed for easy reconfiguration, which presents problems for LFUA inspections. Measures taken by plant operators to prevent disclosure of sensitive information can also limit the effectiveness of visual inspections. The experiences with developing safeguards for facilities in China (of Russian design) or Brazil (where protection of sensitive information emerged as a key issue) show that these issues can be resolved. However, designing safeguard-friendly plants from the start would certainly help address these issues.

Continuous monitoring of material flows can also be used to ensure that an enrichment facility is not producing HEU. One measure of this kind includes installing Continuous Enrichment Monitors (CEMO) that use non-destructive assay measurements to determine the enrichment level of uranium in the pipes. These monitors usually rely on measurements of 186-keV gamma ray radiation from U-235 in conjunction with measurements of X-ray absorption in the pipes to determine gas density. Information

barriers, originally designed to verify the dismantlement of U.S. and Russian nuclear weapons without divulging sensitive nuclear design information, may be required to protect proprietary information. Results of the measurements can be continuously transferred to a remote monitoring site. CEMO equipment has been operating at the URENCO enrichment facility in the United Kingdom. Assuming that the required number of detectors can be installed at a reasonable cost, this technique could provide reliable real-time monitoring of uranium enrichment levels at a facility. However, periodic LFUA inspections would still be needed to ensure that the piping of cascades does not change and to make measurements inside the facility. Some facilities may present additional challenges for continuous monitoring. For example, at the Russian-design enrichment plant in China, steel piping used at the plant was found to limit the effectiveness of standard CEMO monitors. This example underscores the importance of designing safeguard-friendly plants as well as the need to develop new continuous monitoring techniques that could be applied to a broader range of facilities.

Overall, the current technologies and practices allow reliable safeguards of large, declared gas centrifuge or similar enrichment facilities. In a world with an increased number of national enrichment facilities, efforts clearly should be made to develop new enrichment monitoring technologies, improve safeguard procedures, and design safeguard-friendly plants. These efforts would help limit the ability of operators to reconfigure a plant to produce HEU and make it possible to carry out real-time monitoring without revealing sensitive information.

Political and Institutional Arrangements

While technical arrangements can help safeguard enrichment facilities and the infrastructure that supports them, new institutional arrangements may be required to limit the spread of enrichment technologies to new countries and further strengthen safeguards.

One approach to limiting the spread of enrichment technologies is to establish an international norm that encourages countries to meet certain criteria before they can build fuel cycle facilities on their territories. For example, under the U.S. Global Nuclear Energy Partnership (GNEP) initiative, countries that do not already have fuel cycle facilities on their territories (including those on the back end of the fuel cycle) would pledge to refrain from acquiring this capability, relying instead on supplier states to provide them with fuel services. Obviously, unilateral pledges to refrain from acquiring sensitive nuclear fuel cycle facilities to which countries are entitled under the NPT may have little appeal to countries concerned about fuel supply assurances, much less latent nuclear weapons capability. However, some countries may find that the benefits of GNEP justify forgoing their own enrichment programs, especially if fuel supply assurances come with spent-fuel take-back arrangements, as the program intends.

Still, the current proposals have been criticized, and largely rejected, as limiting non-nuclear-weapon states' rights to peaceful use of nuclear technology under Article IV of the Non-Proliferation Treaty. This issue is of increasing importance to many non-nuclear-weapon states in the wake of the indefinite extension of the NPT in 1995, which was predicated on the nuclear-weapon states' progress toward their Article VI obligations to reduce, if not eliminate, their reliance on nuclear weapons, specifically, to sign and ratify the Comprehensive Nuclear Test Ban Treaty and to make progress on a Fissile

Material Cutoff Treaty. The GNEP arrangements may work in some cases, but only if accepted voluntarily as part of a proper incentive package.

Another suggestion is that countries refrain from building enrichment facilities unless they can demonstrate that the facilities are economically justifiable. This proposal is based on estimates showing that an enrichment program, even if it uses the most advanced technology, becomes economical only when it can support about 6–8 GWe of nuclear capacity. A country with a smaller capacity would find it cheaper to buy enrichment services elsewhere.

Economic arguments against indigenous development of enrichment capability will be strong enough for most countries with small civilian nuclear power programs, as they have been in the past. However, if nuclear power becomes more prevalent, more countries will cross the capacity threshold at which indigenous enrichment becomes economically viable, raising the prospect of a spread of uranium enrichment facilities to many more countries. Moreover, as noted above, inefficient enrichment may be tolerable because fuel costs are a small part of the cost of nuclear electricity, and externalities, such as the desire for energy security or independence, often trump narrow economic considerations.

Fuel Supply Assurance Arrangements

One of the most often quoted reasons for the development of enrichment capacity is the need to ensure uninterrupted fuel supplies for nuclear power plants. Although nuclear reactor fuel or enrichment services can readily be purchased on the international market, as can services to fabricate fuel elements from enriched uranium, concerns remain that this market may not be free from political influence and, consequently, that fuel supplies may be interrupted in the future. Civilian nuclear power is a capital-intensive industry, so as countries move toward building nuclear power plants, they will want to protect their investment from political interference.

The market in nuclear materials and services is subject to a number of constraints that make it potentially vulnerable to political pressure. Companies involved in nuclear-related trade normally operate within a framework of intergovernmental agreements, which must take into account obligations imposed by the NPT, guidelines of the Nuclear Suppliers Group, and national policies. For example, supply of natural or enriched uranium or reactor fuel to a non-nuclear-weapon state normally would be conditioned on that state's having IAEA safeguards at the facilities that would use the uranium or the fuel. The conditions, however, might also include having full-scope IAEA safeguards in the recipient country, as required by the Nuclear Suppliers Group guidelines in most cases, or an obligation not to reprocess the reactor fuel without the supplier's explicit consent, as is normally required by intergovernmental cooperation agreements signed with the United States. While the regulation of nuclear trade is certainly justified, it has the effect of making the market less flexible, raising concerns about potential disruptions.

Whether or not the concerns about access to fuel services are justified in practice, it is likely that without international institutional arrangements that guarantee a reliable uninterrupted fuel supply and fabrication services, a number of countries will choose to build their own enrichment facilities to ensure operation of their nuclear power reactors. It is possible that some countries will use that justification to acquire latent nuclear weapons capability or to begin work on nuclear weapons programs.

Although guaranteed fuel supply arrangements have been discussed for decades, the idea has received significant attention in the past few years, resulting in a number of proposals. Broadly, the proposals present two approaches. One focuses on providing a backup in the event that fuel supply is interrupted for political reasons. The other concentrates on a longer-term goal of creating multinational facilities that would give consumer states a stake in their operation and therefore provide reliable access to the fuel services. These approaches are not mutually exclusive; indeed some proposals include both.

Backup Fuel Supplies and Services

Arrangements designed to provide backup supply of uranium or enrichment services usually assume that the existing market mechanisms would work adequately in most situations. The backup would be required only if a country has to deal with a clearly politically motivated disruption of supply. Most proposals assume that the first step in dealing with this situation would be to find a new supplier, with the IAEA acting as a guarantor of the deal if necessary. Two concepts have been suggested to facilitate this process: “enrichment bonds,” which would be obligations to perform enrichment services and grant the necessary export approvals, and “virtual banks,” which would require major providers to allocate a part of their capacity to help deal with potential supply cutoffs.

If a new supplier cannot be found in time or in the event of a lack of spare capacity, most proposals assume that the uranium would be drawn from a bank created for this purpose. Several ways to create and manage this bank have been suggested. Some proposals assume that uranium stocks to back up the guarantee will be created and managed by individual governments. For example, as part of this concept the United States pledged to allocate 17.4 metric tons of its excess highly enriched uranium, suitably blended down to LEU, for a fuel bank. This uranium would be managed by the United States and presumably would be subject to normal constraints imposed on U.S.-origin material.

Another approach is to create a reserve of enriched uranium that the IAEA would manage. In 2007, Russia offered to contribute \$300 million worth of LEU to an IAEA-managed bank (Russia will probably keep the ownership of the material). A private group, the Nuclear Threat Initiative, has raised \$50 million with the goal of making a contribution of at least \$150 million to an IAEA-owned and -managed fuel bank. One idea that has been considered is for the IAEA to have physical control of the material, probably stored in some extraterritorial area. It is believed that this measure would strengthen the guarantee provided by the bank.

Several practical issues may complicate implementation of fuel bank proposals. The first is whether the bank contains LEU or actual fuel elements. Different reactors require fuel of different enrichment levels, a requirement that could be met if the bank contained LEU at the high end of low enrichment levels. More importantly, fuel elements are specific to a given reactor design, and fuel fabrication specifications and the licensing of replacement fuel vary by country and by reactor design. Therefore, it is impractical for the IAEA or any other guarantor to maintain enough fuel elements of all types to satisfy all possible disruption scenarios. Unless states are assured that fuel manufacturers will meet obligations to supply the fuel elements for particular reactor designs when needed, LEU fuel banks will provide little reassurance. Indigenous fuel element manufacturing would alleviate this concern and should be encouraged to reassure consumer states that

fuel supplies cannot be disrupted, although a proliferation of fuel element manufacturing facilities will be uneconomical. Still, it may be a price some states are willing to pay to guarantee fuel elements for their reactors. Indigenous manufacturing of plutonium-bearing fuel elements would be much more problematic from the perspective of proliferation resistance and physical protection against terrorist acquisition. Some arrangements, in particular, those that assume the IAEA would have physical control over LEU stocks, require expanding IAEA involvement into the nuclear fuel cycle—an activity that may conflict with the agency's primary mission of promoting, monitoring, and safeguarding the peaceful uses of nuclear energy. Such proposals often receive little enthusiasm within the IAEA, not least because of the increased costs involved.

A more serious challenge to the assured fuel supply proposals in their current form is that it is not clear the assurances will work when they would matter the most, i.e., in situations of uncertainty about the intentions of the recipient state or if a state is suspected of noncompliance with its NPT obligations. The central requirement of all supply arrangements is that the recipient country should be in good standing regarding its NPT obligations. However, if a country were in good standing, there would be hardly any reason it could not obtain fuel services on the market without resorting to the guarantee. Therefore, in most cases the additional assurance arrangements would be unnecessary. Diversification of fuel supply services, especially political diversification so suppliers are not perceived as controlled by one country or bloc (e.g., the West), is probably the most reliable way of dealing with potential disruptions, whether caused by political or commercial reasons.

Cases that would require the guarantee most likely would fall into the category in which a country, while formally in compliance with its NPT obligations, may raise concerns about its policies, intentions, or long-term goals. In these cases, the IAEA, which in virtually all proposals will be the ultimate judge of country compliance, may not have enough evidence to conclude that the country has violated its obligations, but the suppliers of fuel services would still be under pressure to suspend their contracts. Even in the absence of a formal noncompliance ruling from the IAEA, a country or a group of countries could use formal or informal political mechanisms outside of the IAEA to prevent delivery of fuel services. This was demonstrated in the case of Iran, when the United States was successful in convincing a number of countries to stop nuclear cooperation with Iran long before its enrichment program was publicly disclosed and the IAEA could formally raise the question of Iran's NPT compliance.

Establishing IAEA ownership and control over a uranium stockpile or over enrichment and fuel fabrication facilities may help alleviate the problem of political pressure outside of formal IAEA channels. However, the IAEA is not in the business of fuel supply services, nor is it clear that it wants to be. Physical control over the material and facilities as well as transit and transportation of fuel must also be considered. Unless these matters can be adequately resolved, it is likely that few countries would be willing to rely on the guarantees provided by IAEA-backed arrangements.

Assured fuel supply mechanisms may prove useful in some circumstances, but it is unlikely that they will provide a guarantee strong enough to remove all incentives for construction of national enrichment facilities, even in countries without nuclear weapon aspirations. At the same time, many countries might find these arrangements adequate. Setting up enrichment facilities under multinational or international control could

strengthen the guarantees provided by supply arrangements, but the extent to which this would be the case depends on the details of implementation.

Multinational Enrichment Facilities

A somewhat different approach to the problem of guaranteed fuel supply focuses on multinational or IAEA-managed international enrichment facilities. Partial ownership in a facility could provide additional guarantee of uninterrupted supply of enrichment services, even if the facility is located outside of the consumer country. In some cases, though, the country that has physical control over the facility or controls transportation routes could deny access of its output to other owners. An example again is Iran, which found it very difficult to exercise its rights as a shareholder in the EURODIF enrichment consortium after the revolution in 1979. This case suggests that while multinational facilities could provide an important diversification of sources for fuel services, they are unlikely to solve the issue of supply guarantees. However, they could provide important nonproliferation benefits.

The concept of multinational fuel cycle facilities developed in the 1970s, in response to the previous anticipated expansion of civilian nuclear power. Indeed, several multinational enrichment companies have been successfully operating since then. One example is the URENCO consortium, created by Germany, the Netherlands, and the United Kingdom, which operates enrichment plants in each of the three countries. Another multinational consortium, EURODIF, currently includes Belgium, France, Iran (through an intermediary company), Italy, and Spain among its shareholders. EURODIF's enrichment facility is located in France, which exclusively controls its enrichment facilities and technologies. In the case of URENCO, all participants of the consortium have equal access to the facilities and technology. (It should be noted that the centrifuge technology that will be used at the new EURODIF enrichment facility has been provided by URENCO.)

Several new proposals and projects have emerged recently. Russia has been working to develop an international enrichment center in Angarsk and is actively seeking new participants. Kazakhstan has agreed to participate; Iran has refused. The structure of the Angarsk center will most likely be similar to that of EURODIF—shareholders will have access to the enrichment services and may be involved in management of the facility, but they will not have access to the technology.

Another recent multinational facility (although it is rarely described this way) is the centrifuge enrichment plant being built in the United States by the URENCO-owned company Louisiana Energy Services (LES). The United States will apparently control all output of the plant, but it will probably not have access to the URENCO technology, if only for commercial reasons. A similar arrangement will probably exist at another U.S. enrichment plant that will be built by AREVA, a French company.

Another category of multinational facilities encompasses those which use foreign technology but in which the host country has full control over the plant and access to the technology. This is the case with the enrichment plant in Hanzhun, China, which was supplied by Russia, and to a certain extent with the new centrifuge plant in France, which uses URENCO technology.

Several other new multinational facilities have been proposed. One is a consortium of several Middle East countries that would own and operate an enrichment plant located in a neutral country (probably Switzerland). This plan was suggested as a

way to resolve the issue of the Iranian program and to provide enrichment services to Middle East countries in the future. This proposal is at the early stages of discussion; details regarding ownership, management, and access to technology are not yet clear.

Another proposal, designed to resolve the Iranian issue, called for building a modern centrifuge plant in Iran, supplied and operated by a Western company. It was suggested that the host country would not have access to the technology (centrifuges would be “black boxed”) and the design of the plant would incorporate measures that would allow disablement of the centrifuges in case of a breakout (a measure sometimes called a “poison pill”). While this proposal is unlikely to be accepted, it exemplifies a technical approach to cope with the proliferation concerns associated with a multinational facility.¹

Some proposals suggested that multinational facilities could be placed under IAEA control and located in extraterritorial areas. While this idea may be attractive, practical steps toward its implementation have not yet been discussed.

While multinational facilities may not offer sufficient assurances of supply in some critical circumstances, they offer a number of important nonproliferation benefits. They provide a mechanism by which countries can obtain enrichment services without gaining access to the proliferation-sensitive technologies. They also can provide a framework for cooperation and confidence-building, especially if they are created on a regional basis. And in those cases where an enrichment facility is located in a non-nuclear-weapon state, multinational arrangements can provide additional safeguards against breakout by introducing a set of contractual and other obligations in addition to those required by the NPT.

While no single solution will provide absolute guarantees of uninterrupted fuel supply, the range of arrangements currently under consideration will likely prove sufficient in most circumstances. It is important to emphasize, however, that one of the best ways to reassure customers is to make sure that the enrichment services market is free from political interference and protectionism. As long as this is the case, the incentives for the spread of enrichment technologies outside of the current suppliers may be curtailed, though by how much is difficult to gauge.

Conclusions and Recommendations

Further growth of nuclear power will likely present a substantial challenge to the nuclear nonproliferation regime, for it could potentially lead to a wider spread of enrichment expertise, technology, and facilities. Innovative technical and institutional measures could help manage the proliferation risks associated with nuclear fuel production.

The first priority should be to strengthen safeguards at existing and future enrichment facilities and the front end of the fuel cycle more generally. To this end, continuous monitoring at enrichment plants, using devices such as CEMO detectors, would help. Additional technical and organizational measures should be taken to ensure detection of undeclared feed material. Safeguards should be extended to cover uranium conversion facilities. And to the extent possible, countrywide material balance

¹John Tomson and Geoffrey Forden, *Multilateralism as a Dual-Use Technique: Encouraging Nuclear Energy and Avoiding Proliferation*, Stanley Foundation Policy Analysis Brief, March 2008.

assessments that account for natural uranium flows in various forms throughout an entire country should be improved, to guard against diversion of material.

Current suppliers of enrichment services should set an example by opening their existing facilities to extensive safeguards. It is especially important for nuclear-weapon states, in particular, the United States and Russia, to do so. Existing supplier states should lead in providing transparency and in developing new safeguard technologies and procedures. New facilities should be designed with safeguard-friendly features. New enrichment plants—especially those in nuclear-weapon states, such as the LES, USEC, and AREVA plants in the United States and Angarsk in Russia—should serve as models for incorporating effective safeguards into multinational facilities.

As to institutional measures, those arrangements that ensure reliable access to enrichment services without the spread of technology and facilities should be strongly encouraged. At the same time, the existing suppliers should avoid monopolizing the market, for it will eventually increase incentives for proliferation. One way to meet these conflicting requirements would be for the current leading suppliers to commit to opening all new enrichment facilities to international participation, similar to the way Russia has opened its new facility at Angarsk. Suppliers could also participate in multinational enrichment facilities in countries that do not currently have fuel cycle infrastructures, using this process to strengthen the fuel supply guarantee arrangements and to develop comprehensive safety, security, and safeguard procedures that would apply to facilities in these countries.

Chapter 3: Nuclear Reactors

Close to 440 nuclear power plants are now operating worldwide with a total capacity of more than 370 GWe. These power reactors are located in 31 countries, 12 of which have more than 10 operating nuclear power plants and the other 19 of which operate fewer than 10 reactors each. Only the United States has more than 100 operating nuclear power plants, and 2 countries—France and Japan—have more than 50 operating reactors. This distribution is even sharper when expressed in terms of capacity: only 9 countries have more than 10 GWe, and only the United States has more than 100 GWe. A list of current nuclear power capacity and locations is shown in table 1, obtained from the recent update of the International Atomic Energy Agency (IAEA) Power Reactors Information System (PRIS).² A graphic representation of these data appears in figure 1, reproduced from the PRIS database.

Another 31 nuclear power plants are now under construction, as shown in table 2.³ The largest increments of new capacity are under construction in three countries—Russia, China, and India. And announcements by various countries indicate intentions to construct other plants not reflected in table 2. In the United States, electric utilities have publicly expressed intentions to order at least 30 new nuclear power plants, where only the first three or four utilities actually submitting applications for construction and operation licenses will be eligible to receive subsidies offered in the Energy Policy Act of 2005 (EPAct2005). It remains to be seen whether the other expressions of interest will materialize as firm plant orders. The first application for two new nuclear power plants in the United States have been filed by the NRG utility for its South Texas unit in October 2007. Similarly, many prospective nuclear plants have been announced in China, India, Russia, and other countries. One count has more than 150 GWe of new nuclear capacity planned for construction worldwide. An IAEA estimate from September 2007 indicates a possible global nuclear capacity range of 447–679 GWe by 2030. A graphic representation of these estimates, published in the IAEA brochure *Energy Electricity and Nuclear Power for the Period up to 2030* is shown in figure 2, together with the somewhat more optimistic projections of the World Nuclear Association (WNA).

While the actual new nuclear power plants construction data and proposed plant announcements reflect what is known publicly to date, it is quite possible that a much higher nuclear capacity will be required worldwide if we are to seriously tackle the vexing problems of greenhouse gas emissions and global warming. The more than 400 nuclear power plants now in operation worldwide produce 16 percent of the world's electricity—reducing carbon dioxide emissions by more than 2 billion metric tons per year, when compared to a scenario where this electricity is produced entirely from coal-fired plants. While the total nuclear capacity might reach 600 GWe based on the projections discussed above, it is possible that global nuclear capacity might reach levels two or three times higher than the projected figures, especially in the later half of the 21st century. These large values of nuclear capacity have security implications discussed in the rest of this report.

² <http://www.iaea.org/programmes/a2/index.html>.

³ PRIS database: <http://www.iaea.org/programmes/a2/>. PRIS data last updated on Oct. 16, 2007.

Table 1 - Nuclear Power Reactors and Capacities Worldwide

Operational		
Country	No. of Units	Total MW(e)
ARGENTINA	2	935
ARMENIA	1	376
BELGIUM	7	5,824
BRAZIL	2	1,795
BULGARIA	2	1,906
CANADA	18	12,589
CHINA	11	8,572
CZECH REPUBLIC	6	3,538
FINLAND	4	2,696
FRANCE	59	63,260
GERMANY	17	20,339
HUNGARY	4	1,755
INDIA	17	3,779
JAPAN	55	47,587
KOREA, REPUBLIC OF	20	17,454
LITHUANIA, REPUBLIC OF	1	1,185
MEXICO	2	1,360
NETHERLANDS	1	482
PAKISTAN	2	425
ROMANIA	2	1,308
RUSSIAN FEDERATION	31	21,743
SLOVAK REPUBLIC	5	2,034
SLOVENIA	1	666
SOUTH AFRICA	2	1,800
SPAIN	8	7,450
SWEDEN	10	9,034
SWITZERLAND	5	3,220
UKRAINE	15	13,107
UNITED KINGDOM	19	10,222
UNITED STATES OF AMERICA	104	100,322
Total:	439	371,684

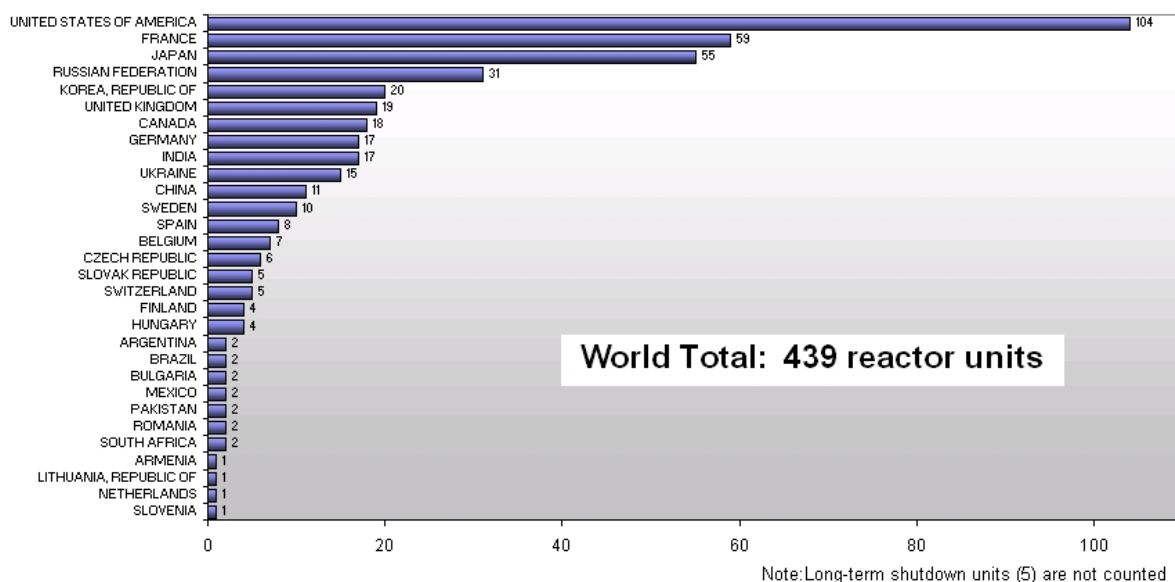
The totals include the following data:

	No. of Units	Total MW(e)
TAIWAN, CHINA	6	4,921

Long-Term Shutdown

Country	No. of Units	Total MW(e)
CANADA	4	2,568
JAPAN	1	246
Total:	5	2,814

Above data from PRIS database. Last updated on 2007/10/16.



