Center for International and Security Studies at Maryland

Can Future Nuclear Power Be Made Proliferation Resistant?

Harold Feiveson, Alexander Glaser,
Marvin Miller, and Lawrence Scheinman

July 2008

UNIVERSITY OF MARYLAND

CISSM
School of Public Policy
4113 Van Munching Hall
University of Maryland
College Park, MD 20742
Tel: 301-405-7601
cissm@umd.edu

This paper was prepared as a joint endeavor between the Advanced Methods of Cooperative Security Program at the Center for International and Security Studies at Maryland and Princeton University's Program on Science and Global Security, with generous support from the John D. and the Catherine T. MacArthur Foundation.

ABSTRACT

For a global expansion of nuclear power to be proliferation-resistant in the long term: (1) international institutional arrangements to oversee nuclear power would have to be largely non-discriminatory and, most importantly, fuel cycle facilities such as reprocessing and uranium enrichment should be under multinational or international authority; (2) once-through fuel cycles afford significant advantages in that nuclear-explosive material is never isolated; it is likely that uranium resources and repository space will not limit the sustainability of the once-through fuel cycle even if nuclear power grows ten-fold over the rest of the century, and it should be high priority to determine the real long-term uranium supply curve; (3) if, however, it is necessary eventually to move to closed fuel cycles, breeder or near-breeder reactors of types different than the liquid metal fast reactor might be preferable; thorium-based reactors and nuclear batteries in particular appear potentially attractive; (4) a real expansion of nuclear power may be possible only in a world of very substantial nuclear disarmament.

TABLE OF CONTENTS

1 – Introduction

If nuclear power is to grow significantly in the next several decades and beyond, it will have to address effectively issues of economics, waste management, sustainability, and safety. This paper focuses on one other issue that will have to be resolved satisfactorily — proliferation resistance. By this term, we mean the strength of the barriers to the acquisition of nuclear weapons by countries and terrorist groups. By "nuclear power system" we refer to the panoply of nuclear reactors and fuel cycle facilities deployed *and* the institutional arrangements in place to manage them, including the extent and depth of international control over elements of the fuel cycle. We take as the time periods of interest, 2050 and 2100.

To make the character of a robust nuclear future more palpable, we assume arbitrarily a worldwide growth of nuclear power from 371 GWe in 2007 to 1500 GWe installed capacity by 2050 and to 4500 GWe by 2100. This growth is consistent with scenarios advanced by two recent studies, one a 2003 interdisciplinary study by MIT[1] and one, based on an economic model, by Kim and Edmonds.[2]

The idea of describing a nuclear power system fifty and one hundred years hence is not outlandish. Most of the advanced reactor concepts now under study by nuclear engineers worldwide are not expected to be ready for first commercial deployment until after 2030 or 2040, and these envisioned reactors would have projected lives of 50 years or more. The 2100 time frame may look more questionable. But nuclear power will have to expand substantially beyond 2050 if it is to play a significant role in climate-change policy, and it will probably have to be based on nuclear technologies developed over the next several decades. In thinking about R&D on new reactor technologies, in comparing open and closed fuel cycles, and pondering which countries in a nuclear future will have nuclear power, we can't limit ourselves only to the world of 2050.

In addition to our assumptions about nuclear growth rates, we also assume that reactor types so far sketched only on paper will be developed along the lines their designers now intend. These reactor types, which mostly fall under the rubric of Generation III and Generation IV technologies, are used in our later analysis of various scenarios, based on different nuclear technologies and fuel cycle concepts.[3]

Clearly any energy future, especially one compatible with climate change, presents daunting challenges. This paper does not seek to compare nuclear to other

---

[1] MIT, *The Future of Nuclear Power*, 2003: available at www.mit.edu. In Appendix 2 of the study, the authors estimate which countries might have nuclear power by 2050 and give low and high estimates of the nuclear electricity production given in billion kilowatt-hours per year. These are then turned into "equivalent" nuclear capacities using a 100% capacity factor. .

[2] Son Kim and Jae Edmonds, "Nuclear Energy in a Carbon-Constrained World," November 1, 2005, University of Maryland, PNWD-SA-7184 (DRAFT).