Data as of August 2007

Figure 1 - Number of Reactors Worldwide

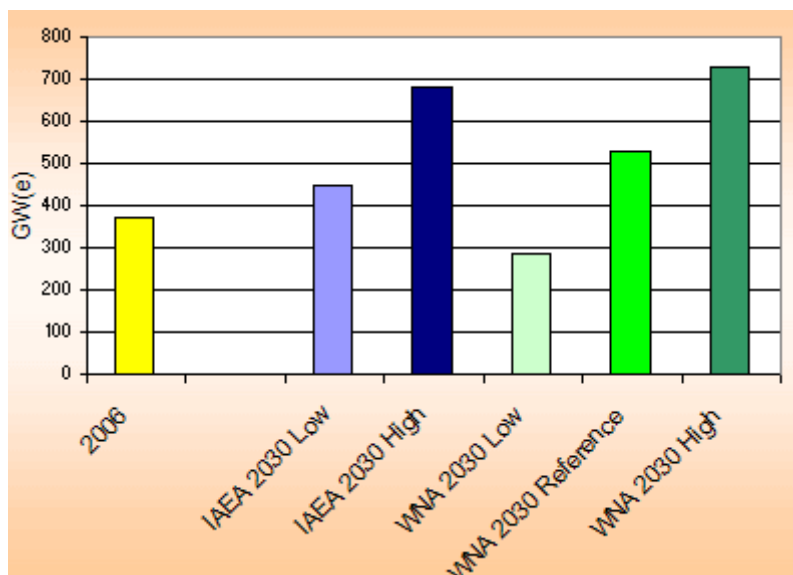
Table 2 - Nuclear Power Reactors Under Construction

Country	No. of Units	Total MW(e)
ARGENTINA	1	692
BULGARIA	2	1,906
CHINA	5	3,220
FINLAND	1	1,600
INDIA	6	2,910
IRAN, ISLAMIC REPUBLIC OF	1	915
JAPAN	1	866
KOREA, REPUBLIC OF	2	1,920
PAKISTAN	1	300
RUSSIAN FEDERATION	7	4,585
UKRAINE	2	1,900
Total:	31	23,414

The totals include the following data:

	No. of Unit	Total MW(e)
TAIWAN, CHINA	2	2,600

Assuming that some of the above projections might materialize, we can segregate countries likely to operate nuclear power plants in the future into three groups with different qualitative characteristics. Most countries will operate between 1 and 5 GWe of nuclear capacity; others will have a nuclear plant capacity greater than 5 but less than 25 GWe; and a few will have a capacity of 25 GWe or more. These groups have distinctive characteristics relating to their acquisition and use of nuclear energy capabilities.



http://www.world-nuclear-news.org/newNuclear/IAEA_report_predicts_nuclear_growth-241007.shtml?jmid=1124551110

Figure 2 – IAEA and WNA Projections of Global Nuclear Capacity

Countries with Nuclear Capacity of 1–5 GWe

Countries with between 1 and 5 GWe of nuclear capacity typically have a limited number of nuclear plants and also a limited countrywide nuclear infrastructure. Most are just starting their nuclear power programs and have a relatively small national electric power supply industry and electric transmission grid. The number of new nuclear power plants that could fit into the electric grid is limited, so no significant increase in nuclear capacity should be expected.

Such countries can be classified as nuclear fuel cycle consumer countries, as they are not likely to have nuclear fuel cycle facilities of their own, relying instead on external supplies of fresh fuel for their nuclear power plants—though a country that completely distrusts the reliability of the nuclear fuel supply market or aspires to nuclear weapons might pursue its own fuel cycle facilities. The spent fuel likely is stored at the nuclear power plants either in wet or dry storage. No nuclear fuel reprocessing is likely to take place in these countries, and they are expected to look for regional solutions to their spent nuclear fuel disposal problems.

Countries with Nuclear Capacity between 5 and 25 GWe

Countries with more than 5 and less than 25 GWe of nuclear capacity have a significant number of nuclear power plants, perhaps in several multi-unit stations. These stations are sited within a large electric transmission grid robust enough to absorb significant capacity nodes and possibly to expand further to contain new nuclear plant capacity. This capacity level might require substantial infrastructure in country to support the operation and construction of current or planned nuclear plants.

Countries at this capacity level fall somewhere between nuclear consumer and supplier status and may be in transition between the two. It is quite likely that these countries will contemplate increases of their nuclear capacity so as to reap the benefits of economies of scale both domestically and possibly in export markets. These countries

likely have some nuclear manufacturing capability, to produce plant components. They may also have some fuel cycle facilities, which they may consider upgrading or enhancing. Countries in this category that exceed the assumed threshold capacity of about 5–10 GWe, will probably consider domestic production of a portion of their own nuclear fuel requirements so as to increase the reliability of nuclear fuel supply, which might constitute a significant fraction of their total electricity generation. These countries may also consider the benefits of reprocessing their own accumulated spent nuclear fuel, to minimize waste and ease the burden on geologic disposal, or to improve nuclear fuel utilization efficiency. They would then be on the cusp of changing their nuclear operations status from that of nuclear consumer to nuclear supplier.

The best current example of such a country is South Korea, which has the technical capability to enrich new fuel and to reprocess spent fuel. Given current international sensitivities regarding security in East Asia, in particular, on the Korean Peninsula, it might be preferable for South Korea to exercise restraint in realizing its technological capabilities. South Korea is now negotiating an extension of its Agreement for Nuclear Cooperation (123 Agreement) with the United States. It will be interesting to see whether South Korea requests an agreement—and if so, whether it is granted—to develop sensitive fuel cycle facilities for enrichment or reprocessing on its own territory. The outcome would be an indication of how advanced nuclear power countries might or might not develop their own indigenous fuel cycle capabilities once they reach independence in power generation capability.

Another good example of a country developing its indigenous capabilities in nuclear power generation and in all aspects of the nuclear fuel cycle is India. India has not signed the NPT, and it exploded a nuclear device in 1974 and a series of five nuclear weapons in 1998. As a result, it has been cut off from general nuclear commerce carried out by countries that have signed the NPT—most of the worldwide suppliers of nuclear equipment, materials, and technology. India has developed an indigenous nuclear power technology based on heavy-water reactors (HWRs) copied from the Canadian heavy-water-cooled natural-uranium-fueled CANDU reactor technology. It has installed (or plans to install throughout the next decade) HWRs that will generate up to about 12 GWe. With limited uranium production capacity, the country is now developing next-generation nuclear plants based on the fast breeder reactor (FBR) technology, with which it plans to expand its nuclear generating capacity considerably. To fuel these fast breeder reactors India will have to reprocess spent fuel from HWRs (and later FBRs), extract the plutonium contained therein, and re-fabricate it into new fuel elements. The process will require handling significant amounts of plutonium-bearing fuels and separating multiple metric tons of plutonium, well before any other country develops plutonium-fuel-based nuclear reactors to a similar degree. Will India be able to implement an adequately detailed, secure material accounting and controls system to handle such large amounts of plutonium in its transition to breeder reactors? Will India be able to carefully account for all the plutonium flows within its own reactors and fuel cycle system, let alone prevent diversion of fissile materials beyond its boundaries? These questions pose significant technical and institutional challenges not only to India but to other countries seeking to expand their nuclear power capacities and capabilities, especially in regions fraught with security tensions.

Countries with Nuclear Capacity of 25 GWe or More

Countries with 25 GWe or greater nuclear capacity typically possess large nuclear plant fleets supported by extensive nuclear supply and manufacturing industries. If advanced nuclear power reactor systems based on closed nuclear fuel cycles are commercialized, they are likely to be implemented first in these countries. Generally, these major nuclear countries are the nuclear fuel cycle supplier states, operating uranium enrichment and fuel fabrication facilities and exporting fuel supplies to other nuclear consumer or mid-capacity countries. The introduction of advanced reactors based on closed fuel cycles and spent-fuel recycling implies that the large-capacity nuclear countries will likely operate fuel reprocessing plants and recycled fuel re-fabrication plants, both possibly colocated in nuclear service centers and also possibly colocated with some advanced reactor capacity. These countries will likely serve as the home bases for a few global nuclear reactor vendors, which will sell modern light-water reactor nuclear power plants and their support services to other consumer countries.

The U.S. Global Nuclear Energy Partnership (GNEP) program, announced by the U.S. Department of Energy (DOE) in February 2006, originally advocated a division of world nuclear power into a large number of nuclear consumer countries with small nuclear capacity and almost no fuel cycle facilities, on the one hand, and a small number of supplier countries with large nuclear capacities, advanced reactors and fuel cycle facilities, and nuclear fuel cycle export monopolies, on the other hand. In this concept, graphically depicted in figure 3, the mid-capacity nuclear countries would represent an intermediate case between the supplier and consumer countries, providing some supply services while still dependent on the large suppliers for some of their reactor and fuel cycle services.

The GNEP view of the world is partly informed by economic reality—only the large nuclear power states likely will have the resources to participate in the full nuclear fuel cycle—and partly by concerns with nuclear proliferation—a desire to discourage nuclear fuel cycle facilities in countries with small nuclear infrastructures because, in such states, nuclear fuel cycle facilities may indicate an interest in nuclear weapons. A state with little nuclear power capacity may acquire the capacity to build nuclear weapons while remaining a member of the NPT, and then actually acquire nuclear weapons by withdrawing from the Non-Proliferation Treaty (NPT), as North Korea did in 2003. Or a state could acquire the capability clandestinely at undeclared facilities, as is presumed to have been the case with Israel before the NPT was signed. Israel is assumed to have developed rudimentary nuclear weapons capability before the NPT was signed, and it has not signed the NPT. Nuclear weapon capability could be kept in a latent state where it is implied and is available but not actually utilized, as might be the case with Iran. Thus, in the GNEP view of world nuclear power distribution, development of nuclear fuel cycle capabilities in countries with limited nuclear capacity will remain a source of nonproliferation concern, because it is assumed that national security motivations are at play, even though other motivations may exist, e.g., energy security and the prestige associated with nuclear energy technologies and facilities.

Generation III+ Reactors

Nuclear reactor development in the large nuclear supplier countries has resulted in the current generation of nuclear power plants offered commercially, frequently referred to as Generation III+ reactors. Generation I reactors were built in the United States, the former Soviet Union, the United Kingdom, and elsewhere in the early 1960s largely to demonstrate the basic principle of reactor design. The larger 600–1200 MWe reactors offered commercially in the 1970–1995 period are referred to as Generation II reactors. The advanced light-water reactors (ALWRs) licensed by the U.S. Nuclear Regulatory Commission (NRC) during the 1995–2003 period are labeled Generation III reactors, and the slightly more refined ALWRs now undergoing licensing review by the NRC, or being developed without NRC licensing, are referred to as Generation III+ reactors. These reactors represent evolutionary improvements of the light-water reactor technology—the backbone of the global nuclear power industry since the 1960s—especially in the area of passive reactor safety.

Advanced Light-Water Reactors

ALWRs are water-cooled and -moderated, and are fuelled with low-enriched uranium (LEU) with enrichment of the fissile isotope U-235 to 4–5%, depending on the reactor design. Fuel enrichment requirements are likely to increase slightly to 6–8% U-235 in the future so as to extract more useful energy per unit weight of fuel, i.e., to improve the fuel utilization efficiency and to reduce the volume of spent fuel per unit of electricity generated. The impetus for increasing fuel utilization efficiency derives, in part, from the rising price of uranium and enrichment services worldwide. As the price per ton of LEU fuel increases, it becomes more important to extract more energy from the fuel to justify its higher fabrication prices. Likewise, at the back end of the fuel cycle, as spent-fuel repositories become more difficult and expensive to site and license, and as the price of spent-fuel storage and disposal increases, it becomes more important to reduce the amount of spent fuel to be disposed per unit of electricity generated. The trend toward increased fuel utilization (i.e., higher fuel burn-up) has been evident over the last 30 years. Nuclear fuel burn-up of 33,000 megawatt days per ton (MWd/t), corresponding to fuel enrichment to about 3% U-235, was the standard during the 1980s. During the 1990s fuel burn-up values reached 44,000 MWd/t, and typical enrichment levels reached approximately 4% U-235. Currently LWRs utilize LEU fuel to burn-up values of 55,000 MWd/t with corresponding enrichment levels of about 5%. The next increment in fuel utilization, now under development, would extend burn-up values to 66,000 MWd/t, with required enrichment levels of about 6% U-235 or higher. This change will require revisions in the operating licenses of future enrichment and fabrication plants.

Currently most LWRs and ALWRs operate on an open fuel cycle, i.e., the spent fuel discharged is stored indefinitely in dry storage casks (no nuclear waste repositories have been opened in the United States or elsewhere), although a few states have explored closed fuel cycle options where the spent fuel is recycled to extract additional energy content. While there is no pressing need to reprocess spent fuel while fresh fuel supplies are abundant, some countries—France, Russia, the United Kingdom, and, since 2008, Japan—reprocess their spent fuel, concentrate the fission products in high-level waste for ultimate disposal, and separate the remaining uranium and plutonium either for recycling as mixed-oxide (MOX) fuel in operating LWRs, or store the fuel for future breeder reactors. The United States halted all spent-fuel reprocessing in the mid-1970s.

Pressurized-Water Reactors and Boiling-Water Reactors

The Gen III+ reactors that will provide the bulk of the near-term expansion in nuclear power come in two types—pressurized-water reactors (PWRs) and boiling-water reactors (BWRs)—and they exist in various stages of regulatory approval. Only one advanced boiling-water reactor (ABWR) design developed by General Electric Corporation (GE) and marketed separately by the GE-Hitachi partnership and by Toshiba Corporation, is commercially available as a licensed Generation III reactor. Four Generation III+ reactors of this type are in operation in Japan, two are under construction by GE in Taiwan, and two were ordered by a U.S. utility in September 2007. Among the PWR types, one reactor based on advanced passive-safety principles—the AP-1000—has been licensed by the NRC and is commercially marketed by the Westinghouse Electric Corporation, now owned by Toshiba. Westinghouse sold four reactors of this type to China in 2007. A larger capacity reactor, referred to as the European pressurized-water reactor (EPR) and developed by AREVA Corporation of France in cooperation with Siemens Corporation of Germany, has been licensed in Europe. Two units are under construction, in Finland and France. Another version of this reactor, customized for the U.S. market, is being developed by Unistar Corporation, a partnership between the U.S. utility Constellation, and the French corporations AREVA and Électricité de France (EDF). This reactor has been submitted for licensing by the NRC, and the Unistar Corporation has indicated its commitment to constructing this reactor in its Calvert Cliffs plant site as well as in two other prospective sites. GE has submitted a third and more advanced economic simplified boiling-water reactor (ESBWR) for licensing by the NRC. Several U.S. utilities have expressed interest in constructing this advanced passive-safety reactor when licensed.

Several other Generation III+ reactor types have been developed by international reactor vendors. However, they have not been submitted for formal U.S. NRC licensing review—a process referred to as Design Certification that can take two to three years to complete and might cost anywhere between \$30 to \$250 million, depending on the number and complexity of the required confirmatory tests and analyses. In this category are several versions of the basic VVER-1000 reactor developed in Russia and constructed in China, India, and Russia; the APR-1400 reactor developed by the Doosan Corporation in Korea, of which two units are now under construction in South Korea; the Canadian ACR-1000 heavy-water moderated reactor now under development and licensing in Canada; and the APWR-1000 reactor developed by Mitsubishi Corporation of Japan and possibly ordered in the United States. A new and smaller sized 1000 MWe class reactor design called Atmea has recently been announced by the AREVA-Mitsubishi nuclear partnership and is aimed at future markets in industrializing consumer countries. Experience has shown that this reactor size may be acceptable to developing countries, even those with limited electric grid capacity, because electric utilities often want to maximize generation capacity at any licensed site due to the difficulty in obtaining new site licenses. While the NRC certification review is considered the “gold standard” of international reactor design licensing, reactor designs that have not been submitted for NRC review are available on the international market and may constitute much of the expansion in nuclear power outside of the United States.

The global nuclear power system will be preponderantly based on ALWR reactors well into the second half of the 21st century, owing to the established global

infrastructure of LWR reactor vendors and suppliers, the high financial and regulatory barriers to new reactor types, and the long operating lifetimes (60 years) of the current Generation III+ ALWRs. These reactors will likely prevail in both consumer and supplier nuclear countries, though new advanced reactor types might emerge within the supplier countries towards mid-century.

Pressurized Heavy-Water Reactors

In addition to light-water reactors, Generation III and III+ designs include the Canadian deuterium-cooled and -moderated natural uranium CANDU reactors. Designed and built in Canada, these pressurized heavy-water reactors (PHWRs) have been exported to Argentina, China, India, Pakistan, Romania, and South Korea. Compared to LWRs, CANDU reactors pose a greater proliferation concern because CANDU reactors have excellent neutron economy, which allows higher plutonium production rates. Since the fuel is natural uranium, it can reside only for a limited time in the reactor before losing its reactivity; thus the burn-up values achieved in CANDU reactors are quite low—on the order of 7000 MWd/t, or less than one-seventh the values now achieved in comparable-vintage LWRs.

Due to the low exposure in the reactor core and the need for frequent refueling, the plutonium produced has little contamination of higher plutonium isotopes than Pu-239 and, hence, can be considered near-weapon-grade. (Weapon-grade is 93% percent Pu-239, or higher). Routine operation of equilibrium cycle CANDU reactors will produce plutonium with Pu-239 content of about 75 percent, and in some cases higher. In any case, the partially burned-up spent fuel from the first cycle in a CANDU or Indian HWR contains near-weapon-grade plutonium.

In general, each higher plutonium isotope produced in a reactor through longer exposure—and higher burn-up values—reduces the usefulness of that plutonium for weapon-making purposes and increases its material handling difficulties. Such impediments could be ameliorated by very experienced nuclear weapons designers, however might pose significant, if not insurmountable, difficulties to first-time nuclear bomb-makers. Higher isotopes of plutonium such as Pu-240 tend to undergo spontaneous fission and release extra neutrons even before a full-sized critical mass could be assembled in a weapon, thus causing an inadequate detonation, or a “fizzle.” The Pu-242 isotope is a neutrons absorber, thus reducing the number of neutrons available for propagating a fast, supercritical chain reaction. The fissile Pu-241 isotope, through its natural decay chain, produces daughter decay products emitting high-energy gamma rays, thus causing material handling difficulties. Another isotope produced in long exposure in a reactor is Pu-238, which emits a large number of alpha particles which cause thermal heating of the plutonium mass.

Safeguarding spent fuel from a CANDU reactor is a complicated, expensive task compared to safeguarding LWR spent fuel, because a CANDU reactor is continuously refueled while the reactor is in operation. At least four spent CANDU assemblies are discharged from the reactor during each day of operation and have to be accounted for, as they move from the fresh-fuel pool, to the reactor core, to the spent-fuel pool, to dry storage casks. In contrast, a light-water reactor is refueled in a batch mode operation once every 12, 18, or 24 months, and the discharged fuel needs to be accounted for during those refueling events rather than continuously. The online refueling scheme requires that

a resident IAEA inspector be present almost continuously to monitor fuel flows in and out of each reactor—and a power station may have several reactors.

Other factors make the CANDU reactor a more difficult type to monitor against plutonium diversion than a light-water reactor. The CANDU fuel assembly, much smaller than that of an LWR, consists of several fuel rods arranged in a cylindrical shape with a diameter of about one foot or less and a length of about three feet. Given the smaller dimensions, lower burn-up, and, hence, lower radioactivity of the spent fuel, it is easier to divert CANDU fuel assemblies than LWR fuel assemblies, which have a length of 10 feet or more and higher radioactivity levels. Additionally, the deuterium heavy-water moderator and coolant absorbs neutrons to produce tritium, an essential ingredient of boosted fission weapons. Consequently, the heavy water in a CANDU reactor can be a source of weapon-useable material. Tritium is also a health hazard, due to its short half-life and its gaseous state. The CANDU reactor does not require uranium enrichment and utilizes only natural uranium, which increases its attractiveness from a nonproliferation perspective. On the other hand, given the relative simplicity of its design and low technology level required for component manufacture, this reactor can be more easily adopted by industrializing countries and those seeking nuclear weapons capability as well as electricity generation. India and Pakistan are cases in point.

Until advanced breeder reactors enter commercial operation, very large stockpiles of plutonium will accumulate in the spent fuel of LWRs and ALWRs. Smaller but significant stockpiles of separated plutonium might accumulate in countries operating reprocessing plants if no plans for near-term utilization of the separated plutonium are formulated. The basic plan for utilizing current stockpiles of separated plutonium is to burn it in ALWRs in mixed uranium-plutonium oxides (MOX) fuel. MOX fuel might contain up to 10% plutonium by weight. The mixed oxide powder is sintered into fuel rods, which are then assembled into fuel assemblies fed into the ALWR, much as LEU fuel would be. The MOX assemblies are then placed in the reactor's core, so that the average core enrichment distribution approximates that of an LEU-only core. Any ALWR whose core has been demonstrated and analyzed to be able to handle MOX fuel to the safety authorities' satisfaction can utilize this fuel form. Experience has shown that most ALWRs are capable of operating with MOX fuel. France, Germany, Spain, Switzerland, and other European countries have operated some of their LWRs on MOX fuel for several years without problems. Breeder reactors, if commercialized in the future, will operate eventually on plutonium fuel only, not requiring any U-235. Thus, plutonium concentrations in breeder fuel will be higher, depending on design, than those in MOX fuel. Fast neutron reactors can also be fueled by other higher actinide elements (e.g., neptunium, americium, and curium) formed in a reactor core. Some of these isotopes are highly radioactive, thus necessitating remote fuel handling and fabrication. Additionally, the transportation of MOX type fuel elements present increased proliferation hazards as well as handling difficulties due to the higher radioactivity of the fuel elements. MOX fuel elements are now routinely transported across France, but most countries engaged in nuclear energy generation do not have the nuclear fuel cycle experience accumulated in France over the last three decades.

Generation IV Reactors

Beyond the currently licensed large (1200–1700 MWe) ALWRs, which will provide most of the global nuclear energy supplies over the next few decades, a new generation of reactors employing different coolants and moderators aimed at providing energy for different applications in addition to electricity generation are now under development. The common features of these Generation IV reactors are their smaller capacity (100–300 MWe), and their highly modularized construction, with several reactor modules to be installed at each site to provide generation equivalent to that of a single ALWR. Their designs are far from mature and have not been submitted for licensing review. Given the high barriers to entering the nuclear energy supply market—plant design costs on the order of hundreds of millions of dollars, a lengthy design certification process by the NRC, and the need to develop special manufacturing industries—it is likely that Generation IV reactors will be introduced slowly over several decades. Historically, it takes about 30 years to design and license a new reactor type and bring it into commercial operation within the electric utility sector. A similar, if not longer, period might be required to design, license, and bring into commercial operation a fuel reprocessing and re-fabrication plant. This pertains only to reactors similar in nature to LWRs with which the regulators are familiar. For new reactor designs, we have to factor in regulators' learning time and the time required to modify or re-qualify the computer codes used in the licensing review process. This additional time has not yet been quantified (at least in the United States) but can extend the licensing process by 5 to 10 years.

The international organization coordinating the various research and development programs related to Generation IV reactor designs is called the Generation IV International Forum (GIF). The GIF has produced a list of six Generation IV reactor designs for further development effort, which are expected to provide the highest value added. Among these, the two most important concepts are helium-cooled, graphite-moderated high-temperature gas reactors (HTGRs), particularly the very high-temperature reactor (VHTR) variant, and the sodium-cooled, un-moderated fast breeder reactor (FBR). The U.S. GNEP Program has introduced a new FBR variant—the advanced burner reactor (ABR)—that represents a very low (in fact, negative) breeding ratio to be used for burning transuranic isotopes.

Both the HTGR and FBR extend the range of energy services provided by nuclear power plants such as the ALWRs beyond electricity generation. The HTGRs allow greater utilization of the thermal output of a nuclear reactor core—two-thirds of which are discharged to the environment as waste heat in electricity generation by ALWRs. High efficiency HTGRs could utilize 45–60% of the thermal energy produced in the reactor's core, thus enhancing the overall cost competitiveness of nuclear power. All this refers to electricity generation only. Other high-energy, low-temperature industrial heat applications, e.g., refinery heat sources, tar-sands oil extraction, or water desalination, could be coupled to the HTGRs. These applications would further utilize the thermal energy generated in the reactor's core and improve the degree of sustainability of the HTGR as an energy supply source.