[3] See, for example, John Ahearne, "Advanced Nuclear Reactors – Their use in Future Energy Supply," *Interacademy Council*, September 30, 2005.

potential climate-friendly technologies such as wind, solar photo-electricity, or carbon capture and storage, nor do we seek to project future nuclear capacity. A nuclear future of the scope indicated is possible we believe, but to achieve it safely will demand that the world construct an adequate technological and institutional framework of a kind we seek to outline.

2 – The Scale of Nuclear Expansion

If , as we assume, worldwide nuclear capacity grew to 1500 GWe by 2050 and to 4500 GWe by 2100, it would save 1.5 and 4.5 gigatons per year of carbon emitted to the atmosphere respectively compared to the alternative of coal-electric plants without carbon capture and storage, and thus represent levels of nuclear power significant in addressing global warming.[4] Also, as indicated, they are levels that correspond to scenarios put forward by MIT and by Kim and Edmonds.[5]

At an 85% capacity factor, the 4500 GWe in 2100 is equivalent to 120 exajoules (EJ) of nuclear electricity. The International Panel on Climate Change project total electricity in 2100 to be in a range roughly between 665 EJ for the A-1 "business as usual" scenario and 245 EJ for the B-1 scenario, which is the most modest in terms of electricity growth. The 120 EJ thus represents a nuclear contribution to total electricity between about 20 percent and 50 percent.

[4] Steve Pacala and Robert Socolow, "Stabilization Wedges," *Science*, 13 August 2004. Pacala and Socolow developed a wedge model to make vivid the climate-change challenge confronting the world. At present, emissions of carbon dioxide worldwide measured in the amount of the contained carbon are approximately 7 billion metric tons. The central business-as-usual projection of the Intergovernmental Panel on Climate Change (IPCC) indicated the emitted carbon growing to 14 billion tons per year in 50 years. To stabilize the atmospheric carbon dioxide at no more than double the pre-industrial level of about 280 ppm, it will be necessary to keep the average emissions over the next 50 years roughly constant, at 7 billion tons per year. This means that carbon emissions compared to business-as-usual will have to be cut steadily over the 50-year period leading to a 7 billion ton reduction by the end of the period – and then a gradual reduction in annual carbon emissions. In the wedge model, the authors imagine the cuts in carbon measured in 7 wedges of 1 billion tons of carbon per year each. For nuclear replacing coal electricity, one wedge equals approximately 700 GWe over the present nuclear capacity of 371 GWe.

[5] The Kim/Edmonds scenario closest to the one we have adopted is the scenario where atmospheric carbon dioxide is limited to 550 ppm, where there is considerable carbon capture and storage, and where uranium is unconstrained. In this scenario, Kim and Edmonds show a total global electricity production in 2095 of 318 EJ, and a nuclear electricity production of 118.7 EJ; at 85% capacity factor this is equivalent to a little less than 4500 GWe. So in this scenario, nuclear represents about 37% of total electricity. The Kim/Edmonds' model is useful because they break up the nuclear electricity production by region, and to some extent by country.

Naturally, one could posit a far greater nuclear contribution to energy in 2100, especially if nuclear could be used to produce hydrogen economically. For example, Bill Halsey at the Lawrence Livermore National Laboratory (LLNL) puts forward a scenario where total energy in 2100 is equivalent to 30-45,000 GWe, and the nuclear contribution is on the order of one-third of this, implying a capacity of about 10-15,000 GWe.[6] Consideration of robust nuclear futures of such a magnitude may be useful for suggesting research strategies on new nuclear technologies that could be overlooked if nuclear engineers thought only of more modest futures. For our purpose, however, which is to think through the technological and institutional implications of a robust nuclear future, the 4500 GWe marker seems adequate.

Given the two markers of 1500 GWe by 2050 and 4500 GWe by 2100, we construct below a growth scenario for nuclear power that we will later use to calculate material flows. See Figure 2.1. This growth scenario is close to the nuclear projections of Kim and Edmonds based on their scenario defined by an atmospheric limit of carbon dioxide of 550 ppm, carbon capture and storage, and no limitations on the availability of uranium.[7]

To achieve the indicated growth, annual construction of nuclear capacity would have to follow a curve something like that shown in Figure 2.2. In this scenario, while starting relatively modestly, nuclear construction would ramp up dramatically in the period 2025-2045. Within these two decades, the annual additions of nuclear capacities would have to increase from about 20 GWe to 75 GWe per year. Such growth rates would be ambitious but not out of the question. The historical peak in nuclear construction occurred in 1984 when 34 GWe were added to the grid. Since 1990, however, new nuclear capacity added has always been lower than 10 GWe/yr.

[6] Bill Halsey, "Advanced Nuclear Technology and a Sustainable Nuclear Future," Postgraduate School, Monterey, CA, October 12, 2005.

[7] For a recent review of the issue of uranium availability, see Erich S. Schneider and William Sailor, "Long Term Uranium Supply Estimates," *Nuclear Technology*, Vol. 162, June 2008.

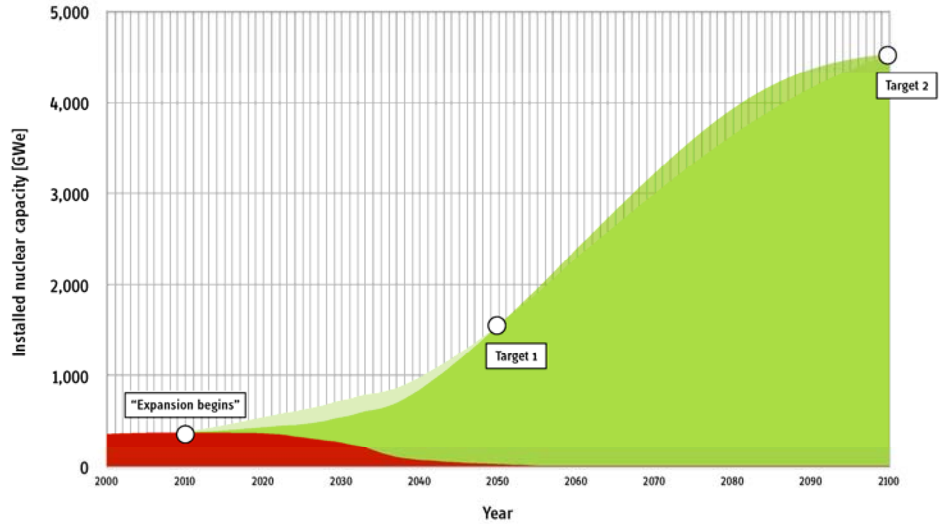

Figure 2.1. Illustrative growth of nuclear capacity worldwide to 2100, based on markers: 1500 GWe by 2050 and 4500 GWe by 2100.

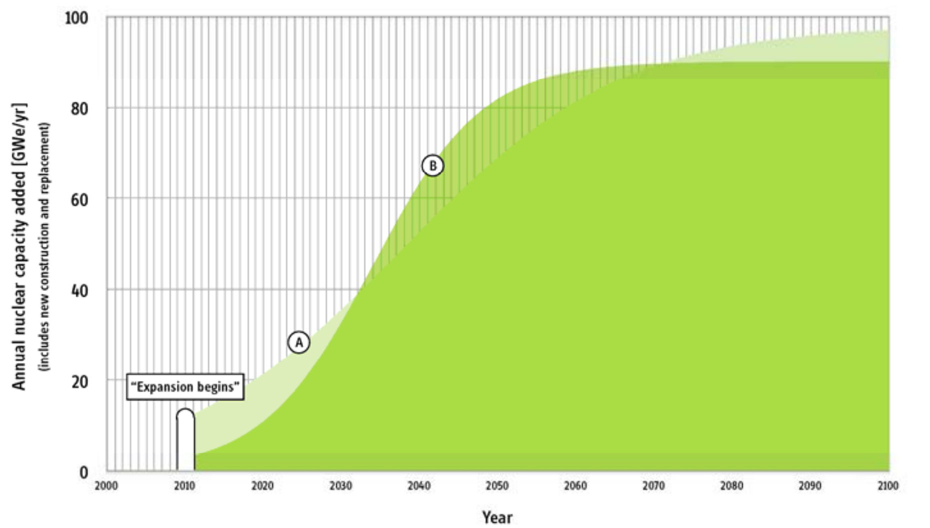

Figure 2.2. Nuclear capacity that needs to be added annually in order to meet the target values of 1500 GWe by 2050 and 4500 GWe by 2100, assuming that a global expansion program starts in 2010. Given the number of reactors under construction today, Scenario A is already difficult to implement. Scenario B, however, would still be compatible with reality, but requires a much higher buildup of production capacities between 2025 and 2045.