Fast breeder reactors produce more fissile material in the reactor's blankets than they consume in the reactor's core. Thus FBRs, in principle, are net fissile material producers. The net fissile gain could serve to start up other FBRs; thus an FBR's

economy, once started, is not only self-sustaining fuel-wise but also allows for system expansion to keep up with the rising demand for electricity, because the plutonium produced, beyond the requirements to recycle into existing breeders, can be used to start new breeders. Whereas current ALWRs utilize about 0.5% of the energy potential of the uranium fuel, FBRs utilize, in principle, up to 60% of the total energy potential of fissile fuel, thus representing an almost inexhaustible energy resource. This is at least the promise of the FBR technology, which explains why it has been pursued for over 60 years despite concerns in the nonproliferation community about the security risks inherent in a global plutonium economy. A short examination of these reactor types is helpful in understanding how they might shape the world's nuclear future.

High-Temperature Gas Reactors

HTGRs were developed in the 1970s and 80s, in the United States by the General Atomics Corporation and in Germany by a subsidiary of the Siemens Corporation. Both HTGR concepts employed a unique uranium fuel coated in carbon microspheres, which was assembled in prismatic fuel elements in the U.S. design and as baseball-sized carbon-coated balls in the German design. These unique fuel forms are the first barrier to radiation release, and their proper production on an industrial scale to stringent quality assurance standards is the weak point of HTGR programs to date. All HTGRs are designed to burn LEU enriched to 8–19% U-235. The higher U-235 enrichment levels required in a HTGR (compared with LWRs), requires re-licensing of commercial enrichment plants to produce higher enriched fuel than currently allowed (4.9% U-235 in most cases), and might require re-licensing of the fuel transport casks as well. One of the concerns with the higher enriched fuels required by the HTGR is that if the fuel is diverted and re-converted to uranium hexafluoride, it might then be passed again through a clandestine centrifuge-based enrichment plant to produce weapon-usable highly enriched uranium. Most of the work of enriching uranium is spent in attaining the level required in an HTGR; the incremental work required to re-enrich that uranium up to weapon grade is relatively small, and the time period required (depending on the size of the clandestine plant and experience of the would-be proliferators) is measured in weeks or at most a few months. Thus the time available for counter-measures becomes that much shorter.

HTGR concepts were designed as high-temperature heat sources for various industrial applications, with electricity generation being a side product. During the mid-1990s both programs languished due to technical and economic difficulties. In the last decade interest has risen again in the VHTR version of the HTGR as a source of high-temperature heat for the chemical production of hydrogen fuel. A request for proposals was issued in 2006 by the U.S. Department of Energy to construct a demonstration VHTR plant at the Idaho National Laboratory as a high-temperature heat source. This project, referred to as the Next Generation Nuclear Plant (NGNP), is now in the bid review stage.

The German Government has abandoned its HTGR program and transferred all related intellectual property to South Africa, and indirectly to China. Consequently, one version of the German HTGR is now under development in South Africa in partnership with the Westinghouse Corporation, another version is being developed by the French AREVA Corporation, and a third version is now being developed by the Institute for Nuclear Energy Technology (INET) of Tsinghua University in Beijing as a prototype for

a large six-module nuclear power plant. Smaller HTGR programs exist in Japan, Korea, and Russia.

Sodium-Cooled Fast Breeder Reactors

Sodium-cooled fast breeder reactors have been built in the United States and abroad since the 1950s. In fact, the first electricity generated by nuclear power in the United States came from the Experimental Breeder Reactor I (EBR-I), operated at the Idaho National Laboratory in 1951. Several other prototype breeder reactors were built in the United States by both private manufacturing corporations and the U.S. Government, until the program was halted by the Carter administration in 1977, due to nuclear proliferation concerns, and dismantled completely by the Clinton administration in 1995.

In 2006 the Bush administration revived government interest in a variant of the FBR program, referred to as the advanced burner reactor (ABR), whose mission would be to burn all neptunium, plutonium, and other higher actinides separated out from ALWR spent fuel, utilizing a new reprocessing technology called UREX+. These programs form the core of the DOE GNEP program. The basic concept is that advanced separation processes such as UREX+ will separate out all transuranic elements, which will be burned in ABR nuclear plants. The greatly reduced volume of high-level radioactive waste will reduce the pressure on final waste repositories such as Yucca Mountain, so much so that foreign spent fuel from consumer nuclear countries could be shipped back to the United States, reprocessed with all the actinide elements burned in U.S. ABR plants, and the remaining spent ABR fuel stored either in repositories within the United States or in repositories in the consumer states. The consumer countries would be supplied with fresh LEU fuel for their ALWR plants. This concept was shown schematically in figure 3, above.

While the United States terminated its FBR program, other countries moved ahead with breeder programs. Global leadership in FBRs moved to France, which still operates its 250 MWe Phénix FBR in Marcoule, and for a while operated the large 1300 MWe Super-Phénix reactor in Creys Malville, east of Lyon. The Super-Phénix was eventually shut down due to concerns about its safety and a lack of international support. It was an international project requiring all participants to agree on and to provide operational funding, and following the accident at the Chernobyl reactor in Ukraine, the socialist governments in France and Italy opposed breeder reactor commercialization. Russia has operated an advanced breeder program centered on its 600 MWe BN-600 reactor, the largest operating FBR nuclear in the world, located in Beloyarsk, in the central Ural Mountains. Russia now plans to construct an 800 MWe BN-800 FBR—the prototype for future Russian FBR designs. A listing of currently operating or shut-down international FBRs is shown in table 3.

The countries with active FBR programs are France, India, and Russia, with large operating plants; China, Japan, and Korea, with prototype plants; and the United States with ABR designs on paper. A list of future construction plans for large FBR plants is provided in table 4. The Indian FBR program is noteworthy in that future FBR fuel will use plutonium, but the fast reactor blankets will breed U-233 from thorium. India is endowed with large thorium deposits, and it plans to utilize this fertile element to produce U-233 to transition its nuclear energy system to thorium-based fuels, relying on an indigenously developed thorium fuel cycle infrastructure.

Table 3 - International Fast Breeder Reactors

Facility	Location	Dates	MWt
BR-2	RUSSIA	1956–1957	0.1
BR-5	RUSSIA	1958–2002	5
BR-10			10
DFR	UNITED KINGDOM	1957–1977	60
Rapsodie	FRANCE	1967–1983	40
BOR-60	RUSSIA	1968–	50
KNK-II	GERMANY	1972–1991	58
BN-350	KAZAKHSTAN	1972–1999	750
Phoenix	FRANCE	1973–2009	563
PFR	UNITED KINGDOM	1974–1994	650
BN-600	RUSSIA	1980–	1470
JOYO	JAPAN	1978–	140
FBTR	INDIA	1985–	40
Super Phoenix	FRANCE	1985–1997	2990
MONJU	JAPAN	1994–1995 (restart?)	714

Table 4 - Future Sodium-Cooled Fast Reactor Systems

Facility	Location	Dates	Power (MWe)
CEFR	CHINA	In construction – 2008	25
PFBR	INDIA	In construction – 2010	500
BN-800	RUSSIA	In construction (delayed)	800
CPFR	CHINA	Conceptual – 2020	600
EFR	FRANCE	Conceptual – 2020+	1500
JSFR	JAPAN	Conceptual – 2025+	1500
BN-1600	RUSSIA	Conceptual – TBD	1600
ABR Prototype	UNITED STATES	Pre-Conceptual – 2020- 2025	95–760

Whether India's ambitious goals can be accomplished on an industrial scale remains to be seen, but its fast breeder program, if implemented at anywhere near planned levels, would represent the largest FBR program worldwide. India is now completing its PFBR—500 MWe Prototype FBR—located in the Kalpakkam site south of Chennai. India then plans to construct during the next decade four additional similarly sized FBRs, all run with plutonium oxide fuel extracted from HWR spent fuel. Once India accumulates experience in the construction and operation of such plants, it plans to construct 1000 MWe FBRs fueled with metallic plutonium, which allows for higher breeding gain and shorter doubling times. India plans a very large number of these larger FBRs, to form the backbone of its nuclear energy generation for the next several decades. India has established a new corporation called Bhavini to construct and operate future standard-design breeder reactors. Each multiple-reactor station will include its own reprocessing plant and fuel re-fabrication plant, thus minimizing the need for long-distance plutonium-bearing fuel transport. While India has demonstrated its capabilities

in spent-fuel reprocessing, it has yet to demonstrate plutonium fuel re-fabrication on an industrial scale—a capability that its FBR plans will require. Eventually India plans to introduce thorium as the fertile material into the blankets of its future FBRs for the production of U-233 and the transition to U-233 fuel cycles.

Whereas HTGRs can operate, for a while, on an open fuel cycle as ALWRs do, future FBRs depend for their start-up fuel and throughout their operating lifetime on spent-fuel reprocessing and plutonium recycling. Since FBRs (except in India) are being designed to operate on plutonium-based fuels, a transition to FBRs will require closing the nuclear fuel cycle on a global scale, with possible large shipments of plutonium-bearing fuels over long distances. The security implications of this transition to a global plutonium economy are discussed in chapter 4.

Proliferation Resistance of Generation IV Reactors

While Generation III+ ALWRs operating on the once-through fuel cycle were used to define the spent-fuel standard for proliferation resistance, new standards will need to be developed to gauge the proliferation resistance of Generation IV reactors. The reactors themselves are not the source of proliferation concern, but rather the fuel supply system prior to reactor operation and spent-fuel disposal after discharge from the reactor, i.e. the related nuclear fuel cycle, are the sources of concern. Different types of plutonium-bearing fuels have somewhat different proliferation resistance and physical protection (PR&PP) characteristics, affecting their ease of diversion and their utility for nuclear or radiological dispersal weapons. The nature of the fuel used will depend on the type of reactor and associated fuel cycle facilities. Thus, when considering plutonium-based fuel, it is important to evaluate the PR&PP characteristics of the reactor, fuel, and fuel cycle facilities together as an entire system.

In fact, throughout the 40-year history of global nuclear power, based largely on LWRs, no country has used commercial nuclear power facilities for proliferation. All proliferation programs were based on separate, dedicated production reactors far removed from commercial nuclear power plants. The only place where commercial nuclear power plants and the weapons fuel cycle are intermingled as a matter of national policy is India. The natural-uranium-fueled heavy-water-moderated and -cooled reactors operated in India, based on CANDU reactor designs, could be utilized to produce military-grade plutonium. Even in routine operation they produce, in some cases, near-weapon-grade plutonium. Furthermore, some Indian heavy-water reactors are meant to produce start-up fuel for breeder reactors that could also produce weapon-grade plutonium in their blankets, depending on refueling frequency.

However, commercial power reactor projects might be used to camouflage clandestine weapon-related activities: experienced nuclear personnel trained to operate commercial nuclear power plants might be siphoned off to a clandestine weapons program; construction of new nuclear power plants might mask procurement for the construction of clandestine fuel cycle facilities for weapons purposes; and the nuclear power sites might act as magnets for terrorist attacks, although the nuclear power plants themselves are not sources of nuclear proliferation. Finally, in the event a country decides to break out of the nuclear nonproliferation regime, the fresh fuel available in or near the reactor might be sent to an enrichment plant for further enrichment to weapon-grade HEU. Any fuel that has been irradiated for only a short period at the time of breakout might be reprocessed to recover weapon-grade plutonium.

These generalizations apply to ALWRs as well as to Generation IV reactors. Consequently, while the detailed structure of each nuclear power plant varies, the proliferation resistance of ALWR nuclear plants and future Generation IV nuclear plants is about the same owing to similar systems of built-in barriers to proliferation, similar physical protection measures taken at each nuclear power plant site, and similar safeguards and materials accounting methods. However, the fuel cycles associated with these reactor types pose very different proliferation risks.

The HTGR fuel cycle, which at least in the early stages of commercialization will be based on once-through operation, will pose an overall equal level of proliferation resistance as the ALWR fuel cycle, though the components of these fuel cycles pose different risk levels. In general, HTGRs operate with higher uranium enrichment levels than do ALWRs. This difference creates the incremental risk that HEU can be produced with less effort from HTGR LEU fuel—a concern if successful diversion of fresh fuel to clandestine enrichment plants is possible, or in cases of nuclear breakout. On the other hand, the HTGR LEU fuel, once fabricated into the carbon-coated uranium microspheres, is more difficult to tamper with and to convert to a uranium chemical form amenable to weapons use. The carbon-coated microspheres packed into graphite fuel balls or cylinders result in a hardened form of carbon-based enclosure around the uranium microspheres, which is difficult to break or dissolve. Even if HTGR fuel elements or fuel balls were diverted, it would be difficult to extract the uranium for further enrichment. Therefore, our assessment is that the front ends of the ALWR and HTGR fuel cycles pose roughly equivalent proliferation risks. The back end of the HTGR fuel cycle, i.e. reprocessing of HTGR fuel forms, has not yet been demonstrated as technically feasible, let alone economically practical, even on a pilot-plant scale. Possible diversion of HTGR spent fuel for clandestine reprocessing is only a remote possibility, because the technical processes required have not been developed.

The FBR raises very different proliferation concerns. All FBR fuel cycles are closed, implying spent-fuel reprocessing and re-fabrication prior to reload back into the reactor. The breeder blanket elements might contain weapon-grade plutonium. Plutonium-bearing fuels—most likely in the forms of mixed uranium and plutonium oxides (MOX)—likely will be transported from the FBR sites to the reprocessing and re-fabrication center and back. The transport route might represent the weakest link in the FBR fuel cycle, and will have to be safeguarded prior to large-scale shipment of plutonium-bearing fuels. Nonetheless, large plutonium shipments between the La Hague reprocessing plant in Northwest France and the MELOX fabrication plant at Marcoule in the Rhone valley in South France—a distance of approximately 600 kilometers—have occurred routinely without problems. These shipments are internal to France, and the accompanying security arrangements are not publicized, though they are assumed to have been strengthened in the wake of the September 11, 2001, terrorist attack. International plutonium shipments from La Hague to locations outside France pose a greater challenge. To transport reprocessed plutonium from La Hague to Japan, special cargo ships with internal security arrangements were designed and built. These ships are tracked by satellites throughout their voyage, and various naval ships have been stationed along the shipping route to provide help if needed. These special arrangements were put in place for a few highly publicized transports. The problems of securing the transport routes against modern-day international pirates (particularly in the Straits of Malacca or around

the Horn of Africa), or the protection of sea transports from would-be diverters would become more difficult as additional nuclear plants are built, particularly in Asia, necessitating a relatively large number of shipment of nuclear materials from the reactor sites to the centers where fuel will be recycled. Keeping track of all future ships carrying nuclear material on the high seas and assuring their security will be neither simple nor inexpensive. Clearly the global community knows what measures to take to resolve such future problems. The passage of specific sections in the International Maritime Convention, the creation of the Proliferation Security Initiative (PSI), and the enactment of United Nations Security Council Resolution 1540 are all steps in this direction. Resources have yet to be allocated to such missions, however.

ALWR spent-fuel reprocessing for plutonium-bearing FBR fuel and breeder fuel reprocessing and re-fabrication plants could be designed to avoid a clean stream of separated plutonium, producing a mixed uranium-plutonium oxide stream instead. Still, a sophisticated proliferator hypothetically might be able to extract plutonium from a mixed oxide stream or modify the operation of the reprocessing plant (with insider help) to produce clean separated plutonium. Though remote possibilities today, these scenarios might become realistic if FBR nuclear power plants become much more common. To further minimize the possibility of FBR fuel diversion, co-location of several FBR plants and their dedicated reprocessing and re-fabrication facilities in a single well-safeguarded nuclear energy center is advisable, although such a center might offer a tempting target to terrorists. Issues related to safeguarding the FBR fuel cycle center and the fuel transport routes are discussed in detail in the following chapters of this report.

Different plutonium-bearing fuels have different proliferation resistance characteristics. MOX fuel, if based on separate uranium and plutonium pellets, would be the easiest to divert because fewer chemical separation steps are required. In addition, most of the plutonium in MOX fuel could be older plutonium, where the higher plutonium isotopes have partially decayed, and the other higher actinide concentrations might be quite low due to the nature of the PUREX separation process. On the other hand, plutonium concentrations in MOX fuel would be lower than in other plutonium-bearing fuels, thus necessitating higher MOX fuel throughput to obtain the desired amount of diverted plutonium.

In an equilibrium FBR cycle (perhaps after a few recyclings), the concentration of the higher plutonium isotopes will be greater and the delay time before recycling will be short. In this case, the plutonium source would be more radioactive, due to gamma radioactivity from the isotopic decay chains as well as alpha emission from Pu-238, thus posing greater diversion barriers. Given the generally higher plutonium content, lesser amounts of fuel would need to be diverted, although it would be more difficult to handle. Considering the higher content of even-numbered plutonium isotopes, the utility of this fuel for nuclear weapons production by relatively inexperienced weapons designers is more doubtful.

ABR fuels, assuming the ABR and its associated UREX reprocessing scheme are eventually commercialized, will be the most diversion-resistant, due to the presence of higher plutonium isotopes and higher actinides in the recycled fuel. The transuranic isotopes and their decay chains result in high gamma, alpha, and neutron doses to would-be proliferators, thereby requiring remote handling behind heavy barriers. The utility of the diverted fuel and fissile material contained therein for weapon purposes is also

doubtful without more extensive chemical separation and removal of the undesired isotopes. However, ABR fuel, if successfully diverted, might be useful for radiation dispersion devices (RDDs), or dirty bombs, assuming terrorists could deliver such weapons effectively.

Chapter 4: Back End of the Nuclear Fuel Cycle

Reprocessing spent nuclear reactor fuel as part of the civilian nuclear fuel cycle raises both proliferation and nuclear terrorism concerns, because the plutonium contained in the spent fuel, once separated, becomes an attractive source of nuclear weapons material. While states have two routes to nuclear weapons acquisition—creating HEU in a uranium enrichment plant or extracting plutonium from spent reactor fuel—terrorists essentially only have one route—acquiring separated plutonium that has become part of the nuclear fuel cycle—because HEU should not exist in large quantities in any future nuclear fuel cycle. Of course, any state that stockpiles HEU or plutonium for its weapons program will also be an attractive target for terrorist acquisition, although generally, weapon-grade materials stored as part of a state's military program will be secured more carefully than materials in the much larger, potentially international, civilian nuclear fuel cycle.

Most spent-fuel reprocessing, both commercially and by government-controlled entities, has used the plutonium uranium reduction extraction (PUREX) chemical separation process. U.S. Atomic Energy Commission laboratories developed this aqueous separation process in the late 1950s as one particularly suitable for producing clean streams of separated plutonium and separated uranium. The PUREX process allows for the recovery of 99.9% of the plutonium generated in the nuclear fuel and a similar fraction of the total uranium content. The separation factor of plutonium from fission products can reach 10^8 , and the separation factor of uranium from fission products can reach 10^7 . The tradeoff is that a waste stream of fission products is generated that contains the higher actinides, along with small amounts of uranium and plutonium, which have very long half-lives, thus complicating the ultimate disposal of the high-level waste streams.

Using the PUREX process, a few tens of thousands of metric tons of spent fuel have already been reprocessed worldwide, yielding approximately 200–300 metric tons of separated reactor-grade plutonium. By comparison, the global military stockpiles of weapon-grade plutonium, separated using the PUREX as well as older separation processes, are estimated at approximately 250 metric tons. PUREX separation plants come in various sizes, which can be categorized usefully as small, medium, or large.

Small Plants

We define small reprocessing plants based on the PUREX process as those with a capacity of 50–200 metric tons of heavy metal per year (MTHM/yr). Examples of such plants include the Trombay military reprocessing plant in India with a capacity of 50 MTHM/yr, the Tarapur and Kalpakkam civilian fuel reprocessing plants in India with a capacity of 100 MTHM/yr, and the 110 MTHM/yr Radiochemical Laboratory military reprocessing plant in Yongbyon, North Korea. The Yongbyon reprocessing plant was sized to handle the spent fuel from North Korea's first 5 MWe plutonium production reactor at Yongbyon as well as the fuel from a follow-on 50 MWe reactor and the discharges from a planned 200 MWe reactor at Taechon. Plants of this size may be constructed in countries with limited nuclear power, assuming they are interested in acquiring reprocessing technology and closing their nuclear fuel cycles. For calibration, a 1 GWe nuclear power plant operated with an annual capacity factor of about 70% will discharge approximately 20 MTHM/yr. It follows that a 100 MTHM/yr reprocessing

plant could handle the spent fuel discharged from approximately 4–5 nuclear power plants of 1 GWe size.

Reprocessing plants of this size represent national plants aimed at treating the spent fuel from reactors in the operating country only. Given the small size of such plants, and the relatively small number of nuclear power plants they can serve annually, the utility and economic justification for such plants are uncertain and open to suspicion. The construction and operation costs of such plants would not justify the economic benefits of closing the nuclear fuel cycle and recycling fissile material at this level. However, a country like India with extensive plans for nuclear energy generation but with limited natural uranium resources might opt for fuel reprocessing and recycling and the transition to breeder reactors as the only route for increased nuclear generation free of uranium resource constraints. Such an option will require substantial reprocessing and re-fabrication effort, essentially trading advanced fuel cycle technology for the use of natural fuel resources.

Thus an industrializing country with limited nuclear plant capacity insisting on its right to construct and operate such reprocessing plant would open itself to the suspicion that it has other motives in mind besides electricity generation. Even if such reprocessing plants operate under IAEA safeguards, with good material protection, control, and accounting (MPC&A) measures, they would arouse suspicions that their purpose is to lay the ground for a country's later withdrawal from the NPT. After NPT withdrawal, reprocessing plants could be completely dedicated to reprocessing low burn-up fuel to produce weapon-grade plutonium.

Plants of this capacity, particularly the smaller ones, are also suitable for clandestine military programs. While still substantial in size (approximately 300 feet by 80 feet), they could be disguised as large concrete-walled industrial facilities. Alternatively, a plant of this size could hypothetically be constructed in a large tunnel, natural cave, or remote desert location to avoid detection. Examples include the clandestine Israeli reprocessing plant at Dimona, which, though smaller than the size range discussed here, was kept secret for many years. Its existence, let alone its location, eluded inspections and investigations for a long time. Similarly, the Russian Government constructed a reprocessing plant serving three production reactors, all located in large excavations inside a granite mountain in Krasnoyarsk-26 (Zheleznogorsk), a closed nuclear city in Siberia. Even the North Korean Yongbyon reprocessing plant (110 MTHM/yr) escaped detection for a few years until global attention focused on it.

Medium Plants

Reprocessing plants with a capacity range of 400–800 MTHM/yr fall into the medium category. Examples include two French plants, UP-2 and UP-3, both with 800 MTHM/yr capacities, located at the La Hague site on the Cherbourg peninsula in Northwestern France; the UK thermal oxide reprocessing plant (THORP) at the Sellafield (Windscale) site, with a nominal capacity of 1100 MTHM/yr but operated at only 800 MTHM/yr; the Russian RT-1 plant with a 400 MTHM/yr capacity operated by the Mayak organization and located in the closed city Cheliabinsk-65 (Ozersk); and the Japanese Rokkasho Mura plant (a modified UP-3) with an 800 MTHM/yr capacity located in the northern tip of Honshu and expected to start commercial operation in 2008. All these plants are operated by large national corporations in countries with significant nuclear

capacity. Some of these plants provide reprocessing services to national nuclear power plants, e.g., the UP-2, RT-1, and Rokkasho Mura plants, while others were built specifically to satisfy international demand, e.g., the UP-3 and THORP. The RT-1 plant also reprocesses spent fuel from Russian VVER-440 reactors sold to former eastern bloc countries and to Finland on the condition that their spent fuel will later be returned to Russia in exchange for fresh fuel. China and France announced in late 2007 a joint feasibility study for a possible UP-3 reprocessing plant in China.

The maximum reprocessing plant size in commercial operation today is 800 MTHM/yr. Plants of this size cost approximately \$6 billion (2004 dollars) to build. Exceptions are the RT-1, a commercial extension of a former military reprocessing plant built by the Soviet Union in 1946 and later converted to commercial use, the cost of which is difficult to estimate, and the Rokkasho Mura plant, whose cost is estimated at approximately \$23 billion. The latter took more than 20 years to build, to exacting Japanese seismic standards, and it incorporates state-of-the-art (and very expensive) safeguard measures. The cost of this plant represents an extreme case, well above the likely average construction costs.

While the reprocessing plants discussed in this category are basically national plants serving large national nuclear power systems, they could also be viewed as possible kernels for future regional reprocessing centers. The UP-3 and THORP could serve the spent-fuel reprocessing needs of the European Union. The RT-1 plant is already serving former Russian client states and provides spent-fuel treatment services to all former eastern bloc countries operating VVER-440 reactors. It would be interesting to explore whether Japan would accept spent fuel at the Rokkasho Mura plant from neighboring countries in Northeast Asia, after demonstrating successful commercial operation for a few years. In some cases, a host country might allocate a portion of its reprocessing capacity to foreign spent fuel in the interests of regional cooperation and common nonproliferation goals. In this context, the IAEA report *Multilateral Approaches to the Nuclear Fuel Cycle* (the MNA report)—INFCIRC/640 released in February 2005—calls for the establishment of regional fuel cycle centers dealing foremost with spent fuel disposal, based in large nuclear facilities dedicated by their national governments to regional applications. Any of the plants mentioned above as possible regional service centers could function along the lines called for by the IAEA.

Some of the medium-sized reprocessing plants mentioned here could also serve an important international role as test beds for the latest safeguards and MPC&A technologies. No diversion of fissile material from reprocessing plants in this category has yet been detected or suspected, with the possible exception of some side facilities related to the RT-1 complex, where small quantities of various radioactive isotopes were offered for sale in what turned out to be sting operations. In particular, the recently completed Rokkasho Mura plant included in its initial design and construction safeguards and MPC&A technologies with an incremental cost of approximately \$1 billion, and a possible increase to its annual operating budget that is yet to be quantified. This amount might be small compared with the total plant cost of \$23 billion, but is quite large compared with the original plant cost estimate of about \$6 billion. Rokkasho Mura has also proved to be an expensive burden to the IAEA, which dedicated considerable inspection resources to the design and execution of safeguards procedures implemented at the plant. Given limited IAEA budgets for safeguards, Rokkasho Mura impinged on

IAEA safeguards capabilities elsewhere. Thus, as measurement technologies improve, the cost of installing safeguards and the related annual operating costs for both plant operators and IAEA inspectors may become substantial. Regional approaches, along with remote monitoring of plant operations, might alleviate these safeguard costs to some extent. Incorporation of safeguards measures in the plant design even at the early stages of the design might obviate the need for later, more expensive retrofits.

Large Plants

Since the inception of the U.S. Global Nuclear Energy Partnership (GNEP) program three years ago, interest in large reprocessing plants, with capacities on the order of 1500–3000 MTHM/yr, has increased. To place this capacity in perspective, older military reprocessing plants in the West based on the PUREX process, e.g., the PUREX plant in Hanford, the two reprocessing Canyons at the Savannah River site, and the B-204 and B-205 reprocessing plants at Windscale in the United Kingdom, all had capacities of approximately 1500–2000 MTHM/yr, even though they handled metallic (rather than oxide) fuels of very low burn-up and relatively low radioactivity levels. These plants operated within the military programs of their respective countries and, hence, were less concerned with international safeguards. Still, some operational experience exists with large reprocessing plants.

One plant under construction in this category is the partially completed RT-2 commercial reprocessing plant in Krasnoyarsk, Russia. RT-2 was designed for a capacity of 1500 MTHM/yr and was expected to handle spent fuel from Russian VVER-1000 reactors (1000 MWe plant sizes). (The RT-1 plant could handle only the smaller sized fuel elements of Russian VVER-440 reactors, of 440 MWe capacity.) Construction on RT-2 started in the early 1980s, stopped in 1986 after the Chernobyl accident, with 30% completed, and has not yet resumed. The spent-fuel storage pool of RT-2 has been completed, and the plant accepts spent fuel from Bulgarian, Russian, and Ukrainian reactors. President Putin, in his February 2006 nuclear centers initiative, envisioned creating an international reprocessing center with IAEA participation centered on the RT-2 plant. With the revival of nuclear power in Russia, it is only a matter of time before this plant is completed and placed in commercial operation.

In the U.S. GNEP program, two types of large reprocessing plants have been discussed. First, GNEP envisions the development and commercialization of a new type of reprocessing plant based on a different aqueous reprocessing technique referred to as UREX. A conceptual design has been discussed for a UREX+ reprocessing plant with a 3000 MTHM/yr capacity at a cost of more than \$8 billion (2006 dollars). This conceptual design includes a colocated fuel re-fabrication plant and would serve as a complete fuel-recycling complex whereby spent fuel would enter one side and new recycled fuel would exit the other side of the complex. In parallel with GNEP, the French fuel cycle company AREVA and its international partners have proposed building a joint reprocessing and fuel re-fabrication plant with a 2500 MTHM/yr capacity using a slightly modified PUREX process called COEX, which would produce a mixed uranium-plutonium stream ready for MOX fuel fabrication. No separated stream of plutonium would leave the plant boundary. The total cost of this recycling complex was estimated at \$16 billion (2006 dollars), of which approximately \$1–2 billion would be dedicated to the re-fabrication

plant. Annual operating costs for this complex were estimated at \$900 million per year (2006 dollars).

While these studies represent hypothetical reprocessing plants, they indicate an interest in large future national reprocessing centers. This regime would be characterized by the following factors:

- reprocessing based on modified PUREX process if not the completely new UREX process;
- a complete recycle services plant with colocated reprocessing and fuel re-fabrication steps;
- a higher degree of fractionating the various process streams for better treatment downstream, with particular attention to the higher actinides, and with final co-extraction of uranium, plutonium, and possibly the higher actinides, to avoid the production of clean plutonium;
- much larger plant capacities, on the order of 2400–3000 MTHM/yr, i.e., three times the size of the current reprocessing plants; and
- a higher initial investment in the range of \$10–20 billion (2006 dollars), including the re-fabrication plant, waste stream handling facilities, and modern safeguards and MPC&A measures incorporated in the design from the start.

The driving forces for this departure from past experience include a recognition that the PUREX process, which was designed for the production of clean separated plutonium for military purposes, is not ideal for future commercial requirements; the realization that the fuel recycling operation should be designed as a single step rather than separating the reprocessing and fuel re-fabrication steps; the need for process flow sheet modifications, the co-location of recycling steps, and better waste stream treatments; and a recognition that the cost of future recycling plants will be significantly higher than previous medium-sized plants (by a factor of about three if not more). This cost could increase even further with the recent rise in construction costs. Finally, to compensate for the expected higher construction costs, it is necessary to increase the recycling plant capacity (by a factor of about four) to take advantage of economies of scale, thereby reducing recycling costs approximately to current levels for medium-sized plants.

The implications of these trends, should they materialize, are significant. Large plants cannot be built by industrializing countries. Given their large capacity, only a small number of such plants would be required for many decades. The expansion of nuclear power plants worldwide might not justify more than two or three such plants for some time. It is likely that such recycling plants would be constructed by nuclear-weapon states with advanced nuclear infrastructures such as the United States or France. Once operating, such plants would not just serve domestic and regional markets, but they could also seek clients from around the world. This operating mode would rely on increased long-distance transport of spent fuel and recycled fuel. The logistics of such operations and their international security and nonproliferation consequences have yet to be evaluated in detail.

The large plants proposed recently would pose significant new technological challenges to the international safeguards regime and to plant MPC&A measures. Process flows would become so large that it would be difficult to account for all fissile material

flows within the plant and to close the materials balance over different sections of the plant. It would be more difficult for the IAEA to verify, through direct measurements and statistical analysis, that no significant quantity of fissile material had been diverted. Fissile material unaccounted for (MUF) always occurs in any plant. Most of the MUF is located in the process piping within the plant. This material could be recovered on an annual basis when the entire plant is flushed during the general maintenance period. Assuming an acceptable MUF fraction is 0.1%, a plant with a capacity of 3000 MTHM/yr might have three tons (3000 kg) of fissile material unaccounted for each year. Since 8 kg is considered a “significant quantity” of plutonium, very low MUF values would still equal many significant quantities of plutonium. Therefore, the drive for acceptable economies of scale in reprocessing will create greater proliferation uncertainties and will pose significant safeguards and MPC&A challenges. Two factors compensate against these potential uncertainties. Firstly, most of the MUF values are not really lost but represent materials accumulated in process piping and holding tanks. With the periodic flushing down of the reprocessing plant piping system at the end of a reprocessing campaign, most of the missing material is recovered. Secondly, and more importantly, is the integrity of the safeguards system. So long as we are assured of the integrity of the safeguards system—personnel as well as equipment, we would know that it would not hide diversion attempts, and we would work diligently to close the material balances across the plant and provide better understanding where the presumed missing material might be located.

Physical Protection at Reprocessing Plants

Another proliferation concern about reprocessing plants is how secure the plants are from fissile material theft or from sabotage. Such attempts could be made easier by the presence of insiders providing information. The record so far indicates that no commercial fuel reprocessing plant (RT-1 during the 1990s excepted) has suffered a fissile material diversion event (so far as is known) or has been subjected to successful attack. Nevertheless, the past is not necessarily the best predictor of the future.

Plant size is an influential factor when reviewing possible future trends. Smaller reprocessing plants, being the oldest built, historically have employed the least sophisticated MPC&A systems and might be considered the most diversion prone. However, these plants, which often lack transparent economic justification, are most likely constructed by their host countries with military uses in mind. As such, small plants are likely to be heavily guarded and protected against any attempted external attack. Therefore, even though such plants might not employ advanced MPC&A methods, they may be well protected against theft or sabotage.

Medium-sized plants, which represent the current generation of operating reprocessing plants, employ the best MPC&A measures designed and installed when those plants were constructed more than 10–20 years ago. These measures have been enhanced but still are not equivalent to measures now incorporated into plant design. Thus, the Rokkasho Mura plant has better safeguards and MPC&A systems than THORP, designed 20 years ago. In fact, a plutonium pipeline at THORP was punctured in 2006, leaking plutonium solution into the cell in which it was located for months before this break was discovered. Although current mid-sized plants are better protected against diversion than smaller reprocessing plants, they often lack state-of-the-art protection

measures. These plants are operated by large state corporations that provide reasonable protection against sabotage, but still they are probably less protected than smaller plants. Furthermore the larger physical size and the larger operating staffs required for mid-sized plants imply that the opportunities to find and recruit an insider are statistically greater. In both types of operating reprocessing plants, protection against diversion is not achieved just by more guards and guns, but first of all by a rigorous materials control and accounting system. Such systems and the training of their operating personnel have advanced over the last 30 years or so, and represent the main barrier against material diversion. While guns and guards might protect against outside intrusion, materials control and accounting is used to protect the material inside the plant, as well as to account for outside shipments.

Large reprocessing plants and breeder fuel reprocessing plants have yet to be constructed. We can speculate that even with the best MPC&A measures, it would be difficult to guarantee that a small amount of fissile material had not been diverted. On the other hand, given the large size and the strategic nature of the operation for the host country, it is likely that such plants would be well protected against external attack, with or without insider help. The best protected plants should be future breeder fuel recycling plants. Colocating them inside breeder energy centers would confer an additional degree of security against external attack. At the other end of the scale, small reprocessing plants would make the application of future advanced MPC&A measures more effective. Put simply, advanced safeguards applied to 100 MTHM/yr plants should be more effective than similar measures applied to a 3000 MTHM/yr plant. In both cases rigorous materials control and accounting is essential.

In summary, the current mid-sized reprocessing plants are probably the least protected, relative to small or large plants, against either diversion or sabotage. Future breeder fuel reprocessing plants, if designed and constructed as parts of integrated energy centers, will likely have the best protection. All other plants represent intermediate situations between these two extremes.

Breeder Fuel Reprocessing and Recycling Plants

Breeder reactor fuel reprocessing plants are distinct from the LWR fuel reprocessing plants discussed above, because they handle mostly plutonium-bearing fuels, whereas LWR fuels contain low-enriched uranium (LEU). Breeder fuel will contain some uranium if MOX fuel is used. Breeder reactors consume plutonium in their core while concurrently producing even more plutonium than they consume in their blankets. The excess plutonium above the reprocessing needs of the plant—the breeding gain—could accumulate over time to provide inventory for future breeder reactors.

For the breeder system to work efficiently, reprocessing and recycling plants must be integrated with the routine operations and fueling cycles of the breeder reactors they support. Whereas LWRs can operate on an open fuel cycle without reprocessing, breeder reactors depend on periodic spent-fuel discharges and fuel recycling. Breeder reactors might be commercialized in a few countries starting around 2030, and they might gain greater global acceptance and spread during the second half of the 21st century. Breeder fuel reprocessing and recycling plants should be developed concurrently, so they are commercialized a few years after commercial breeder reactors start operating. Since breeder reprocessing plants will mostly handle plutonium-bearing fuels, some of which

could be close to weapon-grade, plant location, ownership, and operation will become serious issues. For example, breeder reactors could be government-owned but contractor-operated facilities located in closed nuclear energy centers that are colocated with fuel reprocessing and recycling plants.

Given these considerations and the higher concentrations of plutonium in the breeder fuel, breeder fuel recycling plants will be designed to reduce the fissile material content in any section of the plant and lessen the chance of a nuclear criticality accident. These measures require greater numbers of process equipment items and parallel operating steps. Breeder reprocessing plants would operate at smaller capacities compared with similar plants handling LWR fuels. It is now envisioned that breeder reprocessing plants would be constructed in the 100 MTHM/yr capacity range, serving the recycling needs of 10–15 breeder reactors. In general it is assumed that breeder reactor reprocessing would operate on a modified PUREX process, producing MOX fuel elements with higher plutonium concentration than would be the case for LWR MOX recycling. Whereas in the latter the MOX fuel should have fissile content similar to the nominal LEU fuel originally in the reactor, breeder reactor fuel could include plutonium concentrations of up to 20%, i.e., a factor of 2–4 higher than the U-235 content in LWRs. These higher plutonium concentrations imply that smaller amounts of breeder fuel would be required to drive a breeder, compared to the amount of LEU fuel required to drive a similar capacity LWR. This difference accounts for the smaller size of the breeder fuel reprocessing plant compared with LWR reprocessing plants and for the need to more carefully control the design and process vessel sizes of the breeder recycling plant to prevent criticality accidents.

Two other characteristics of breeder reactor fuel cycles that have security implications are the use of metallic rather than oxide fuels (and the possible transition to a UREX reprocessing process) and the advanced burner variant of the breeder reactor design.

Future UREX+ Reprocessing and Recycling Plants

The U.S. GNEP program adopted the UREX+ family of reprocessing cycles as the main future U.S. nuclear fuel reprocessing and recycling process. UREX processes would be applicable to LWR fuel reprocessing to provide fuel for advanced burner reactors (ABRs) and would also be applicable for recycling breeder reactor fuel. The following two main features of the UREX process distinguish it from PUREX:

1. No clean separation of plutonium. Plutonium will eventually be extracted with all other higher actinides and will then be further mixed with uranium to produce mixed uranium, neptunium, plutonium, actinide oxide fuel, or a similar composition of metallic fuel for breeder use. In any process the plutonium will always be co-extracted with neptunium, rendering it much less useful for weapons.
2. High degree of fractionation of all other waste streams. Groups of waste products will be separated by chemical characteristics or by radioactive decay times, to ease ultimate waste disposal, by handling each waste fraction according to its specific attributes.

The factors driving the adoption of the UREX processes were essentially three: breaking the logjam in the licensing and operation of the Yucca mountain repository by

significantly reducing the amounts of waste to dispose of and their long-term radio-toxicity; disposing of excess separated plutonium by combining it with the higher actinides and burning it in ABRs; and reducing the need for new, small, sensitive fuel-cycle facilities in developing countries by offering them an attractive lease–take-back fuel supply and disposal option. This option is made possible by freeing up significant space at Yucca Mountain due to the adoption of the UREX processes.

An example of the waste stream fractionation made possible in the UREX family of processes is the UREX+1b process, which will produce the following:

- clean, separated uranium for possible LWR use;
- long-lived technetium fission products for transmutation in a reactor or accelerator;
- strontium and cesium fraction, with average half-lives of about 30 years, which could be disposed of in an engineered facility;
- uranium, neptunium, and plutonium in the higher actinide fraction, either in MOX or metallic form, to be burned in ABRs; and
- remaining fission products including lanthanide isotopes, to be sent to a waste repository.

This high degree of fractionation allows recycling of useful fractions and special disposal options for the waste streams tailored for their specific characteristics. The plutonium and neptunium in the higher actinide fraction (referred to as the transuranic or TRU fraction) will have inherent radioactivity characteristics that will allow self-shielding and provide a high degree of protection from would-be diverters. In comparison, clean, separated weapon-grade plutonium has a spontaneous neutron generation rate of 60 neutrons per gram per second and a gamma radioactivity of 0.2 Roentgens per gram per hour at 0.5 meters, whereas a TRU stream produced in a UREX+1b process would have a spontaneous neutron generation rate of 300,000 neutrons per gram per second and a gamma radiation dose of 200 Roentgens per gram per hour at the same distance.

The UREX process, depending on which version is adopted, could provide a high degree of self-shielding. The problem is that most nuclear power plant operators do not want to handle highly radioactive fuel in their power plants, and the cost of remote fabrication and handling of the fuel increases costs considerably. Thus, this type of fuel might be applicable to special-purpose government-owned nuclear centers where plutonium is separated in TRU form for burning in ABRs. If breeder reactors gain acceptance on a large scale, a transition from the highly radioactive TRU fuel to the cleaner PUREX separation type fuel would be required. This change would increase the proliferation concerns associated with the fuel, unless various institutional and technical measures were incorporated to provide the requisite safeguards. In this case, operational and economic concerns would drive fuel cycle development in directions different from nonproliferation concerns.

This dichotomy may, however, be moot as the next U.S. administration might scrap the GNEP program and embark on a different nuclear energy and nonproliferation program. Regardless of the type of program, the main technical features envisioned in GNEP—UREX reprocessing and ABRs—would require 30 years or so to develop and

commercialize. Over that time period up to seven U.S. administrations could come and go, each of which could cancel or significantly modify these programs. The main problem facing the prospects for fuel recycling in the United States is the consistency of supportive government policies across several future U.S. administrations.

Pyro-Processing or Electro-Refining Reprocessing

An alternative fuel cycle for breeder reactors, called “pyro-processing” or “electro-refining,” is based on metallic fuel. Since the early inception of breeder programs, two competing breeder reactor and fuel cycle concepts existed. The older mainstream effort, pursued mostly by industrial design corporations such as Westinghouse, General Electric, and Atomics International, was based on a central breeder reactor fueled with plutonium oxide fuel and operated in a high breeding-gain mode. Plutonium-based fuel would have been reprocessed in a large-scale fuel cycle facility operated on a modified PUREX process. The excess plutonium would accumulate to supply new breeder reactors when required by the increasing demand for electricity.

The alternative technological approach was developed by the Argonne National Laboratory (ANL) and demonstrated in Idaho in the experimental breeder reactor (EBR) programs. EBR II was a 65 MWe breeder development program that operated successfully from the mid-1960s to mid-1990s and demonstrated the alternative breeder approach based on metallic plutonium fuel. The fuel was reprocessed, re-fabricated, and recycled into the reactor in a dedicated small fuel-cycle facility located adjacent to the reactor building. The metallic fuel recycling process demonstrated in the integral fuel-cycle facility was based on pyro-processing and melt refining of the molten plutonium fuel pins. Between 1964 and 1969 the facility recycled about 30,000 irradiated fuel pins with turnaround times of approximately two months after discharge. The recycling facility’s throughput averaged about 100 kilograms of plutonium fuel per month.

The alternate breeder reactor and fuel cycle designs derived from this experience are referred to as the integral fast reactor (IFR). According to this concept, breeder reactors, operating on metallic rather than oxide fuel, would be clustered in energy centers with a dedicated recycle facility per center providing complete recycling services for all spent fuel discharged from the center’s reactors. The dedicated fuel recycle plant would have relatively small capacity, e.g., 100 MTHM/yr. By contrast, an oxide fuel reprocessing capacity would not be limited by the size of a hypothetical energy center; it would correspond to the capacity of the well-spread breeder market and the technological limitations of the modified PUREX process employed.

A metallic fuel recycling plant would involve electro-refining of the metal fuel melt. In an IFR fuel plant, the fuel would first be melted, mixed with a cadmium salt solution, and placed in an electro-refining cell. Uranium would be electrochemically separated from the IFR spent-fuel melt and deposited on the cathode, while plutonium and the higher actinides, with different electrochemical potentials, would accumulate in the electrolyte salt solution and then be deposited on a separate cadmium cathode. The fission products would be partially deposited in the melting cell and removed for treatment. The noble metal fission products would remain in the cadmium salt electrolyte and would then be sent to a fission products consolidation and treatment cell.

The equipment required for the spent-fuel melting and for the fissile material recovery in the electrochemical separation cell would be relatively small in size. No front-end oxide-reduction step would be required. No plutonium separation and

purification steps would be required, or in fact allowed. No clean plutonium stream would exist anywhere within this reprocessing scheme, and the recovered plutonium would always be accompanied by the higher actinides co-extracted with it and never separated. As a result, the entire fuel recycling facility would be much smaller than a conventional PUREX type reprocessing plant. Due to its smaller size this IFR fuel cycle facility could be combined as an integral part of a single breeder-fuel cycle complex—hence the IFR term—or for better economics, a larger IFR recycling plant could provide recycling services for an entire breeder energy center.

This IFR fuel-recycling scheme has been proposed for recycling breeder reactor fuel only. If applied to LWR fuel reprocessing as an alternative to the PUREX process, the recycling plant would have to be larger to handle the much larger throughput from accumulated LWR spent fuel and would require a front-end oxide-to-metal lithium-reduction process. By the early 1990s, the industry oxide-fuel breeder reactor design, which was more advanced, consolidated with the Argonne IFR program, which was strong in fuel-cycle facility design but relatively weak in reactor design. The joint program adopted the General Electric modular Super-Prism breeder reactor design, modified to operate on metallic rather than oxide fuel, and the fuel type and fuel cycle services provided by the ANL-designed IFR fuel recycling facility. With the termination of the entire DOE breeder program in the mid-1990s, this U.S. reactor-fuel cycle combined concept became moot. Meanwhile, other international fast reactor programs have progressed along the lines of the preferred industry concept with oxide fuel breeders served by a large centralized reprocessing plant operated on a modified PUREX process.

By 2005 the U.S. breeder reactor program and its associated fuel cycle program had been revived as parts of GNEP, which has developed two parallel breeder programs. The main effort involves an advanced burner reactor (ABR), conceived as a non-breeding fast reactor for actinide burning only, coupled with a UREX+ process that produces a co-extracted stream of plutonium and all higher actinides, or, at a minimum, a stream of plutonium and neptunium. In no version of the UREX process would a clean separated stream of plutonium be produced. This new ABR design and the associated fuel cycle facility—both yet to be developed—would be initiated as a combined industry-DOE program to be led by Idaho National Laboratory (INL) over a multi-year, if not multi-decades, program.

In parallel with this effort, the Argonne IFR program has reemerged, now centered on a small (100 MWe), highly modular reactor concept operated on an IFR metallic fuel and fuel-cycle design. The reactor and fuel-cycle design stress long-lived fuel and a self-sustaining breeding cycle (breeding ratio of 1.0, i.e., a breeding gain of essentially zero beyond recuperation of reprocessing losses). One variant of this design is conceived as an export reactor that would give the host country minimal involvement in the fuel cycle. The reactor design incorporates a plug-in scheme, including fuel provided in a closed cassette. A new metallic fuel cassette would arrive every 20–30 years, be loaded into the reactor, and the old cassette removed and sent back to a supplier country for reprocessing and recycling. The idea is to provide a proliferation-proof design for export to developing countries with limited nuclear infrastructure and increasing electricity demand.

Given this brief history of the U.S. breeder program, one can only marvel at the tenacity and ingenuity of those involved in U.S. breeder reactor designs over more than

50 years. One might also despair at the lack of continuity and unexpected changes in technical direction wrought by political pressures. The lack of political support and technological continuity has stimulated very interesting innovations—while also removing the program from commercial reality. The comparison with the U.S. light-water reactor (LWR) program could not be more striking. The conceptual LWR design was developed for the U.S. Navy during the 1950s and transferred to industry in 1958. Since then the basic concept has remained essentially unchanged, backed by a utility industry that desires one or two main designs with minimal changes and emphasizes ease of operation, economics, and proven designs at the expense of brilliant innovations. Given this historic record and the likelihood that the new presidential administration in 2009 will chart its own course on the breeder program, the fate of the fast reactor in the United States is uncertain, even though the need for this technology will only increase over time. Other FBR programs such as those in China, France, India, Japan, and Russia, driven by their own internal national logic, might continue and expand regardless of U.S. policies in this area.