3 – Proliferation Resistance

In a recent report, an expert group of the Generation IV international forum presented a comprehensive evaluation methodology for proliferation resistance and physical protection.[8] Its objective was to identify paths by which various threats could be mounted and to examine the capability of systems to respond to the threats. The principal threats identified were:[9]

- Concealed diversion of declared materials
- Concealed misuse of declared facilities
- Overt misuse of facilities or diversion of declared material (breakout)
- Clandestine dedicated routes
- Material theft by sub-state actors
- Radiological sabotage by sub-state actors

The resistance of a system to these threats will depend on a variety of measures, such as the inherent technical difficulty of diversion due to radiation, mass-handling, and other barriers, the detection probability provided by safeguards, and the time and costs required for a potential proliferator to achieve a diversion. The obstacles to proliferation will be both intrinsic technical barriers and extrinsic institutional barriers.

In the following analysis, we will refer to all of these threats in assessing the proliferation resistance of future nuclear power under varying assumptions.

4 – Five Scenarios

To help understand the implications for proliferation of a substantial expansion of nuclear power, we consider five nominal scenarios based predominantly on specific reactor types:

- Advanced light water reactors (LWRs) and/or gas-cooled thermal reactors on a once-through fuel cycle

  In this scenario, LWRs and gas-cooled reactors such as the pebble bed reactors operate on a once-through fuel cycle through 2050 (as described in the MIT study) and also to the end of the century. The reactors will be fueled by low-enriched uranium. Spent fuel will be put directly into geological repositories.

[8] Proliferation Resistance and Physical Protection Evaluation Methodology Expert Group of the Generation IV International Forum, *Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems*, Revision 5, issued by the OECD Nuclear Energy Agency, September 30, 2006, GIF/PRPPWG/2006/005.

[9] The Expert Group included also as a threat, information theft by a sub-state actor. It also put the sub-state threats into a separate category of physical protection. For simplicity, we simply include all the threats, including by sub-state actors, into the rubric proliferation resistance.

- Actinide burning based on fast reactors

  This is the vision of the Global Nuclear Energy Partnership (GNEP). Spent fuel from LWRs and from a fleet of fast reactors will be reprocessed to separate plutonium and other transuranics (TRU – americium, curium, and neptunium). These will be fabricated into fuel for fast reactors and will be fissioned in the fast reactors in several cycles, such that the plutonium and other TRU are eventually mostly burned away. The fission products will be put into geological repositories.

- Fast breeder reactors in a closed fuel cycle

  We imagine, in equilibrium, a division of LWRs and fast breeders in roughly a 55-45 ratio, similar to that described in the MIT study. Spent fuel from both types of reactors will be reprocessed and the separated plutonium used to start-up and re-fuel the breeder reactors.

- Thorium fuel cycles

  Several different thorium cycles are considered. In particular, we note the possibility of breakeven breeding in a molten salt reactor. While such a reactor requires enriched uranium (typically 20 % U-235) for startup, relatively little further supplies of enriched fuel are required during subsequent operation. The U-233 produced by neutron absorption in Th-232 is never separated from the fuel, and it is also denatured by the addition of U-238 which means that isotope separation would be required to obtain weapons-grade U-233. In addition, the isotope U-232, which has a high gamma-emitting daughter, is produced during reactor operation, thus further complicating attempts to obtain weapons-usable U-233 from this cycle.

- Nuclear batteries in a hub-spoke configuration

  At a central facility, reactors nominally in the range of 20-100 MWe would be fueled either with 20% uranium or plutonium, sealed, and then transported to countries deploying the reactors. The reactors would not need to be refueled during their core life, nominally 20 to 30 years, at the end of which time they would be sent back to the central facility, where the plutonium would be separated and re-fabricated into cores for the replacement reactors.

The five scenarios are described in more detail in Appendix A. Although clearly many technological hurdles stand in the way of the new technologies, we assume for purposes of illustration that they will all be overcome. Also, while each scenario highlights a particular reactor concept, there will be some mixing of reactor types as is discussed in the Appendix.

Here we highlight a few of the characteristics of the scenarios that are most relevant to our later analysis of proliferation resistance.

Many more countries with nuclear power

Today, the countries with nuclear power programs are mostly either already nuclear weapon states or industrialized democracies with no current intentions to acquire nuclear weapons. See Figure 4.1.[10]

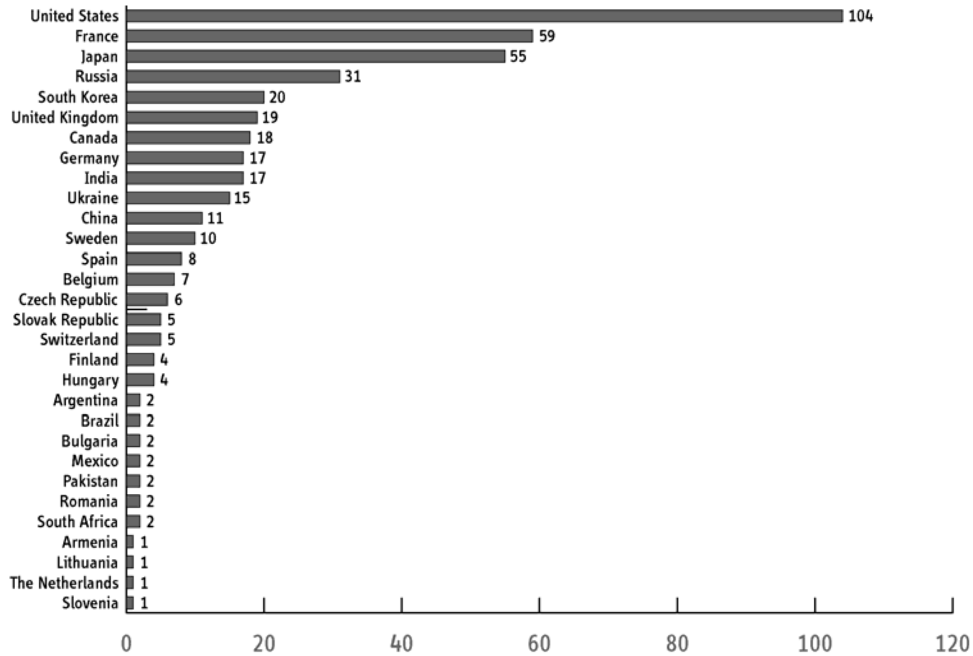

Figure 4.1 – Number of Reactors in Operation Worldwide

A robust nuclear future will, however, present a different picture. The scene of significant nuclear growth over the next half century will have to be largely in the developing countries. This is where by far the greatest increase in electricity production is projected. If one adopts the MIT estimates of which countries will have nuclear power in a 1500 MWe nuclear future in 2050, they include many which today have essentially no or a negligible amount of nuclear power: Italy, South Africa, Portugal, Brazil, Argentina, Algeria, Morocco, Bosnia-Herzegovina, Indonesia, Pakistan, Philippines, Vietnam, Egypt, Iran, Saudi Arabia, Turkey, Thailand, North Korea, and several former Soviet republics.[11] See Figure 4.2.

[10] IAEA, PRIS data base, February 2008.

[11] The 2003 MIT study on the future of nuclear power assumed an installed nuclear capacity of approximately 1,500 GWe(e) in 2050 and developed a scenario for a country-by-country distribution of nuclear capacity based on “various country-specific factors, such as current nuclear power deployment, urbanization, stage of economic development, and energy resource base” [p. 111]. Based on these assumptions, the MIT study concluded that 58 countries would plausibly have commercial nuclear plants in a 1500 GWe scenario for 2050.

The introduction of nuclear power in these countries suggests the magnitude of the safeguards and institutional challenge, given that some of the new countries will doubtless raise international concerns of the kind now being highlighted by Iran's nuclear energy program. Naturally, the spread of countries with nuclear power will be still more substantial by 2100. One potential attraction of the nuclear battery scenario is that many of the new countries might well be content to import the batteries without attempting to develop their own fuel cycle facilities or nuclear infrastructure.