Metal vs. Oxide Plutonium Fuels

The two different breeder reactor fuel designs that have evolved in the United States—based on oxide and metal fuels—have distinct operational and nonproliferation characteristics.

Oxide breeder fuel designs evolved first in the United States and then in other international programs, complementing the LWR fuel infrastructure based on mixed uranium-plutonium oxides, though breeder MOX would have higher plutonium content than LWR MOX. Fuel would be recycled based on a PUREX process. A clean stream of plutonium would be produced and mixed with a clean uranium stream for conversion to recycled fuel use. The new or recycled fuel would be relatively non-radioactive and could easily be handled by breeder plant operators. However, the ease of operation, essential for gaining electric utility acceptance, poses nonproliferation concerns.

Plutonium oxide fuels—particularly fresh fuel or that from the first recycle without significant buildup of higher plutonium isotopes and their decay chain products—are relatively non-radioactive and lack self-protective qualities. This fuel is easier to handle—or divert—through direct contact or glove-box operations, rather than through remote-control shielded operations. The relatively large (though yet unspecified) size of a breeder oxide fuel recycling plant and its relatively high concentration of plutonium in the MOX fuel might raise issues regarding the reliability of MPC&A methods and the adequacy of safeguards employed in the plant. It has yet to be analyzed, let alone demonstrated, that proliferation resistance and physical protection measures in these plants and throughout the breeder fuel cycle would be adequate to account for all fissile materials and ensure that no fuel has been diverted. Transporting fuel from breeder reactor plants in various locations to a centralized fuel recycling plant could increase the chance of fuel diversion. High burn-up MOX fuel, particularly fuel containing recycled plutonium, might include about 50% or more of the higher plutonium isotopes above Pu-239, about 2% of the heat-generating Pu-238 isotope, and about 1% of the Am-241 isotope with energetic gamma rays emitted by its decay products. Such plutonium in the MOX fuel would be difficult to handle manually, or in glove-box operations, and might require remote-controlled, shielded operations to extract.

Metallic fuel, in general, is less desirable than oxide fuel for proliferation reasons. If diverted, metal fuel can be used directly for weapons without requiring an oxide-to-metal reduction step. This concern did not apply to EBR II, because the breeder fuel never went outside the reactor-fuel recycling complex. This concern might also be obviated in the case of a closed breeder energy center with a centrally located fuel recycling facility. So long as all the facilities within the center's perimeter are adequately protected, the security of the internal fuel flows could be assured. Diversion also would be more difficult if the higher actinides are co-extracted with the plutonium metal, due to the high radiation barrier. Experienced electrochemists with insider support could conceivably modify the electric potential in the electro-refining cells and achieve plutonium separation from the higher actinides to create a relatively clean stream of plutonium. Whether it is possible to remove clandestinely produced clean plutonium from a closed energy center is another issue.

On the other hand, metallic-fuel breeder reactors that use co-extraction might not be attractive to utility companies, because high neutron doses and penetrating gamma radioactivity make it difficult for reactor operators to handle the fuel. Higher radiation levels within a plant risk exposing utility staff to higher radiation doses, translating to higher health care and liability costs for the company. Hence, it is not clear the benefits of operating breeder reactors with metal fuels would outweigh the higher operational costs. This is another case of conflicting operational and nonproliferation concerns related to breeder reactors and their fuel cycles. The basic issue remains as to whether the long-term energy security benefits of breeder reactors justify their increased operational complexity and the proliferation concerns related to their fuel cycle. As oil prices move beyond \$100 per barrel, the energy benefits of this nuclear technology seem more attractive and, hence, deserve renewed attention.

The GNEP breeder designs, if pursued, pose their own operational and nonproliferation concerns. The ABR design operating on a UREX fuel cycle will provide fuel with a degree of self-protection due to the co-extraction of plutonium with neptunium and other higher actinides. Furthermore the entire concept of a burner reactor with no or small net plutonium breeding should be attractive on nonproliferation grounds as the best way to dispose of excess plutonium, as opposed to burying it in the ground where it might eventually be recovered. The problem is that an inert matrix fuel such as plutonium-zirconium needs to be developed and tested, and a breeder core design without uranium needs to be developed. The reactor's core should avoid any internal, axial, or radial blanket containing fertile material to prevent new plutonium production even as fresh external plutonium is burned down. This could require the joint development of a new reactor core and plant design coupled to a new fuel development program. It is not clear that DOE and its national laboratories wish to embark on such a program or are qualified to do so.

Furthermore, the ABR, if pursued, is a temporary or intermediate concept only, designed to burn down current excess supplies of separated plutonium before a transition to a full-fledged breeder economy. In the long view, is it worth the time and effort to develop what might be only an intermediate-stage fast-reactor program? Might it not be better to continue on a long-term breeder reactor development program while improving control of the separated plutonium stocks, until the time comes to commercialize breeder reactors? The next U.S. administration will have to grapple with these issues. Other

countries such as Russia and India have opted to avoid this intermediate step and to proceed straight to the FBR stage. India has done so due to uranium shortage considerations and the desire to rapidly expand its nuclear capacity based on non-uranium-consuming power technologies. Russia values its plutonium highly and would use it only in the most efficient mode—burning it in FBRs. Russian plans for plutonium recycling in LWRs have not yet materialized, and their survival is uncertain without significant U.S. funding.

The small modular export version of a zero-gain self-sustaining breeder, while attractive in terms of providing energy to developing countries with limited nuclear infrastructure, poses its own nonproliferation issues. The long-lived self-sustaining cassette core is an attractive nonproliferation feature. However, the desirability of exporting to potentially unstable countries a reactor concept based on plutonium fuel (rather than LEU-fueled LWR reactors) is debatable. Fresh plutonium-based metal fuel cassettes produced from separated LWR plutonium might be attractive diversion targets if the cassettes can be opened and the plutonium extracted, thereby providing hundreds of kilograms of metallic plutonium ready for weapons application. Recycled plutonium cassettes including the higher actinides would be more attractive from a proliferation perspective, because any attempted diversion would require chemical separation of the actinides from the plutonium, and the actinides' radioactivity presents a substantial radiation barrier. Would such a barrier prove adequate against a determined national diversion attempt after NPT withdrawal? Would the prize of acquiring several hundred kilograms of metallic plutonium be worth withdrawing from the nonproliferation regime and facing all the attendant sanctions? These issues have yet to be analyzed.

Technical Approaches to PR&PP

The protection of fissile material inside a fuel cycle facility includes many aspects that fall under the general heading of proliferation resistance and physical protection (PR&PP). Some of these measures were discussed in previous sections, e.g., colocating recycling facilities with breeder reactors, or the co-extraction of plutonium and other more radioactive transuranic isotopes to provide a radiation barrier against theft. This section examines additional technical measures for PR&PP for the back end of the fuel cycle, keeping in mind that PR&PP measures should be viewed from a comprehensive system-wide perspective.

Safeguards and MPC&A at Fuel Recycling Plants

The basic technical approach to PR&PP is the application of a good safeguards system to the fuel cycle facility in question and to all other nuclear related facilities in the country. The main requirement of the safeguards system is accounting for all fissile materials. Each inspected facility is divided into several areas in which accounting is conducted using specific measurement procedures. Material balances in each area are integrated with those in adjacent areas using input-output analysis. This process is repeated sequentially on all material balance areas within the facility until the entire balance is reconciled or “closed.” Material accounting is performed as well in other nuclear related facilities in the country where fissile material may have been transported, until the material balances close not only internally for each facility but also jointly between interconnected facilities.

Proceeding in this fashion, it might be possible to close the fissile material balance over an entire country's nuclear activities, leaving flows of material into and out of the country, which could be checked against international supplier and shipper records. Such a comprehensive fissile material accounting process could, in principle, provide a national level safeguards evaluation. A major question is what should be done in case the fissile material balance does not properly close, raising suspicion of inadvertent loss or intentional diversion. The IAEA is charged with carrying out safeguards inspections in each country based on the agreement the country has signed with the IAEA. However, the extent to which the IAEA can proactively seek additional information regarding the causes for a material imbalance is unclear. The safeguards department of the IAEA engages in accounting but lacks investigative or policing powers. At what point do such issues stop being a technical discrepancy and become a political issue to be handled by the IAEA director general or the Board of Governors? Recently, particularly in the cases of Iran and North Korea, some members pushed the IAEA to act more proactively as a nimble investigator rather than as accountants. Is this a role the IAEA is qualified to assume? In the Iraq proliferation investigation case, the United Nations Security Council (UNSC) created a special purpose organization—UNSCOM/UNMOVIC—to carry out very intrusive (and, it turned out, confrontational) investigations inside Iraq, cooperating and to some degree supplanting the role of the IAEA in the nuclear area, and including chemical and biological weapons inspections. Should the IAEA in the future assume, on a standing basis, equivalent investigative functions? Should it be provided budget and personnel to carry out such functions? If a material breach of the safeguards agreement is discovered, the IAEA notifies the Security Council, which is responsible for enforcement. But what kind of enforcement will be forthcoming, given the veto powers of the council's five permanent members? These issues have yet to be resolved. Suffice it to say that the IAEA may not want to assume such additional powers, nor is there a consensus that it is qualified to do so.

Regardless of the IAEA's eventual role, the technical area of process stream measurements to provide the data required for materials accounting could be further improved. In addition, colocating and even integrating the reprocessing plant and the fuel re-fabrication plant could improve facility security, as has been demonstrated in the Rokkasho Mura reprocessing plant in Japan. Future plants could merge the flow sheets of the reprocessing and re-fabrication sections into one integrated recycling facility. Rokkasho Mura also illustrates the need to integrate safeguards considerations into the design of the fuel recycling facility before construction starts. Defining material balance areas on the process flow sheets makes it possible to specify in advance where physical barriers between plant sections should be located, what types of material measuring devices should be installed at what points based on the radiation characteristics of each material flow, and how to design the measuring point so it cannot be bypassed and yet it is accessible to inspectors as required.

Another lesson from Rokkasho Mura is the need to integrate the different material flow measurements from across each material balance area and across the entire plant, to provide a continuous, comprehensive picture of the plant material balance. Measuring gamma radiation; counting fuel elements entering the process; counting empty hulls leaving the process; integrating neutron emissions measurements; measuring product outflows, acid and reagent concentrations, oxidation-reduction potentials, and fluid

density—all should be integrated to provide real-time indications of the status of the material balance across the entire fuel recycling facility. While this measurement integration process has not yet been demonstrated, understanding has been gained on how to incorporate enough measurement points across the facility and how to develop the full-plant material accounting computer code.

Rokkasho Mura also illustrates the importance of inspectors' permanent presence on site. IAEA inspectors can monitor the performance of the measuring devices, assure that no tampering has taken place, download collected data where required, and be available to respond to an emergency. Stationing inspectors permanently on site is expensive, but it may be required to ensure adequate safeguards, given the significant material flows at large reprocessing plants. It is also important that the inspectors be allowed free access to the plant without infringing on commercially sensitive plant design information. And yet, inspectors must not identify so much with the plant that they lose their independent perspective. Careful preparation and rotation of inspectors would be required. Inspector access to the plant also would have to be well coordinated with the physical protection functions to prevent conflicts.

At the same time, Rokkasho Mura suggests the need for informed discrimination in allocating limited IAEA safeguards resources. As long as there is confidence in the integrity of the Japanese safeguards system, and as long as we are sure of the Japanese Government's resolve to forgo nuclear weapons, dedicating significant IAEA resources to safeguarding the Rokkasho Mura plant is not really essential. From a nonproliferation perspective, given the limits on the number of safeguards inspectors and the budget of their department, it might be more useful to dedicate additional safeguards resources to more problematic countries such as North Korea, Iran, India, and others. The problem lies in the nature of the informed discrimination process. Who should reach such decisions, based on what criteria and what degree of openness of the related deliberations? These issues are difficult to handle in the diplomatic and political spheres of the IAEA decision-making process.

Finally, to protect the plant and prevent diversion, it might be necessary for plant management to institute human performance and reliability programs to select, train, and monitor plant personnel. Standard industry procedures on personnel selection, simulator training, using a two-person rule in sensitive areas of the plant, limiting access to sections of the plants on a need-to-work basis, and similar measures should be implemented.

Clandestine Reprocessing Plants

When discussing clandestine production of plutonium, the issue is not just whether it is possible to divert material from a safeguarded reprocessing facility but whether it is possible to produce plutonium, possibly weapon-grade, secretly. A reprocessing plant is of little value without a supply of spent fuel to reprocess, though a one-time campaign based on a single large diversion might yield several tens of kilograms of separated plutonium, which will provide all the initial supply of weapons the proliferator country might require. Thus, the first item for consideration is whether it is possible in the present global nonproliferation environment to construct a clandestine plutonium production reactor, the spent fuel from which would be used to make plutonium. This feat likely would be difficult in the current safeguards environment, especially with the IAEA Additional Protocol, reconnaissance satellites, and other sources of intelligence, such as radioactive-emissions-detecting monitors fielded by

several countries in various overt or secret programs. A counterexample is the Syrian plutonium production reactor in Al Khibar, under construction since 2001 (at least), until it was destroyed by the Israeli air force in August 2007. That reactor was not discovered through IAEA actions, and in fact, the United States and Israel, which obtained from their intelligence resources information about the reactor, were not ready to disclose it to the IAEA due to the perceived politicization of the IAEA decision-making process. A new production reactor might be constructed as a legitimate safeguarded project with the intent to subvert its declared operation to military purposes without alerting IAEA inspectors, or in preparation for eventual withdrawal from the NPT. The Iranian reactor at Arak is a case in point.

Spent fuel from commercial reactors can hypothetically be diverted along transport routes to a clandestine reprocessing facility either in country or in a third country. This option, while technically possible, will most likely be discovered early and would be tantamount to a nuclear breakout event, if carried out by a state. Spent fuel, being highly radioactive, is transported in large, heavily shielded casks (see chapter 5). It would be difficult to hijack and hide such a large item. The radiation signature of the cask and other homing and signaling devices possibly attached to the cask could allow real-time monitoring of the cask movements from a distance, even assuming that the cask is not directly accompanied by security personnel. Thus, this route to obtaining spent fuel for clandestine reprocessing would not provide enough time for plutonium extraction before an alarm is given, leading to possible counteraction. The Syrian reactor in Al Khibar, however, came close to refuting this conclusion, though we do not know yet where reprocessing of the spent fuel to be generated in that reactor would have taken place.

Finally, a clandestine reprocessing plant of simple design hypothetically could be discovered, since the volatile, long-half-life fission products such as Kr-85 and other xenon and iodine isotopes might be released to the atmosphere when spent fuel is dissolved. Tracking a radioactive plume emitted from the plant and working back to the origin of the plume using local meteorological data would make it possible, at least in principle, to locate the clandestine reprocessing plant. However, this tracking method would require either a large number of sensors or some knowledge of where a secret plant might be located and when it would be in operation, to detect the radioactive plume in sufficient strength so the signal exceeded the atmospheric Kr-85 background level. If the clandestine plant were hidden over a vast expanse of uninhabited land, significant time might elapse before detection could be achieved, by which time the plume could disperse sufficiently that backtracking to its source would be difficult. Complex local microclimates might also impede tracking the plume back to its true source, as was the case in 2004 with the suspected “second” reprocessing plant site in North Korea. Moreover, the noble gas emissions from reprocessing plants could be trapped in special cold traps available commercially. In the absence of telltale radiation discharges, the location of a clandestine plant cannot be reliably identified by remote radioactive detection techniques. It was learned subsequently that the North Koreans did not use cold traps, and although they did have a second reprocessing line available in Yongbyon, they did not use it. The difficulty in tracking the Kr-85 plume had more to do with geographic and climatologic conditions than with human ingenuity.

Political and Institutional Approaches to Reducing PR&PP Concerns

PR&PP systems should involve multiple approaches ranging from technical to political and institutional. The latter could involve co-location of the reprocessing and re-fabrication plants, and regional reprocessing centers, as discussed above. Additional political and institutional approaches are discussed in this section, specifically, fuel lease and take-back arrangements and regional fuel reprocessing centers, aimed at reducing incentives for a state to acquire independent nuclear capabilities that provide it with a latent proliferation capability, whether exercised or not.

Breakout from the NPT Regime

The routine commercial operation of a reprocessing plant depends on its country's adhering to the NPT. Moreover, an additional important factor is the issue of transparency, related to the integrity of the safeguards system. As long as the inspected country is willing to provide all the information requested by inspectors and render its fuel cycle operations transparent to the safeguards regime as a matter of state policy, there are little grounds for proliferation concerns. The transparency issue is the one separating Japan, on the one hand, from North Korea and Iran, on the other. This issue is the source of ongoing concerns about the intentions behind Iran's enrichment program. Perhaps one of the greatest concerns today involves countries that build sensitive nuclear facilities under the guise of peaceful uses of nuclear power, then withdraw (break out) from the NPT to pursue nuclear weapons. Article X of the NPT allows any country to withdraw from the treaty after providing 90 days' notice, a right North Korea invoked in 1993–1994 and again in 2003, and one that Iran might invoke in the future.

After a country withdraws from the NPT, its previously declared and safeguarded facilities, along with possible clandestine facilities, can be used to produce weapon-grade plutonium. Furthermore, spent-fuel elements from the first and second discharges from the first core of any reactor operated in the state, which might still remain in the spent-fuel pool, would contain significant quantities of near-weapon-grade plutonium. Reprocessing these fuel elements could yield tens of kilograms of plutonium. This plutonium might be useful for weapons designed by experienced designers, or it might provide sufficient political leverage to the country, regardless of its actual weapons utilization.

A clandestine reprocessing plant that exists prior to breakout might thereafter operate in a more open manner, including plant enhancements and increased personnel that might have been difficult for the state to provide while the country was still a member of the NPT. The only sources of spent fuel for reprocessing would be older spent fuel stored in pools, fuel residing in the reactor cores, and fresh fuel reloads purchased ahead of time and stored for future use. Once these fuel sources have been reprocessed, no new fuel supplies would be available and the reprocessing plant might shut down.

Proposals have been made to raise the cost of withdrawal, e.g. requiring the return of materials, equipment, and technology obtained while the country was a member of the NPT regime. Other approaches involve binding UN Security Council resolutions, negotiated in advance, to impose sanctions after withdrawal if weapons programs are suspected, thus circumventing the UNSC veto. In any case, the methods for dealing with this contingency are primarily political and not technical. A more elaborate discussion of these proposals would be interesting but is beyond the scope of this report.

Fuel Lease and Take-Back

Fuel lease and take-back arrangements were the standard fuel-cycle operating mode during the early days of the U.S. nuclear power program. This concept was further established on a large commercial scale by the former Soviet Union, which provided its eastern bloc nuclear power plant clients with fresh fuel with which to operate their Russian-designed nuclear power plants. The spent fuel discharged from these reactors was taken back to the former Soviet Union, mostly for reprocessing at the RT-1 (Mayak) plant in Chelyabinsk-65, releasing the consumer countries from any waste disposal obligations. The fissile content of the discharged fuel remained in Russia. This operating mode removed any incentives for former Soviet client states to pursue domestic fuel reprocessing. Russia handled the back end of the fuel cycle and guaranteed fresh fuel supplies. As another hedge against latent proliferation intentions, possibly harbored by client countries like Romania, it helped that Russian troops were stationed in country.

The GNEP program recently proposed fuel lease and take-back arrangements. The United States would be in a position to offer nuclear fuel on a lease–take-back basis to interested foreign countries in the future, once a UREX reprocessing plants is operational (or becoming near operational), and once ABRs are available to burn excess plutonium. Just as in the former Soviet model, the United States would provide fresh fuel at world market prices (or at a slight discount), and would take back the spent fuel, keeping the remaining fissile content in the United States, but also disposing of the nuclear waste. The consumer country would be guaranteed fresh fuel at attractive prices, it would avoid the need to construct expensive reprocessing facilities and, most importantly, it would be relieved of waste disposal responsibilities. Reprocessing facilities could not be justified on economic grounds anyway, given the small nuclear capacity of most consumer countries, and the lease–take-back arrangement would provide another convenient reason to forgo the construction of sensitive fuel-cycle facilities. These arrangements would not work if the consumer country harbored nuclear weapons production intent. However, rejection of an economically and environmentally attractive offer for fuel lease and take-back would send a signal that other considerations are at play, affording time for political intervention and possible resolution of the security concerns. This proposal depends on commercial deployment of a UREX recycling plant and the ABR, both technologies that will require more than 20 years to reach maturation. Thus, full implementation of this proposal is doubtful for at least two decades or more.

In 2006, in parallel with the U.S. GNEP program, Russia's President Putin proposed a nuclear centers initiative. While this initiative focused on the International Uranium Enrichment Center (IUEC) a parallel effort was also proposed, centering on the partially completed RT-2 plant in Krasnoyarsk. Russia would take back the spent fuel and reprocess it, for a fee; payments for spent-fuel take-back could provide seed money for plant completion. The fissile content would most likely remain in Russia, while the waste fractions would be returned to the consumer country. Depending on contract terms and conditions, it is possible that the waste streams could be disposed in Russia for an additional fee. In 2006 Russia and Iran signed a contract of this type for handling the spent fuel discharged from the Russian-built Bushehr reactor in Iran. The Iranians did demand, however, that they be given credit for the fissile content of the fuel (reprocessed uranium and plutonium) to be kept in Russia. This contract, if and when executed, could offer a precedent for future fuel take-back contracts. If combined with fresh-fuel supply

contracts from the IUEC or other sources, this arrangement with Iran would represent the first near-term implementation of a lease–take-back nuclear fuel supply arrangement under modern conditions. We should keep in mind that Iran adamantly rejects any fuel supply and disposal arrangement that does not allow uranium enrichment in a domestic Iranian plant.

The major drawback of lease–take-back fuel supply arrangements is that very few countries currently are willing to take back spent fuel not burned in their own nuclear power plants for the benefit of their own citizens. The concept of spent-fuel disposal as a commercially and economically attractive business proposition has not yet materialized, due to high reprocessing costs and domestic political concerns regarding the environmental impact of waste disposal. Only Russia prior to GNEP had sporadically expressed interest in this concept as a commercial arrangement. China might propose such arrangements in the future, once commercial spent-fuel reprocessing is developed. The United States will most likely not accept spent-fuel take-back arrangements until the UREX/ABR complexes or others are implemented and Yucca Mountain is opened for waste disposal. Thus the lease–take-back concept, though attractive from a nonproliferation perspective, may not be realized for many decades in the United States.

One way of instituting a version of the lease–take-back concept occurred in 2007 with the signing of the Agreement for Nuclear Cooperation (123 Agreement) between the United States and Russia. This agreement allows for the disposition of U.S. origin fuel in Russia, for an appropriate fee and under the right environmental and nonproliferation conditions. This opening might eventually allow shipment of spent fuel from U.S. nuclear power plants to Russia. Additionally this agreement opens the door (at least in theory) for instituting joint lease–take-back agreements between a U.S.–Russian consortium and consumer countries. Fresh fuel would be supplied from the United States or the Russian IUEC, and the spent fuel would be taken back to Russia. The supply logistics and payment terms and conditions have yet to be worked out. However, such joint projects most likely will have to wait for a warming in U.S.–Russian relations. To a large extent such joint proposals will depend on a resolution of the Iranian nuclear crisis to the satisfaction of both the United States and Russia, and may be held hostage to other foreign policy concerns, e.g., U.S. missile defense deployments in Eastern Europe. In time, this proposed arrangement could be extended to other fuel suppliers and fuel reprocessors, joining to offer multiple-source lease–take-back nuclear fuel supplies.

Regional Fuel Reprocessing Centers

A related proposal is the concept of the regional spent-fuel reprocessing center, first proposed in its modern form in the IAEA MNA report (INFCIRC/640). This report identifies spent-fuel reprocessing and spent-fuel disposal as the elements of the nuclear fuel cycle most amenable to regional solution. For example, large national fuel-reprocessing facilities could be converted to regional facilities, thus relieving their national owners of the economic burden of operating plants for the benefit of a possibly small domestic market. Regionalizing such facilities might attract other clients, improving the economics of these facilities. Regarding waste disposal, national nuclear waste repositories, or even national spent-fuel storage facilities, are becoming too expensive to site, license, and operate, and they might face significant local political opposition. In the face of such difficulties, a regional waste disposal site in a remote location available to any one of the participating countries might be the better solution.

This would be the case if one country within the region has a large landmass with suitable sites for a repository, away from population centers, although political opposition within that country to taking foreign nuclear waste could be a problem. The granite mountain ranges west of the Krasnoyarsk region in Russia as well as sites in the Gobi desert in China might be examples. The other participating countries would presumably be willing to pay to move spent-fuel disposal from their own countries to a foreign location. The prospect of removing the spent-fuel disposal problem is the main incentive to join a regional spent-fuel disposal center.

Regional solutions to the spent-fuel disposal problem would require a treaty signed by all participating countries. A model is the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC) Agreement signed between Argentina and Brazil for the joint safeguarding and inspection of their nuclear power plants. This treaty, based in part on provisions in the Treaty of Tlatelolco, includes the IAEA as a third party providing technical support services. The ABACC Agreement could be extended to other South American countries, e.g., Chile and Mexico. Another potential complication is prior consent rights imposed on fresh fuel supplies by supplier countries, principally the United States. Under such supply contracts, the United States is guaranteed prior consent to consumer country decisions regarding spent-fuel disposal, particularly to the transfer of U.S. origin fuel from the consumer to a third country. Thus, a regional spent-fuel disposal treaty would have to include not only the participating countries within the region but also all countries with prior consent rights on the nuclear fuel discharged from regional nuclear power plants. The IAEA would also likely be involved in the treaty, to provide safeguard services and technical support.

Conclusions

The back end of the nuclear fuel cycle is the area with the greatest uncertainty regarding future directions and plans. This uncertainty will remain until the scope of the global nuclear revival becomes clearer. Should the expansion of nuclear power remain limited, the global nuclear fuel cycle could remain open for at least several decades. A few countries will have spent-fuel reprocessing facilities; however, the economics of these facilities will remain uncertain in the face of rising costs and uncertain demand.

On the other hand, if nuclear energy growth accelerates due to global warming concerns, then the rising demand and prices for uranium-based fuel will make closed nuclear fuel cycles more attractive. The basic decisions will be whether to recycle, and if so, with which type of reactors (e.g., LWRs, ABRs, FBRs). All other issues relating to the back end of the fuel cycle will flow from these basic decisions. LWR fuel recycling, the most likely near-term option, will require the construction of PUREX reprocessing plants or, in the future, UREX+ plants, which will allow greater fractionation of the spent fuel to ease the radioactive waste disposal issue.

The transition to breeder reactors, either in ABR, FBR, or other forms, will require the joint development of the breeder reactor and its optimized fuel recycling facility. Should breeder reactors represent a larger fraction of the growth in nuclear capacity, then LWR spent-fuel reprocessing, conducted in part to provide fresh fuel supplies for future breeders, might have to be modified to produce the fuel form required for future breeder reactors.

Closing the fuel cycle will require greater attention to PR&PP measures designed to reduce the chance of nuclear proliferation and nuclear terrorism. PR&PP measures should be considered on a holistic approach encompassing entire reactors, fuel cycle facilities, transportation, and storage, nationally and internationally. Moreover, these measures should be designed into each fuel cycle facility from the early development stage and cover all aspects of plant design and operation. Full implementation of such measures will not be cheap, as seen with the Rokkasho Mura reprocessing plant, the most modern plant built to date. Safeguards measures in future fuel recycling plants might be even more expensive as more sophisticated measurement and analysis tools become available, unless these measures are incorporated early in the plant design, rather than retrofitted later.

In general it will be difficult from a nonproliferation perspective to distinguish between recycling plants operated on the PUREX, UREX or any other cycle. All waste chemistry plants will have similar qualitative nonproliferation characteristics. The distinguishing factors will relate more to plant size and to the various output streams produced at each plant. The mostly dry pyro-processing method has the advantages of small plant size and co-extraction of plutonium and the higher actinides, which provides a degree of self-protection. This characteristic could, however, be negated by knowledgeable insider electrochemists. The greater advantage of the pyro-processing plant might be its co-location with the reactors it serves within a well-guarded energy center.

Finally, all technical measures intended to secure the back end of the fuel cycle from proliferation attempts should be supplemented by political and institutional means as part of an overall systems approach to the fuel cycle. Measures such as co-location and integration of the reprocessing and re-fabrication plants into an integrated fuel recycling facility operated within a well-guarded center should be implemented. Co-location of reactors and fuel cycle facilities within common energy centers would provide an extra measure of security.

An important consideration is whether the implementation of closed fuel cycles and fuel recycling will be limited to a few supplier countries. Consumer countries should be offered attractive lease-take-back contracts by the supplier countries to reduce the demand for sensitive domestic fuel cycle facilities. IAEA-backed fuel supply assurance measures may be required to increase national willingness to rely on imported nuclear fuel rather than domestic fuel sources and fuel cycle facilities. All these activities could be tied to regional spent-fuel disposal centers, where the currently intractable disposal issue might be addressed more effectively.

The proliferation risk associated with different reprocessing facilities varies as a function of the size of a state's civilian nuclear sector. Small national nuclear programs with small reprocessing plants might be the most prone to state-sponsored proliferation, because if these countries withdraw from the NPT, they risk relatively little damage to their energy sector from a subsequent embargo on nuclear trade. On the other hand, countries with large nuclear power programs would suffer much more and, hence, are not likely to proliferate, although today most of these states already are nuclear-weapon states. We assume that countries with medium-sized nuclear energy systems will not want to risk their investments in nuclear infrastructure by NPT withdrawal. Such countries might, however, in extreme cases, cooperate with other countries with little or

no nuclear infrastructure in joint clandestine proliferation programs located in the smaller countries. Mid-sized reprocessing plants will most likely be less attractive for state-sponsored proliferation, because the commercial incentives to operate them at full capacity for both domestic and international clients weighs against proliferation tendencies.

Physical protection of nuclear facilities is vital, to reduce the likelihood that terrorists might acquire weapons material. Even so, a state that withdraws from the NPT, or one that has not signed the NPT in the first place, might reject cooperation on physical protection, out of suspicion that the offer was intended only to compromise the security of its nascent nuclear weapons program and facilities. Support for Pakistan in enhancing the security of its nuclear weapons even though Pakistan did not sign the NPT, has been provided in indirect bilateral fashion. Perhaps the only other feasible approach is to discuss best practices on physical protection on a voluntary basis in a neutral forum such as the IAEA, in the hope that if states choose to produce weapon-usable material, they will do so in as secure a manner possible to reduce the threat of nuclear terrorism.

Chapter 5: Transportation and Storage

Introduction

In a world with more widespread use of nuclear power, the transport and storage of nuclear materials at any point in the nuclear fuel cycle become important security issues. These security challenges are similar to those faced today, at least for the next several decades, although the measures and systems will have to be expanded to ensure adequate proliferation resistance and physical protection of the greater mass of material in transit between or in storage at a greater number of locations. Security challenges vary considerably, depending on the material and form in which it is found and the types of facilities and the countries in which they are located. In addition, the time frame under consideration is important, because new reactors and their associated fuel cycles (e.g., breeder reactors) may significantly alter the security aspects associated with transport and storage but will not become widespread until the later half of the 21st century, if then.

Material Sensitivity

Security of nuclear materials in transport and storage depends more on what is being protected than on the amount. The most sensitive item is assembled nuclear warheads. Though not associated with an increase in nuclear power, it is useful to remember that the transport and storage of nuclear weapons present security challenges that deserve top priority, because the impact of a lost or stolen nuclear warhead on international peace and security is clear and incontrovertible. This concern arose with former Soviet states, giving rise to the U.S. Cooperative Threat Reduction program, and it should receive attention with new nuclear states such as India, Pakistan, and North Korea.

Highly enriched uranium (HEU), especially in metallic form, is the next most proliferation-sensitive material, especially regarding nuclear terrorism, because a first-generation fission bomb can be fashioned from approximately 15–30kg of HEU metal (depending on the exact design), the “gun-type” assembly mechanism required to detonate such a weapon is relatively simple, and the low gamma-ray signature associated with U-235 makes HEU difficult to detect in transit. HEU oxide still found in some research reactor fuel assemblies and in naval reactor fuel, and highly enriched uranium hexafluoride, which may be produced at enrichment plants, are also very sensitive materials, because the steps required to produce HEU metal from these compounds are not difficult to master—hence, the urgent need to replace HEU research reactor fuel with LEU fuel assemblies. HEU naval reactor fuel is unrelated to an expansion in civilian nuclear power, yet represents an important security concern, because this fuel may not receive adequate material protection, accounting and control, as was the case with Russian naval reactor HEU fuel after the breakup of the former Soviet Union.

Weapon-grade plutonium (i.e., greater than 93% Pu-239) is comparable to HEU in terms of its proliferation and terrorist concern. Smaller quantities are required to make a nuclear explosive (typically 5–10 kg of weapon-grade plutonium, again, depending on design), but plutonium requires a more sophisticated implosion mechanism to create a significant fission yield, it is toxic to handle, and it has a more readily detected gamma-ray signature, making it somewhat easier to detect in transit. While neither HEU nor weapon-grade plutonium are envisioned in future nuclear fuel cycles, these materials may

be produced by states wishing to develop nuclear weapons. If so, secure transit and storage of these materials is of paramount concern to prevent terrorist acquisition.

Separated reactor-grade plutonium, of which approximately 200–300 tons exist today, is less suitable for nuclear weapons than weapon-grade plutonium, but nonetheless is of proliferation concern. Successful detonation of reactor-grade plutonium in a weapon is more difficult because the probability of pre-detonation increases due to the presence of other plutonium isotopes. Nevertheless, a nuclear yield is still possible.⁴ Even a relatively small nuclear explosion is large by conventional explosive standards, and the radioactivity released would dwarf that from any radiological dispersal device or so-called dirty bomb.

The term “reactor-grade” plutonium covers a wide range of material depending on the exact isotopic composition of plutonium contained in the material. This composition in turn depends on the degree of fuel burn-up. For intermediate burn-up in the range of 30–40 GWd/t, a typical range for current U.S. spent fuel, the isotopic contamination is significant but not so great that low-yield explosions are unlikely. At burn-up levels above approximately 100 GWd/t and, similarly, for MOX fuel with a burn-up of 40 GWd/t or more, the level of plutonium isotopic contamination is significant, so these materials are of less concern for explosives, although they pose a radiological hazard.

Reactor-grade plutonium is certainly not the most attractive material for a state’s nuclear weapons program. In fact, so far as we know, no state to date has used reactor-grade plutonium for weapons. However, it may be attractive to terrorists and, hence, must be protected. Moreover, separated reactor-grade plutonium can be handled with considerably less radiation hazard than can spent fuel. Consequently, it has been suggested that intermediate burn-up reactor-grade plutonium, whether in MOX or in separated form, should be treated similarly to weapon-grade plutonium. While this is a reasonable risk-averse approach, it places increased demands on physical protection in transport and storage, which may not be easy to meet with current IAEA safeguard budgets. Future leaders will have to decide whether improved safeguards should be adopted for reactor-grade plutonium, with a commensurate increase in IAEA funding, or whether excess reactor-grade plutonium should be eliminated by consuming it as MOX fuel or in fast reactors.

Fresh MOX fuel is on a par with separated reactor-grade plutonium in terms of material sensitivity, because it contains reactor-grade plutonium that can be separated chemically from MOX fuel without inordinate effort because of the relatively low radiation barrier.

Spent reactor fuel is the next most sensitive material, because although it contains reactor-grade plutonium that can be separated chemically, its high radiation levels make it very difficult to handle safely. Discharged LWR or ALWR spent fuel, having remained between three and five years in the reactor’s core, is highly radioactive. In fact, this material is self-protecting, because gaining control of even one spent-fuel element and removing it is a difficult task, even for plant operators (let alone a terrorist group). Even then, dangerous, sophisticated, remote-controlled, time-consuming, expensive processes would be required to gain access to the plutonium. Thus, plutonium in spent LWR fuel is

⁴ Carson J. Mark. “Explosive Properties of Reactor-Grade Plutonium,” *Science and Global Security* 4 (1993): 111–128.

referred to as the “spent-fuel standard,” against which the security of plutonium in various forms is compared.

The next most sensitive material is low-enriched uranium (LEU), namely, uranium enriched to less than 20% U-235. LEU cannot be used directly to make explosives, nor is it very radioactive. The principle proliferation concern with LEU is that it can be reinserted into a uranium enrichment facility to make HEU. In fact, the amount of separative work required to turn LEU at 4–5% U-235 enrichment into HEU is approximately half to one-third that required to turn natural uranium into HEU. LEU is of no use to terrorists, because they will not have access to enrichment facilities to convert it to HEU. However, states may be tempted to divert LEU to covert enrichment facilities or to use LEU stocks to produce HEU after withdrawal from the NPT. Consequently, the transport and storage of LEU presents some proliferation concerns but only for states that also have enrichment facilities.

Radiological sources (e.g., Co-60 and Cs-137) currently used in a wide range of industrial, agricultural, and medical applications are also of concern. Millions of such sources exist worldwide under varying levels of protection. Such sources are not closely related to the level of nuclear power in use around the world, and they are of little military value to states. However, they may become worrisome radiological weapons in the hands of terrorists. Like spent reactor fuel, such sources require heavy shielding to handle safely, radioactive dispersal is not easy and, consequently, radiological dispersal devices made from these sources would create few casualties. However, they could have significant economic and psychological impact, and cleanup efforts may be expensive. Hence, such sources should be protected but, given the monumental effort required to secure all sources, one must balance the benefits of protection against the costs in light of other important materials that need to be secured.

At the bottom of the list, ranked according to proliferation resistance and physical protection concern for nuclear fuel-cycle materials, are the feed stocks of natural uranium, either in the form of uranium ore (“yellow cake”) produced from uranium mining, uranium tetrafluoride (UF₄), or uranium hexafluoride (UF₆). These materials are of little use to a terrorist but are the ingredients for uranium enrichment plants and for some reactor fuels (e.g., CANDU reactors and graphite-moderated plutonium production reactors). Hence, they constitute a proliferation threat when coupled with uranium enrichment plants or power reactors that use natural uranium as fuel, assuming the state also has a reprocessing facility with which to extract the plutonium.

Time Frames

Different projections exist for the rate at which nuclear power may expand in the future and the date at which different types of nuclear systems may be commercially viable. Suffice it to say, as discussed in chapter 3, the nuclear world in the next few decades will be much as it is today, perhaps with a modest expansion in the number of nuclear power plants and the associated transport and storage of nuclear material. The transport and storage of materials may grow in quantity, but this growth will not change the security picture qualitatively from what it is today.

The near-term security concerns involve the transport and storage of HEU for research reactors, LEU, spent fuel, and small amounts of separated reactor-grade plutonium and MOX fuel. The transport of HEU for research reactor fuel will decline over time due to the ongoing conversion of research reactors to LEU fuel. The transport

and storage of separated reactor-grade plutonium and fresh MOX fuel takes place on a relatively small scale, mainly within France and the United Kingdom and to a lesser extent between France and Japan in the case of separated reactor-grade plutonium, and between a few advanced nuclear states in Europe in the case of fresh MOX fuel (e.g., Belgium, France, and Switzerland). Thus the transport and storage of LEU and spent reactor fuel from once-through fuel cycles will constitute the greatest transport burden, though they are not high security risks compared to other elements of the nuclear fuel cycle and are, in general, well protected in relation to that risk.

In the mid-term (20–50 years), a growth in nuclear power could include an increase in the number of states with nuclear power reactors and some increase in the number of advanced nuclear states (and perhaps states of proliferation concern) engaged in uranium enrichment, plutonium reprocessing, and the beginnings of closed fuel cycles, perhaps with the addition of plutonium-fueled reactors. In this time frame, the transport and storage of separated reactor-grade plutonium and MOX fuel will become more serious concerns. A few geologic repositories for spent fuel, mostly from once-through cycles, should be open and receiving spent-fuel shipments and, in some cases, vitrified wastes containing the residue from reprocessing. Hence, safeguarding spent fuel at repositories will become an issue, especially as the radiation barrier decays over time, though much less troublesome than safeguarding plutonium-bearing fuels in transport and storage. Almost all commerce in HEU for research reactors should be eliminated by this time.

In such a world there will be more bulk handling of nuclear materials, especially in countries new to nuclear power, with the corresponding need for technical and institutional controls on the associated material in these new nuclear-power states. In fact, it probably should become a requirement before nuclear supplier states engage in nuclear commerce that consumer states demonstrate proficiency in safe, secure nuclear transport and storage, especially for new nuclear-power states. Clearly, this is an area where more advanced nuclear states can help, providing both technical safeguards expertise and successful institutional models for regulating and securing aspects of the nuclear fuel cycle. Nuclear supplier states can certainly help train other countries and share best safety and security practices to ease this transition.

In the long term (beyond 2050), if nuclear power expands as some predict, one can envision much more widespread use of closed fuel cycles, either to supplement dwindling supplies of uranium at affordable prices or to reduce the volume and perhaps the radioactive burden at repositories. In this world, the burden on transport and storage depends greatly on whether reactor-grade plutonium is separated from spent fuel or left with the other actinides, the level of burn-up associated with spent fuel, and whether fuel fabrication plants are colocated with reprocessing facilities, thus eliminating the need to transport separated reactor-grade plutonium. If a plutonium economy develops, the transport and storage of separated reactor-grade plutonium and plutonium-bearing fuels will become the most serious concerns, although these concerns may be dwarfed by those associated with the spread of uranium enrichment and spent-fuel reprocessing plants. If a state produces HEU or weapon-usable plutonium, the degree to which the state takes adequate measures to secure the transport and storage of these materials will be of paramount importance to guard against terrorist acquisition, arguably more important than the proliferation behavior of the state itself. In this case, the political and economic

stability of the country and the security of the weapon-grade material against acquisition by terrorists will be crucial.

Transportation Issues

Transportation safety and security currently is the responsibility of commercial enterprises, under the supervision of national authorities. The guiding philosophy for the transport of fresh LEU fuel is that security should be guaranteed by the physical package itself. IAEA safety guidelines for the transport of nuclear materials (*Regulations for the Safe Transport of Radioactive Material*, 1996 edition) have been adopted so widely by the international community that they have become de facto transport safety regulations, though they are not regulations in the formal sense. They are now being expanded to include transportation security. The actions required to transport nuclear material safely are similar to the actions needed to transport it securely. This is a good example of successful multilateral coordination and cooperation led by the IAEA, although the effort may be difficult to duplicate with respect to storage security (i.e., physical protection) because the latter involves sensitive information and, hence, national sovereignty considerations. Therefore, if nuclear power expands in the future, the IAEA will become the natural organization to coordinate approaches to safeguarding material in transit.

Nuclear material transport currently is quite secure. For example, HEU, MOX, and LEU fuel are often transported under armed guard, although this is not the case for LEU in the United States. However, the United States, through the U.S. Nuclear Regulatory Commission, has revised the guidelines for securing nuclear and radiological material in transit by revising the threats against which transport must be designed to respond, i.e., the “design-basis threat,” by increasing the standoff distance for material in transit and hardening transport containers against sabotage. Spent fuel, for example, while not guarded, is shipped in heavy containers weighing approximately 15–25 tons each to protect against radiation hazards. This protection greatly reduces the threat of terrorist theft and sabotage. Therefore, current physical protection measures for transportation probably are adequate to meet current threats.

To further improve U.S. security, the design-basis threat, which involves a single-threat scenario, should be redesigned to include a range of possible scenarios, because not all plausible threats are lesser, included cases in a single worst-case scenario. For example, requiring a security system to handle a large number of well-armed terrorists may stress the firepower of the security forces, but it makes early detection of such attacks more likely. Small attacks stress the likelihood of detection and, hence, possible warning times, emphasizing a different aspect of one’s security posture.

LEU transport will experience the largest near-term increase in volume under most future nuclear power scenarios, followed by the transport of spent fuel if spent-fuel take-back arrangements are implemented in conjunction with reprocessing and disposal of nuclear wastes in geologic repositories. Since LEU is relatively benign as far as state proliferation and terrorist threats are concerned, the security of LEU shipments should receive low priority, unless the country in question has an indigenous uranium enrichment capability. Scarce resources could then be freed to meet higher priority security concerns. Cost-benefit assessments should be applied to assess the overall security of nuclear material in transit in each country with nuclear power plants.

Conversely, serious transportation security issues will arise if states move to closed nuclear fuel cycles. MOX transport in France currently is handled according to national regulations. However, if the use of plutonium-bearing fuel spreads, international standards will need to be developed. Initially, the expansion of reprocessing facilities and MOX fuel fabrication will be limited to a few countries (e.g., France, Japan, the United Kingdom); however, if nuclear power expands, toward the middle of the 21st century, spent-fuel reprocessing and plutonium-bearing fuel fabrication will occur in other, perhaps less secure, states. Other closed cycles, for example, recycling actinides in fast reactors as envisioned under the U.S. GNEP program, would pose fewer problems for transportation security, because plutonium is not separated from the other actinides and the material is self-protecting due to the radiation barrier.

Clearly, the safest and most secure scheme is not to move material at all. Colocating reprocessing facilities with MOX fabrication plants eliminates the need to transport separated reactor-grade plutonium. If closed fuel cycles become more widespread, co-location should be encouraged, because it eliminates one important transportation risk, allowing states to focus on the security of fresh MOX fuel transport alone. Japan has taken this approach by colocating a fuel fabrication plant at the Rokkasho-Mura reprocessing plant now under construction.

Technical approaches to transportation security include tracking devices on containers with nuclear material that are not easily destroyed or spoofed, to help locate diverted shipments when monitored from abroad. This measure would also help with supply logistics, perhaps making it attractive on commercial grounds alone, and would certainly help locate covert enrichment or reprocessing facilities. The presence of tracking devices would help deter diversion in the first place. A state could jam or block the transmission of the tracking signal, if sufficiently motivated, but this action would provide advance warning that material is unaccounted for and would likely implicate the state. Inspectors could also track shipments by inspecting seals on containers, probably at greater expense, but this approach is vulnerable to state interference. The best protection against terrorist theft or sabotage of nuclear materials in transit are heavy containers (which are required in any case for highly radioactive materials) and armed response forces (if not armed guards).

If sensitive nuclear materials are found missing from storage sites, detection methods can help search for them amidst commercial transport. "Black boxes" on shipping containers that integrate radiation signatures over a long time can detect small quantities of radioactive material. Similarly, portal radiation monitoring, perhaps using active interrogation techniques to detect U-235 or heavily shielded plutonium, can in principle detect or deter covert shipments at ports of entry, although the probability that U-235 can be successfully detected is questionable. Obviously, these measures must be designed to minimally impact the normal flow of commerce; otherwise, they will never be adopted.

From the security perspective alone, the most attractive transportation regime in a world with expanded nuclear power is one in which LEU and spent fuel are the principal materials in transit. In a world with closed nuclear fuel cycles, the greatest transportation concern involves separated reactor-grade plutonium and plutonium-bearing fuels, especially if Generation IV reactor designs are commercialized. Colocating reactors, fuel reprocessing, and fuel assembly facilities eliminates the need for fresh-fuel and spent-fuel

transport and, hence, is the best approach to minimizing security concerns associated with closed fuel cycles. Co-location also helps secure the storage of any weapon-usable nuclear material. However, concentrated nuclear energy centers typically have large power output to obtain economies of scale and, hence, may not be suited to small or medium-sized electricity grids.

Storage Issues

Developing international regulations for the secure storage of sensitive nuclear materials is challenging. Unlike transportation, physical protection at storage sites involves state or private security forces and possibly sensitive or classified information regarding the contents being stored and the methods of protection. Moreover, unlike interstate commerce, storage is the sole province of the state wherein the storage site is located. Hence, many leaders consider it to be a sovereign issue. Finally, a state's approach to security will be influenced by its own security culture, making universal regulations less acceptable unless they are pliable or vague. Nevertheless, international standards (as opposed to regulations) for securing stored nuclear material may be possible and should be developed in a world with expanded nuclear power. Minimizing the likelihood of insider threats against stored HEU and separated plutonium—a difficult problem—is particularly important for minimizing the likelihood of terrorist acquisition.

Of greatest concern is securing foreign nuclear material that is a likely source of a terrorist bomb. Again, from this perspective, materials in nuclear weapon programs pose a greater security concern than those in the nuclear power industry. Despite U.S. efforts under the Cooperative Threat Reduction program, securing Russian nuclear weapon-usable material is still a concern, although many of the most egregious security problems have been addressed over the past decade and a half. Similarly, securing nuclear weapon materials, if not the weapons themselves, in new nuclear states—India, Pakistan, and North Korea—should also be of concern, because these states may not have adequate security procedures in place, and there tend to be more actors in their midst interested in acquiring such materials.

In the near term, the best approach for developing international consensus is for interested nations to share voluntarily best practices for securing nuclear materials of different types, with the goal being for states to adapt physical protection methods to their own situations. This approach involves some risk of making facilities more vulnerable to theft or sabotage by divulging too much information on physical protection. Nevertheless, the IAEA is a useful forum for discussing best practices or approaches to physical protection and, at the very least, to gain consensus that high standards are in the security interests of all states possessing nuclear materials. As an inducement to securing nuclear materials, nuclear supplier states may refuse to engage in nuclear commerce with states that do not have well-developed and effective physical protection methods. Admittedly, it will be difficult to verify that these methods are adequate, because states—especially those with poor security—typically will not allow international “red team” exercises to verify the proficiency of their security measures; also, questioning the adequacy of a state's physical protection will likely be dismissed as politically motivated. Finally, if the bar for nuclear commerce is set too high, states may opt for indigenous uranium enrichment or plutonium reprocessing and fuel fabrication capabilities, a worse outcome for strengthening proliferation resistance and physical protection.

Covert storage facilities for indigenously produced HEU, LEU, spent fuel, or separated plutonium will be difficult to detect, except perhaps by identifying suspicious transportation activities. However, covert LEU storage is important only if a state also has a covert enrichment plant or can covertly produce HEU at a declared enrichment facility, and covert storage of spent fuel is important only if a state has a covert reprocessing plant or can divert plutonium without detection from a declared reprocessing facility. HEU should not be in circulation in future nuclear fuel cycles, thus eliminating the concern with covert HEU storage unless the country can make HEU indigenously using a covert enrichment facility. In this sense, many of the concerns associated with nuclear material storage are also concerns with national enrichment and reprocessing facilities. If reprocessing facilities proliferate, then storage concerns are magnified considerably.

Diversion of material from declared storage sites, in the event that a state withdraws from the NPT, cannot be addressed by better security at storage sites. This scenario requires effective international sanctions or responses aimed at the breakout state.

Separated Reactor-Grade Plutonium and Plutonium-Bearing Fuels

The most secure place to store reactor-grade plutonium is in spent fuel. However, the impulse to reprocess spent fuel does not derive from security concerns but rather from efforts to exploit the energy content of the plutonium or to reduce spent-fuel disposal requirements. Today, the most important storage concern, aside from the storage of HEU for research reactors, is the security of approximately 200–300 metric tons of separated reactor-grade plutonium that exists largely in the France, Japan, and the United Kingdom. Russia and the United States also have large inventories of separated, excess plutonium in storage from dismantled nuclear weapons (approximately 250 metric tons between the two). This material is well protected now, but this may not remain the case if reactor-grade plutonium is separated and stored in other countries. Physical protection standards need to address such eventualities.

One argument in favor of MOX fuel cycles, and fast reactor fuel cycles more generally, is that they consume plutonium and, hence, remove it forever as a source for diversion or theft. This argument depends on a future nuclear infrastructure in which plutonium is burned at the same rate it is produced, to minimize, if not eliminate, separated plutonium inventories worldwide. Such schemes rely on greatly increased transport of spent nuclear fuel and fresh MOX or plutonium fuel elements.

MOX storage today does not represent a significant security concern, because the quantities are relatively small, and they are located mostly in France and the United Kingdom. However, if closed nuclear fuel cycles become more widespread, fresh MOX fuel storage will become an important security concern, especially if it exists as fresh fuel at the reactor site. Physical protection of this material is as important as that for separated reactor-grade plutonium. Invoking just-in-time delivery of plutonium-bearing fuel may seem attractive to minimize storage requirements, but it will likely run afoul of concerns by the consumer country about fuel supply assurances. Spent MOX fuel, as noted above, is of much less concern in either storage or transit.

Spent-Fuel Storage and Geologic Repositories

Currently, most spent nuclear fuel is stored at interim locations at reactor sites, either in cooling ponds or in dry casks. If nuclear power expands, LWRs using a once-through cycle will dominate power production for at least the next several decades. Consequently, the inventory of reactor-grade plutonium in spent fuel, now approximately 800 metric tons, will grow. This spent fuel will pose a formidable storage problem, albeit one with relatively low proliferation or terrorist risk unless the fuel is reprocessed. Until repositories open, most spent fuel will be kept at the reactor site, either in wet or dry storage. Co-location with the reactor site suggests some shared physical protection measures. The fuel elements themselves are safeguarded by the IAEA; hence, diversion of the elements, fresh or spent, by a host country likely would be discovered. Perhaps the most important issue will be to ensure that new nuclear power states adopt and adequately implement appropriate physical protection for their reactor sites and spent-fuel storage locations.

Spent fuel is inherently safe from theft because of its high radiation level. It can only be moved in heavily shielded containers weighing about 15–25 tons (dry casks weigh much more, around 150-200 tons). Hence, diversion by states or terrorist groups would be difficult. In addition, sabotage threats are not very significant. In the case of wet storage, it is difficult to disperse radioactivity from cooling ponds, even if one could destroy the ponds themselves. Dry casks also are difficult to breach in such a way that significant radioactivity is released. Diversion is perhaps the greatest risk, should a state decide to reprocess spent fuel at a declared or clandestine reprocessing facility or simply withdraw from the Non-Proliferation Treaty and reprocesses spent fuel at a designated reprocessing facility, as was the case in North Korea. Hence, spent fuel constitutes a latent, as opposed to imminent, threat because it would take a year or more to acquire sufficient plutonium—reactor-grade plutonium at that—for a few weapons.

As geologic repositories open in the future, they too will need to be safeguarded, because they will contain substantial amounts of reactor-grade plutonium from once-through fuel cycles. This material becomes more accessible as the radiation barrier recedes over many decades. If fast reactors are commercialized in the future, worldwide inventories of spent fuel can be recycled and the actinides contained therein burned. Spent fuel from fast reactors will pose little security risk, because the plutonium content is low and, in any case, is of mixed isotopic content. Thus, repositories designed to accommodate spent MOX fuel (with significant plutonium isotopic contamination) or spent fast-reactor fuel will require limited safeguards.

The most intriguing aspect of spent-fuel repositories is the way in which they can mitigate other proliferation concerns. For example, to discourage indigenous uranium enrichment, advanced nations could provide multinational fuel supply assurances, perhaps under the auspices of the IAEA, coupled with spent-fuel take-back, as discussed in chapters 2 and 4. Fuel supply assurances alone often fail to convince consumer states to forgo national enrichment. However, coupling fuel supply assurances with spent-fuel take-back could encourage states to forgo indigenous enrichment or spent-fuel reprocessing if the reprocessed spent fuel is retained by the supplier state for eventual disposition in repositories, thus alleviating a major environmental concern for small nuclear power states with limited space for geologic repositories. Moreover, refusing

such a bargain would be a clear sign that the consumer nation has motivations other than energy independence for its indigenous enrichment program.

While this proposal is rational from a security perspective, it will be very difficult to implement because most states experience political difficulty opening repositories for their own nuclear waste, much less that from other countries. The amount of spent fuel from developing countries will be small, about 15–20 percent of the amount generated by the advanced nuclear power states, but this fact does not resolve political opposition to the perception of taking another state's nuclear waste, even if it is rational to do so. Moreover, the vision embodied in GNEP—that fast reactors and actinide recycling make it possible to reprocess spent fuel from consumer nations, burn it to produce electricity in the supplier nation, and store the resulting waste with relatively little additional burden on the supplier state's repositories—will not be realized for many decades due to the immaturity of the underlying technologies. Thus, it should come as no surprise that many countries doubt the sincerity of these proposals, especially coming from the United States, which has experienced such difficulty opening the repository at Yucca Mountain and which has eschewed fast reactor technology since the mid-1970s.

Still, this vision for the future is attractive, offering fuel supply guarantees and spent-fuel take-back coupled with spent-fuel storage by the supplier state to help address concerns with nuclear proliferation. In this sense, geologic repositories coupled with fast reactors become important for national security and not just waste disposal. Regional repositories, justified on security grounds, would also be worth exploring.

Chapter 6: Concluding Observations

Security concerns probably will not dominate decisions regarding the expansion of nuclear power. Economics, reactor safety, and a politically acceptable solution to waste disposal will be more important. However, security concerns could scuttle the expansion of nuclear power. For example, a regime change that ushers in leaders who withdraw from the NPT after the state has developed substantial nuclear infrastructure could quite rapidly alter perceptions of the security risks associated with nuclear power. Similarly, a major smuggling incident or the detection of inventory differences that are perceived as, if they are not in fact, diversions of weapon-usable material, will have a negative impact on the nuclear power industry. Just as a nuclear power accident anywhere will be perceived as a nuclear accident everywhere, so too a nuclear security breach anywhere will raise security concerns everywhere. Therefore, approaches to mitigate these eventualities should be devised prior to a major expansion of nuclear power, if this expansion is to be politically sustainable.

Political Dimensions to Security

While technology certainly plays an important role in mitigating the security risks associated with expanding nuclear power, the most important steps will be political: for example, overcoming mistrust that undermines the smooth functioning of international fuel supply markets, strengthening international institutions charged with monitoring and safeguarding the civilian nuclear fuel cycle, achieving consensus on appropriate sanctions for NPT withdrawal, and overcoming political resistance to international cooperation regarding physical protection.

In the near term, any expansion of nuclear power will involve the spread of more advanced versions of current light-water reactor (LWR) designs. In fact, the majority of the world's nuclear power reactors will be LWRs for most of the 21st century. Low-enriched uranium (LEU) fuel will dominate the fuel cycle. Highly enriched uranium (HEU) fuel will still be used in some research reactors, although plans to phase out HEU for most research reactors by 2018 are proceeding apace. Many countries will acquire their first power reactor in this time frame, though most of the gigawatts generated will be in states with more advanced nuclear infrastructures, particularly in Asia. In addition, there will be relatively few new spent-fuel reprocessing plants due to the large startup costs and the lack of an immediate need for reprocessing.

Uranium enrichment is a different story. The greatest security concern in the next few decades will be the spread of uranium enrichment plants, especially those based on gas centrifuges or laser isotope separation, and the latent nuclear weapons capability that goes with them. This spread will be justified largely on economic grounds—the sovereign desire for assured fuel supplies and energy independence, or in some instances the desire to increase the export value of indigenous uranium resources. The spread of nuclear reactors, per se, is not a serious security concern, nor is the LEU fresh fuel or spent fuel associated with these reactors.

In the far term, closed fuel cycles and a plutonium economy may develop. This will be based on mixed uranium-plutonium oxide (MOX) fuel cycles initially, and then perhaps other plutonium-bearing fuels appropriate for fast neutron reactors that burn plutonium along with the long-lived actinides, thus eliminating separated plutonium and ameliorating waste disposal problems. In this time frame, the transport and storage of

separated reactor-grade plutonium and plutonium-bearing fuel will become serious physical protection concerns, along with the proliferation resistance of the reprocessing plants themselves. In the far term, more states will have acquired nuclear power plants, and uranium enrichment facilities may spread to quite a few countries unless managed properly in the next few decades. The need for geologic repositories for nuclear waste will also become more obvious in this time frame, if not before. Moreover, these repositories can play an important security role by facilitating fuel lease–take-back arrangements by supplier states in exchange for consumer states’ forgoing enrichment and reprocessing facilities.

Limiting the spread of uranium enrichment and spent-fuel reprocessing facilities (i.e., sensitive nuclear facilities), while at the same time satisfying the commercial need for such facilities in politically acceptable ways, will remain the most challenging nonproliferation goal in a world with expanding nuclear power. Access to nuclear energy should be made as easy as possible for the vast majority of states interested in electricity production, while placing a spotlight on suspect proliferators so the international community can husband its political resources for the difficult cases. Hence, the international nuclear fuel cycle should be structured along commercial lines as much as possible. Market forces can help reinforce security goals by discouraging the construction of sensitive national nuclear facilities if these facilities cannot compete in the international market, although the cost of nuclear fuel is only a small fraction of the cost of generating nuclear electricity.

Legal issues will be less important for managing the expansion of nuclear power in a responsible manner. The nuclear fuel cycle is perforce a government-regulated activity. Hence, international, regional, and national legal and regulatory practices are already well established. New laws are not needed, but not all laws are enforced. Some are inconsistent or conflicting, and others are not universally implemented. Greater consensus on national legislation and a greater willingness to implement domestic laws that regulate aspects of the nuclear fuel cycle are needed, perhaps encouraged through shared best legal and regulatory practices under the aegis of the IAEA or the World Nuclear Organization (WNO).

NPT Withdrawal

Perhaps the biggest proliferation challenge associated with the expansion of nuclear power is the problem of state withdrawal from the NPT after acquiring sensitive nuclear facilities within a peaceful nuclear power program. The case of North Korea comes to mind. Clandestine production of weapon-usable material while a state remains within the NPT is less likely due to existing safeguards, although the latter are not universally applied because some states have not signed the Additional Protocol. And in any case, the safeguards are not infallible, as demonstrated in the past with the Iraqi and North Korean nuclear programs and more recently with Syria’s apparent attempt to build a clandestine nuclear reactor. While existing safeguards have revealed a lot about Iran’s current uranium enrichment efforts, Iran’s past research on enrichment, went largely unnoticed.

One approach would be to deny some states access to sensitive nuclear facilities. However, efforts to manage proliferation risks that discriminate between states will not be politically acceptable, especially given concerns about the current inequitable status and treatment of non-nuclear-weapon states under the NPT. One should not

overemphasize this point, because some non-nuclear-weapon states are quite content with this division. Nevertheless, indefinite denial of access to sensitive nuclear facilities is unlikely to appeal to many states, although temporary de facto distinctions may be acceptable.

Building a shared consensus that nuclear power is the inalienable right of all states, while nuclear weapons should be foresworn, is the goal of the NPT and the NPT regime more broadly. Today, that consensus has frayed, in part due to perceptions of inequality between the nuclear and non-nuclear states under the NPT. Frustration among some non-nuclear-weapon states that the nuclear-weapon states have not done enough to reduce their reliance on nuclear weapons (i.e., Article VI commitments) needs to be addressed, especially because the indefinite extension of the NPT in 1995 was predicated upon the entry into force of a Comprehensive Nuclear Test Ban Treaty (CTBT) and progress toward a Fissile Material Cutoff Treaty, both of which have failed to materialize.

Progress on CTBT ratification and a Fissile Material Cutoff Treaty would help regain international confidence that the NPT is not a one-sided bargain. Additional moves by the nuclear weapon states to reduce their reliance on nuclear weapons may also help. Two editorials by George Shultz, William Perry, Henry Kissinger, and Sam Nunn list additional concrete, near-term steps that could be taken to this end, regardless of whether one believes their ultimate vision of a nuclear-weapons-free world is desirable or attainable. The suggestions include revising U.S. and Russian nuclear doctrines inherited from the Cold War (in particular, the reliance on nuclear delivery systems placed on high alert), further reductions in the number of deployed U.S. and Russian nuclear weapons, and eliminating short-range nuclear delivery systems.⁵

Deterring NPT withdrawal is another option. Clearly NPT withdrawal implies the cessation of civilian nuclear commerce with that state. This action limits the arsenal size a state can acquire to that which can be developed from uranium or plutonium in country at the time of withdrawal. The amounts may be quite small for countries that do not have indigenous uranium reserves or breeder reactor programs and, hence, may discourage withdrawal. More importantly, halting civilian nuclear commerce will impose a significant cost on that state's energy sector. Still, national security imperatives may prevail, as we have seen in the case of North Korea, and small nuclear arsenals may result. India, although not a signatory to the NPT, withstood isolation from international nuclear cooperation to pursue its nuclear weapons program.

Requiring the return of all nuclear material and equipment provided to a state while it was a member of the NPT after withdrawal adds costs, but this requirement may be difficult to enforce. Threats to destroy such material or equipment in the event it is not returned lack credibility, because carrying out such threats may not be politically acceptable unless evidence for a nuclear weapons program is incontrovertible. In addition, the potential collateral damage from such attacks could be self-detering. Technical options could automatically dismantle or destroy certain equipment, especially delicate equipment such as gas centrifuges, after a state withdraws from the NPT; however, states or commercial enterprises will be reluctant to accept such measures even

⁵ George Shultz, William Perry, Henry Kissinger, and Sam Nunn, "A World Free Of Nuclear Weapons," *Wall Street Journal*, January 4, 2007; George Shultz, William Perry, Henry Kissinger, and Sam Nunn, "A World Free Of Nuclear Weapons," *Wall Street Journal*, January 15, 2008.

if they have no plans to withdraw from the NPT, because malfunctions could lead to the destruction of billions of dollars in investment.

The political will to respond to NPT withdrawal cannot be legislated. However, UN Security Council resolutions stating that NPT withdrawal constitutes a threat to international peace and security could provide prima face justification for the use of force, thereby putting states on notice that actions are likely following withdrawal. Eliminating the withdrawal clause in Article X of the NPT has been suggested, but again, without enforcement, such changes on paper will make little difference to determined proliferators, and the task of renegotiating a treaty with over 180 member states would be formidable.

Perhaps the best deterrent to NPT withdrawal is to require that all new sensitive nuclear facilities be multinational in ownership and operation, even if they are on the soil of suspected proliferators. Joint ownership and operation have important benefits for proliferation resistance. Joint ownership prevents the host state from using facilities to make nuclear weapons material unless it expropriates the facility, which would likely incur strong international pressure to restore joint ownership. Joint operations may also provide early warning of covert activities within the host state, because close contact with host state scientists and technicians provides an important additional source of information regarding the state's intentions. Multinational nuclear arrangements clearly cannot prevent proliferation; however, they make it more likely that proliferation will be detected early and that strong pressure will be brought to bear to reverse such decisions, thus possibly deterring them in the first place.

Multinational Nuclear Arrangements

Multinational facilities not only enhance deterrence but also provide incentives to forgo sensitive national nuclear facilities. In fact, they make sense on economic grounds alone. Joint ownership spreads the capital and operating costs across multiple partners, provides income if services are sold outside the multinational consortium, and helps assure access to fuel supplies. Moreover, the economies of scale that can be achieved with large plants imply that services can be rendered more cheaply than with smaller national facilities.

Other incentives such as fuel supply assurances in the form of performance bonds, escrow accounts, fuel banks, or national guarantees are probably less reliable because they may fail when they are needed most, that is, when trust in international markets wane and a supplier cartel threatens to use access to nuclear fuel supplies for political coercion. Fuel banks also are impractical if actual fuel elements are stockpiled because of the wide range of different fuel types that would need to be stockpiled. Clearly, stockpiling LEU is the only practical approach. Fuel elements can either be produced indigenously or by international suppliers, unless the latter are deemed unreliable if they come under political pressure. If a cartel refuses to provide nuclear fuel for politically motivated reasons, the entity that controls a fuel bank or fuel element manufacturing facilities would have to side against the cartel, which may be difficult. Avoiding cartels and encouraging a diverse fuel supply market help; however, the diversity of the international nuclear fuel market is neither guaranteed nor can it be assured for 60 years (the investment lifetime associated with nuclear power reactors). Consumer states are right to question whether future fuel supply markets will behave more like a cartel than a truly open market, because large enrichment and reprocessing plants are capital intensive

and the technology for developing such plants is held today only by a few advanced nuclear-power states.

Reducing the number of sensitive nuclear facilities worldwide is an important nonproliferation benefit of multinational facilities. However, deciding which states can host multinational nuclear facilities may be problematic. A logical approach would be for states with existing enrichment and reprocessing facilities to offer them voluntarily for multinational participation, either in equity, joint operations, or both, though not joint research and development. However, this approach may appear discriminatory, because current facilities are located almost exclusively in nuclear-weapon states. Another approach would be to require, perhaps at the 2010 NPT review conference, that all new sensitive nuclear facilities be multinational. Such a policy could also appear discriminatory, but it does allow complete access to the peaceful uses of nuclear energy, though not at the level of national facilities. Specifying a limited time frame during which multinational facilities are the only ones that can be constructed could make the proposal more acceptable to non-nuclear states.

Denying access to the technology associated with sensitive nuclear facilities has obvious nonproliferation benefits, but this approach tends to be politically less acceptable to non-nuclear-weapon states because it is discriminatory. To address the complaint that such proposals inhibit the technical aspirations of non-nuclear-weapon states, facilitating joint research and development activities—for example, by providing easy access to nuclear research facilities in more advanced states—would help avoid the perception that states which forgo sensitive nuclear fuel cycle activities will be left behind in important scientific and technical developments.

Defining criteria that states must meet before they are allowed to participate in multinational nuclear arrangements is important but can be self-defeating. For example, it has been suggested that to qualify for inclusion, states must 1) implement a comprehensive safeguards agreement, 2) ratify the Additional Protocol, 3) have a good nuclear safety and security track record, 4) implement UN Security Council Resolution 1540 to help prevent nuclear materials from falling into terrorists' hands, and 5) have strong nuclear export controls. Political and strategic considerations are often added to this list, along with energy audits to demonstrate that nuclear power makes economic sense for a given country. The difficulty with such lists is that they represent the nonproliferation concerns of supplier nations with little regard for the concerns of consumer states and, hence, they fail to attract much interest from non-nuclear-weapon states in good standing with the NPT, much less those that are not, as Bruno Pellaud has pointed out.⁶

A minimal list would include the first and third criteria. However, even then consensus may be difficult. Clearly, all states have a stake in safe and secure nuclear facilities, because radiation from a reactor accident can drift across borders, and the international ramifications of a security breach can affect many states. For this reason, considerable cooperation already occurs between states regarding the safety of nuclear reactors. However, physical protection standards are less well defined and could fall prey to recriminations, whether politically motivated or not, regarding the competence or corruption of a state's security apparatus. Similarly, assessing energy audits, the

⁶ Bruno Pellaud, "Multilateral Nuclear Arrangements: Status and Outlook," *ESARDA Bulletin*, no. 36 (June 2007).

acceptability of a state's export control regime, and the degree to which the Additional Protocol or UNSC Resolution 1540 have actually been implemented in a given state will always be subject to differing interpretations, some of which may be politically motivated, thus discouraging some states from participating in multinational nuclear arrangements.

Perhaps the greatest drawback with joint ownership and operation is the potential access to intellectual property from which a country could design an indigenous facility, as the case of A.Q. Khan, who worked with URENCO before returning to Pakistan, demonstrates. This is the principle reason for denying joint research and development. The EURODIF uranium enrichment consortium is one example of joint ownership and operation, without the technology-sharing present in the URENCO case. Russian proposals to turn the Angarsk uranium enrichment facility into a multinational facility without technology sharing should also be explored.

Preventing Terrorist Acquisition

Terrorists may acquire nuclear weapons material through collaboration with a state, by theft, or by purchase on the black market. The latter two routes are much more likely in failed states, where the security apparatus ceases to function efficiently. Preventing theft requires adequate material protection, control, and accounting. Moreover, one should not lose sight of the fact that nearly all weapon-usable nuclear material lies outside of the commercial nuclear power sector, a fact that should remain true until spent-fuel reprocessing becomes more widespread. Deterring state collaboration and preventing the collapse of a state's security apparatus are discussed here.

Deterring states from collaborating with terrorists is difficult. Encouraging universal adoption and implementation of UN Resolution 1540 helps, since it requires that states adopt national legislation making it a criminal offense to collaborate with non-state actors in the acquisition or trafficking of nuclear weapons materials. Improved nuclear forensics is also important to verify the source of nuclear material, either pre- or post-detonation. This information creates the possibility of holding the state from which the material came responsible for the terrorist's action, thus discouraging collaboration and encouraging effective measures for physical protection within the state. However, it is doubtful that forensics can ever produce such an unambiguous fingerprint. Worldwide databases of isotopic, and perhaps chemical, signatures associated with nuclear materials from different facilities would help, although not all states will participate. An incentive for a country's participation and cooperation is to rule itself out as the source of the material in the event a terrorist nuclear device is intercepted or a nuclear detonation occurs. Such efforts may discourage some states from collaborating with terrorists on nuclear weapons, but deterrence will not be perfect.

If the leadership of a state with a significant nuclear power infrastructure loses political control, security measures put in place for physical protection in peacetime could evaporate overnight. Predicting such political shifts is difficult. Few foresaw the collapse of the former Soviet Union, which created enormous security problems in its civilian research and military nuclear infrastructures, though less so in its civilian nuclear power sector. Pakistan today raises similar concerns. If sensitive nuclear fuel-cycle facilities spread to a large number of countries in the future, political instability will be cause for concern. There are few technical options for alleviating this concern. Nuclear emergency search teams of the sort deployed by the United States during the Cold War

can locate nuclear materials and defuse nuclear explosives. Whether such teams could secure storage sites or retrieve nuclear materials in other countries without the cooperation of local security forces is doubtful, not least because such cooperation may not be forthcoming in the event of a state's political collapse. These teams were never designed to prevent nuclear weapons material from falling into malevolent hands in the event of political collapse. Options to delay access to sensitive storage sites by terrorists, or to make nuclear materials more difficult to use, would help. Buying time may be very important under these circumstances. Clearly, the emphasis should be on preventing sensitive nuclear fuel-cycle expansion to countries that do not have well-developed political, legal, and security institutions, to minimize the chance that sensitive facilities will be transferred to states that may fail.

Evolution of the IAEA

Safeguards

IAEA safeguards attempt to detect diversions of nuclear material in a timely manner (which, it is hoped, will deter diversions), and to detect undeclared facilities and material stocks. The technical objective is the timely detection of "significant quantities" of fissile material, defined as 25 kg of U-235, 75kg of U-235 in the form of LEU (approximately 2 metric tons of LEU), or 8 kg of separated plutonium. The current means of detection consist largely of access control, video monitoring, seals, and material balance assessments. Traditionally, safeguards have been used to verify that national declarations of a state's nuclear facilities and nuclear materials were accurate. The Additional Protocol has been designed to ensure the completeness of national declarations—a more challenging task. To this end, the IAEA relies upon techniques such as environmental sampling and short-notice random inspections to detect undeclared facilities or activities.

The Additional Protocol requires signatories to declare the location of all nuclear research and development centers within their countries and to grant greater access to these and other facilities and to the scientists and technicians working at them. This protocol allows the IAEA to assemble more accurate and complete State Evaluation Reports on nuclear activities within a country. Still, the effectiveness of the Additional Protocol is limited by its lack of universality; it is voluntary, and 70 countries have yet to sign. While not sufficient to detect all possible cheating scenarios, IAEA safeguards probably can detect the most egregious cases, they may deter others, and their clear violation promotes international consensus for sanctions when efforts to gain additional information on a state's activities are thwarted. Safeguards arguably are effective because no safeguarded HEU or plutonium has ever been diverted to weapons use in the three decades of their existence, so far as we know, although the incomplete picture of Iraq's nuclear activities prior to the 1991 Gulf War is cause for skepticism. Although the Additional Protocol was added in 1997, IAEA safeguards still did not detect early Iranian uranium enrichment activities or the Syrian undeclared nuclear reactor. Whether the IAEA would have discovered these activities later, in time to bring pressure on the state to halt its undeclared activity, is an open question.

Nevertheless, as nuclear power expands, more advanced safeguards need to be developed to minimize the chance of undetected diversion. In particular, continuous monitoring of plant processes should supplant the existing practice of random inspections

that consist of IAEA inspectors taking limited samples at strategic points in a plant. The main barrier to incorporating continuous monitoring is the sensitivity of proprietary information. For example, continuous enrichment monitoring (CEMO) detectors can accurately measure enrichment levels at any point in a gas centrifuge cascade, thus guaranteeing that no HEU is being produced; however, such techniques may divulge proprietary information about plant design and operating efficiency. Information barriers that restrict access to certain data have been suggested, but commercial confidence that proprietary information can be adequately protected remains elusive. Nevertheless, if adopted, continuous monitoring would enable IAEA inspectors to readily determine the absence of proscribed material and to provide more accurate and timely plant-wide material balance assessments, an important step for countrywide material balance assessments.

Designing safeguards into facilities from the beginning is more efficient than grafting them on after plants have been constructed. Consequently, greater efforts should be made to involve safeguards experts, including those from the IAEA, in the design phase of any new plant. This action may also be economically attractive. Nuclear power reactors with inherently designed safety features have demonstrated higher reliability and, hence, higher operating efficiencies compared to reactors with retroactively installed safety features. Whether the same is true for safeguards is less clear. In any case, proactive designs would avoid costly retrofits. At the same time, close IAEA involvement in the plant design could make facilities more vulnerable to security breaches, particularly theft or sabotage, by malevolent actors who might gain inside knowledge from IAEA participants.

Expanding the IAEA safeguards mandate is also important. The Additional Protocol calls for expanded access to a state's nuclear infrastructure and personnel. Short-notice inspections clearly should be streamlined so inspectors can arrive quickly at facilities, circumventing the need for visas and other delays that can undermine the value of such inspections. Beyond the Additional Protocol, the IAEA should have the ability to inspect suspicious activities that may be related to a nuclear weapons program even if no nuclear materials are involved (currently the IAEA can only investigate activities that involve nuclear material). This could require access to sensitive military sites, which is why such proposals have not been adopted in the past. More importantly, the IAEA inspection mandate should include provisions for the automatic expansion of inspection rights, without the current requirement for Security Council or IAEA board approval, when a state is found to be in noncompliance with its IAEA Comprehensive Safeguards Agreement or even if material balance discrepancies occur that could raise suspicions if not addressed quietly and quickly. A lack of host nation cooperation would be grounds for referring the case to the UN Security Council. Such an expanded safeguards mandate requires an expanded budget as well as appropriate priorities for inspections so funds are not wasted monitoring low risk facilities. Such prioritizing raises the perennially difficult issue of equitability. The IAEA cannot be viewed as an organization that focuses its safeguard efforts only on states of concern to a small number of other NPT signatories, especially the five nuclear-weapon states.

Toward this end, Pierre Goldschmidt has suggested that the UN Security Council adopt a binding resolution providing for automatic enhanced IAEA verification and inspection authority in those states found to be in noncompliance, that noncompliant

states sign safeguards agreements covering all nuclear facilities within 60 days, and that a noncompliant state's right to conduct sensitive nuclear fuel-cycle activities be suspended for 10 years subject to subsequent IAEA verification of compliance.⁷ Such measures would increase the IAEA's authority to verify compliance with the NPT, thereby resolving more rapidly concerns of the sort that currently exist with Iran. Such measures do not erode a state's sovereign right to the peaceful uses of nuclear energy under Article IV of the NPT, because they would be invoked only when the IAEA finds a state to be in noncompliance.

Physical Protection

A central concern with the expansion of sensitive nuclear fuel cycle facilities is physical protection, control, and accounting for weapon-usable material, especially separated plutonium in closed fuel cycles (HEU should not exist in future civilian nuclear future cycles). Yet efforts to improve physical protection have received less attention. Currently, physical protection is the province of the state. U.S. efforts tend to focus on sensors and barriers, while many other countries rely on guards and guns. Intrinsic barriers (e.g., radiation barriers and massive containers) provide the best means to guard against theft and sabotage; however, there is no intrinsic barrier against the theft of separated plutonium or HEU.

If a state withdraws from the NPT, physical protection of weapon-usable material within the nascent nuclear-weapon state is of paramount importance, to reduce the threat of terrorism. However, sharing information on physical protection is politically difficult for supplier states after the recipient state withdraws from the NPT or when suspicions exist that the recipient may be engaged in a covert weapons program, because such cooperation may appear to sanction their actions. Ensuring good physical protection is especially important if a state is pursuing nuclear weapons, because material in its hands may be more vulnerable to theft than similar material from more mature nuclear-weapon programs. Concerns with Pakistan's physical protection measures are a case in point, especially with the country's proximity to Islamic extremists.

Voluntary efforts to share best practices on physical protection are useful, especially if participants are cognizant of differences in security culture. Still, such attempts suffer from the dilemma that exposing too much information about physical protection could compromise security if this information falls into the wrong hands.

Suggestions for improving physical protection raise the question of whether the IAEA is the most appropriate institution to oversee this effort. Institutionally, the IAEA is the only organization designed to detect the diversion of nuclear materials. Moreover, the IAEA's reputation as an honest broker has improved in the wake of the UNSCOM inspections in Iraq in the early 1990s and the inspections to detect Iraqi weapons of mass destruction prior to the 2003 U.S. invasion. However, physical protection is different from monitoring NPT compliance because it is intimately tied to state police or military organizations. Currently, the IAEA can play only an advisory role regarding physical protection.

Clearly, IAEA personnel and budgets must expand if the organization is to have any hope of adequately monitoring an expanded international nuclear fuel cycle. States

⁷ Pierre Goldschmidt, "The Urgent Need to Strengthen the Nuclear Non-Proliferation Regime," Policy Outlook #25, Carnegie Endowment for International Peace, January 2006.

should be encouraged to send their best experts to the IAEA, as Japan does, thereby improving the quality of the inspectors and analysts. Whether the political will exists to strengthen and fund the IAEA so it can adequately safeguard and secure an expanded international nuclear fuel cycle remains to be seen. Without such changes, the expansion of nuclear power will invite proliferation, if not nuclear terrorism.

Consequence Management

If nuclear power expands in the decades ahead, it is certain that at some point material will be found missing. The international community should anticipate and plan for such events, because without concrete mitigation plans, these events have the potential to shake world confidence in nuclear power, perhaps causing irreparable harm. Special teams to track and locate missing material might be useful, assuming they get the necessary cooperation from other states. At the very least, states should work out protocols, perhaps coordinated with the IAEA, for the necessary collaboration between foreign and domestic law enforcement agencies, intelligence agencies, and military forces to respond if a significant quantity of nuclear weapon-usable material is found missing.

Uranium Enrichment

It may be tempting to conclude that the most proliferation resistant and secure nuclear future is one dominated by LWRs using once-through fuel cycles. This scheme avoids the need for reprocessing and plutonium-bearing fuels. However, in this world, concerns with assured fuel supplies may drive some countries to acquire national uranium enrichment and fuel fabrication facilities, even if they have relatively few nuclear power plants. Enrichment plants are a proliferation concern only because they may be diverted to HEU production covertly or following NPT withdrawal. In their normal operation, they do not involve weapon-usable materials. HEU is easier than plutonium to fashion into nuclear explosives due to the simple gun-type mechanism required for efficient detonation, and HEU weapons are harder to detect in transit and, hence, better suited for covert delivery than plutonium weapons. Limiting the spread of uranium enrichment plants, providing adequate safeguards if they do spread, and detecting the presence of covert uranium enrichment plants will be the main challenges facing a nuclear world dominated by once-through nuclear fuel cycles. Detecting LEU diversion could help locate covert enrichment facilities. However, the biggest problem posed by the proliferation of uranium enrichment facilities will be NPT withdrawal followed by HEU production.

Physical protection of LEU is less important because LEU is of little use to terrorists. Similarly, enrichment plants are less attractive targets for sabotage, because no radiation would be released, and terrorists cannot commandeer them to produce HEU. Only if a state produces HEU in its enrichment plants does physical protection become of paramount importance. Hence, physical protection of uranium enrichment plants and the material they produce goes from a relatively minor concern to a major concern depending on state actions regarding HEU production and storage.

Gas centrifuges will be the most common enrichment technology in the future, so they represent the greatest near-term proliferation challenge. Gas or thermal diffusion plants, such as those in the United States, are large and costly and, consequently, will be phased out as nuclear power expands. Nor are novel chemical and plasma isotope separation techniques sufficiently well developed to be likely technologies for future

enrichment plants. However, aerodynamic separation (e.g., the Becker nozzle) and laser isotope separation are sufficiently well developed in the laboratory that they may compete commercially with gas centrifuges in the future. Even if these technologies are not economically competitive with gas centrifuges, it is very important to monitor their spread, because they may be used in covert programs. For example, aerodynamic separation was used in the South African nuclear weapons program to produce HEU for six bombs before the program was dismantled, and laser isotope separation currently is used to purify isotopes for medical and industrial applications. Although neither technology has been used for large-scale separation of U-235, they are cause for proliferation concern, because their small footprints make them ideal for covert facilities. Moreover, proliferators may turn to these technologies as export controls on gas centrifuge technology tighten. They should be closely monitored.

Gas centrifuge plants are relatively small and consume relatively little electrical power, making concealment easier. Hence, they too are ideal for covert enrichment plants. Perhaps their greatest vulnerability is their fragility to mechanical shocks while running, making them relatively easy to destroy with explosives. The U-235 enrichment level is determined by the number of centrifuges connected in series in a centrifuge cascade, and the plant output is determined by the number of cascades operating in parallel. Thus, the pipe configuration of a plant is critical. Changes in piping can convert a plant from LEU production to HEU production with few external, visible signs. In fact, some Russian and Chinese enrichment plants can be reconfigured from a central control room without any physical changes in pipe configuration.

The spread of advanced, or “supercritical,” centrifuges are in some respects of less concern than the spread of less sophisticated, or “subcritical,” centrifuges, because the former are difficult to operate and even if blueprints are stolen, they are difficult to manufacture or reverse-engineer without substantial technical knowledge. Thus, a repeat of the A.Q. Khan saga is less likely with supercritical centrifuges. However, supercritical centrifuges are not required to produce HEU for nuclear weapons or LEU reactor fuel. A.Q. Khan has already disseminated subcritical centrifuge designs, the so-called P1 and P2 centrifuges, which although inefficient are perfectly adequate for producing enough HEU for a few bombs each year.⁸ Russian centrifuges also are not as advanced as their Western counterparts, but they are more reliable and, hence, make effective LEU (and HEU) production cascades. Therefore, the proliferation of subcritical centrifuge designs, along with the network of suppliers, will be the primary proliferation concern over the next few decades.

Current IAEA safeguards for enrichment plants include intermittent (once a year) visual inspections of plant pipe configuration blueprints and tamper-indicating devices on piping, camera surveillance of the centrifuge hall to detect unauthorized operations, sample collection at selected locations to verify that HEU is not present, and material balance assessments to determine how much natural uranium is consumed and how much LEU is produced. Detecting the diversion of LEU (or natural or depleted uranium) is important, to guard against covert HEU production. Detecting LEU production in excess

⁸ 2-3 SWU/year and 5-6 SWU/year for the P1 and P2 centrifuges, respectively, compared to 40 SWU/year for existing TC-12 URENCO centrifuges, 130 SWU/year for the more advanced TC-21 centrifuge, and approximately 250 SWU/year for the most advanced U.S. centrifuge designs. It takes approximately 5,000 SWU to make enough HEU for a nuclear weapon.

of declared amounts is important for the same reason. Safeguarding against covert HEU production at declared plants is easier, because no HEU should be present. Any amount is a violation, thus relaxing the need for measurement accuracy. While these efforts make it difficult to produce HEU covertly or to divert significant quantities of material without detection, more extensive, and probably intrusive, inspections will be required to achieve higher confidence levels.

Techniques to continuously monitor flow and enrichment levels at all centrifuge outputs would greatly improve safeguards; however, this aim conflicts with the need to protect proprietary information and could be expensive. In fact, continuous monitoring of enrichment levels makes the exact cascade configuration less important—a point of some significance, because the cascade design is also proprietary information. If continuous monitoring cannot be achieved, then current safeguards should be improved by allowing more frequent access to centrifuge plants, improved data collection on the weights of uranium hexafluoride (UF₆) feed cylinders, and more accurate assays of depleted uranium tails to improve the accuracy of plant material balance assessments. Again, allowing safeguards to be built into enrichment plants from the start would help avoid safeguards that interfere with plant operations later on.

Covert uranium enrichment plants based on gas centrifuge or aerodynamic or laser isotope separation will be difficult to detect. Performing a countrywide material balance assessment to ensure that large stocks of LEU or natural UF₆ are not missing is one option. Monitoring national conversion plants that produce uranium hexafluoride from uranium ore is easier, because these plants are large and difficult to hide. Ensuring that no significant quantities of uranium hexafluoride are diverted from such plants is straightforward. The remaining task is detection of covert uranium hexafluoride imports. Greater latitude for IAEA inspectors to conduct inspections and interviews with scientists and technicians in a suspect country could help detect covert shipments and plants. Still, accurate countrywide material balances will be challenging. It is difficult to know if such measures, coupled with intelligence on centrifuge production or purchase, will be sufficient to detect or deter small, covert enrichment plants under all circumstances.

Denying nations the right to build indigenous uranium enrichment plants is politically impractical, attractive as it might seem, not least because Article IV of the NPT specifically gives non-nuclear-weapon states the right to build such facilities. However, discouraging national enrichment facilities by offering as an alternative involvement in multinational enrichment facilities is a more attractive approach. At the very least, this approach would separate states with no nuclear weapon aspirations from those who want to keep the option open, thereby focusing attention on the latter category of states.

If this incentive is insufficient, spent-fuel take-back arrangements that include waste disposal by the supplier state should be quite attractive, because they remove the burden to the consumer state of having to find suitable geologic repositories. Spent-fuel take-back and storage options should persuade all but the most paranoid leaders, or those with nuclear weapons aspirations, to forgo national enrichment programs. However, it will be difficult for supplier states to offer such guarantees for many decades. Some supplier states are having difficulties opening repositories for their own spent fuel, and the commercialization of fast reactors and their fuel cycles, which make this option feasible for supplier states, are decades away.

Spent-Fuel Reprocessing

In the near term, spent-fuel reprocessing will not expand rapidly even if nuclear power expands, because most nuclear reactors will operate on once-through cycles using LEU. To the extent reprocessing occurs in the near term, it will be limited to states with existing reprocessing facilities. This suggests that MOX fuel cycles will be limited in the near term, perhaps confined only to those states currently using MOX fuel on a limited basis.

However, in the far term, spent-fuel reprocessing will become much more common if breeder reactors or burner reactors are commercialized. The aqueous PUREX method is the most mature reprocessing method today and will likely be the dominant reprocessing technology for at least the next several decades. Considerable research has gone into alternate methods that avoid creating pure plutonium streams, e.g., different variants of the UREX process. However, none of these have been implemented on an industrial scale, and it is not yet clear if they will be adopted commercially.

Pyro-processing, or electro-refining, is another technology that generally is more proliferation resistant than PUREX because plutonium is not separated from the minor actinides. The plutonium and minor actinides are fashioned into fuel elements and burned in fast reactors. This fuel is self-protecting because it has approximately 1000 times more gamma radiation than reactor-grade plutonium and approximately 1000 times the spontaneous neutron emission rate, making it less suitable for explosives. Currently, though, this technology is designed for metallic fuel elements and not the oxide fuels associated with LWR fuel cycles; spent oxide fuels would have to be converted to metallic form before they could be reprocessed with this technique. It is also unclear whether plant operators can create sufficiently clean plutonium mixtures by adjusting the electro-chemical potential of the process. While pyro-processing is attractive in principle, only pilot plants have been constructed to date (e.g., as part of the experimental breeder reactor, EBR-II, in the United States). Considerable work remains before such systems become commercially viable.

Small, rudimentary, clandestine reprocessing facilities that could produce several bombs' worth of plutonium each year are possible but with considerable obstacles: they would require reasonably skilled technicians to operate; plant workers would likely suffer higher radiation exposures if the plant uses less sophisticated construction materials to avoid export controls; volatile fission fragments may be detected in the environment; and, most importantly, such plants need spent fuel from either a covert reactor or diverted from commercial spent fuel, both of which can be detected under current safeguards. Therefore, covert reprocessing plants for spent fuel will be difficult to create.

Extracting plutonium from diverted fresh MOX fuel would be less difficult. But diverting reactor-grade plutonium into a state weapons program may not be very likely, because states would prefer weapon-grade plutonium if they are going to the trouble to build nuclear weapons. Hence, states are more likely to withdraw from the NPT, then reprocess low burn-up fuel to produce weapon-grade plutonium. Safeguards are the current and preferred method for deterring and detecting the diversion of plutonium from reprocessing plants. In general, it is very difficult to detect the diversion of one significant quantity of plutonium (8 kg) using existing safeguards. Material balance discrepancies of 8 kg over one year are common for large plants that reprocess 1000 metric tons of spent fuel each year (containing approximately 10 tons of plutonium), thus

creating significant false alarm problems. This is true regardless of the chemical processes used (e.g., PUREX, UREX, or pyro-processing). Continuous monitoring would help close the material balance over shorter time periods, although the diversion of small quantities over extended times could still go unnoticed. Still, advanced safeguards can reduce the amount of material unaccounted for if applied throughout the reprocessing plant and, hence, limit the magnitude of this problem.

The Japanese reprocessing plant at Rokkasho Mura represents a model approach to safeguarding future reprocessing plants. Traditional and advanced safeguards were designed into the plant, with IAEA and Japanese experts working together to examine diversion scenarios and possible solutions. Japan has gone a step further by allowing international operators to help run the plant during startup so the IAEA can establish a baseline for plant operations, thus making it easier to detect suspicious discrepancies in the future. Still, with a design throughput of 800 MTHM/yr, a material balance accuracy of 0.1% leaves 800 kg of heavy metal unaccounted for, which contains approximately 8 kg of plutonium. Thus, as reprocessing plants become larger, more stringent material balance assessments will be required.

Although the economic rationale for reprocessing is less clear in the near term and the technologies involved are difficult to master, reprocessing represents a significant proliferation concern if closed fuel cycles become widespread. Again, technology denial is not a viable strategy because it is inherently discriminatory. A better approach would be to limit the expansion of large national reprocessing facilities by encouraging or requiring participation in multinational reprocessing facilities, especially for medium and small nuclear-power states.

Multinational reprocessing facilities would have the same proliferation benefits as multinational enrichment facilities: reducing the total number of plants worldwide, increasing the likelihood that material diversion will be detected, and deterring host nation expropriation of such facilities because strong responses are more likely.

Regarding terrorism, reprocessing plants will not need special physical protection measures beyond those already in place. Terrorist theft from reprocessing plants is difficult. Most sabotage scenarios will cause few deaths due to the heavy shielding already in place for radiation protection and the difficulty of dispersing radioactive materials over large areas. The major challenge will be to protect separated plutonium or plutonium-bearing fuels from theft either in storage or transport. Colocating reprocessing plants with fuel fabrication plants, and better yet with nuclear power reactors in large self-contained energy centers, reduces the need for transportation. Nonetheless, one should not lose sight of the larger terrorist challenge associated with stockpiles of weapon-grade plutonium in Russia and the United States, or the potential for theft of spent naval reactor fuel or research reactor fuel containing HEU that may be stored at unsecured sites.

Transport and Storage

The most pressing transport and storage issue in the near term is the elimination of HEU for research reactors. Otherwise, the near-term proliferation and physical protection challenges associated with transport and storage are manageable, because the greatest volume of material will be LEU and spent fuel from once-through cycles, neither of which is particularly sensitive material. Moreover, spent fuel is transported in very

heavy casks for radiation protection, making them very difficult targets for theft or sabotage. Conventional physical protection and safeguards should be adequate in the near term.

The transport and storage of separated plutonium and plutonium-bearing fuels will be a major challenge, if or when spent-fuel reprocessing occurs on a large scale. In this case, separated reactor-grade plutonium and plutonium-bearing fuel will be produced in substantial quantities, necessitating transport and storage. Improved physical protection at reprocessing plants will be required to secure such materials. Plutonium-bearing fuel in transport, or stored at reactor sites, will also require added physical protection. Just-in-time delivery, which is already practiced by some suppliers, would reduce inventories at reactor sites, but it may make consumers more vulnerable to fuel supply disruptions. As next-generation plutonium-burning reactors are developed, , minimizing the inventory of separated plutonium and plutonium-bearing fuel in storage will be attractive, as will an international fuel cycle where plutonium is burned at the rate it is produced.

Geologic repositories should be viewed as an integral component of the security equation, because spent-fuel take-back, coupled with subsequent reprocessing and actinide burning in fast reactors, allows reprocessing states to provide the full range of nuclear fuel services to small, and potentially medium, nuclear-power states, and it alleviates the problem of finding suitable long-term storage sites in these countries. Such arrangements provide strong inducements for states to forgo national enrichment and reprocessing facilities, thus reducing the proliferation threat or at least focusing attention on states that reject the offers. However, these inducements are many years away because they depend upon the commercialization and certification of fast reactors and their associated fuel cycles.

Appendix A: Workshop Attendees

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