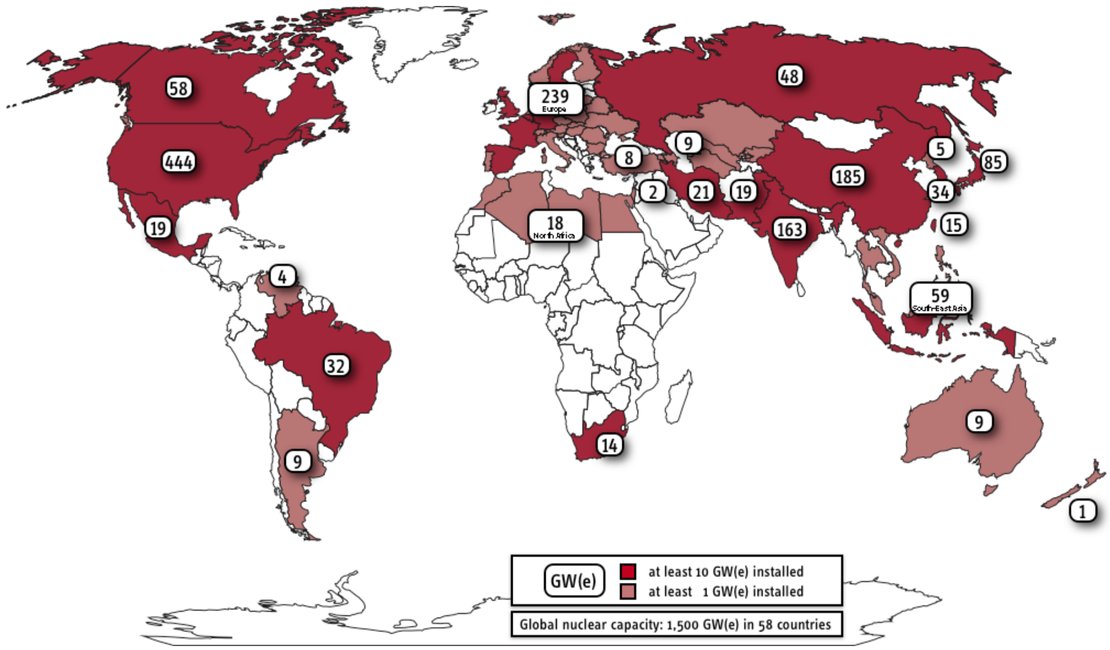

Figure 4.2. Hypothetical Distribution of Reactors Worldwide in the 1500 GWe MIT Scenario.

Material Flows in the Five Scenarios

Table 4.1 shows some of the material flows associated, *at equilibrium*, with each of the five fuel cycles featured – based on a 1 GWe capacity. As described in Appendix A, however, all the scenarios will involve some mixing of fuel cycles, thus affecting the cumulative material flows through 2050 and 2100. The cumulative flows associated with a 1500 GWe capacity are shown in the Appendix.

Table 4.1 – Implications of five pure fuel cycles based on 1 GWe.

	LWR (once-through)	GNEP (MIT) LWR + Burner	FBR	Thorium MSR	Nuclear Battery
Initial Core	60 MT of LEU at 4.5%	33 MT of LEU at 4.5%	4000-5000 kg of plutonium	17.5 MT of 20% LEU	50,000 kg of Pu/TRU
Front end: Externally supplied services and materials					
U(nat) Requirements	200 MT/yr	110 MT/yr	small	50 MT/yr	—
Enrichment	125,000 SWU/yr	70,000 SWU/yr	—	40,000 SWU/yr	—
Fresh Fuel	20 MT/yr of 4.5% LEU	11 MT/yr of 4.5% LEU	—	1 MT/yr of 20% LEU	—
Front end: Self-generated fuel					
Fresh Fuel (recycled)	—	780 kg/yr of Pu and MA	1500 kg/yr of plutonium	—	1700 kg/yr on average
Back end					
Total Discharge Spent Fuel	20 MT/yr	14 MT/yr	15-20 MT/yr	(5-9) MT/yr on average	10 MT/yr on average
Total Discharge Fissile Material	200 kg/yr of plutonium	780 kg/yr of Pu and MA	1700 kg/yr of plutonium	25 kg/yr of Pu on average	1700 kg/yr on average
Separation Fissile Material	—	780 kg/yr of Pu and MA	1700 kg/yr of plutonium	—	1700 kg/yr on average

Annual Requirements per GWe.

This assumes LEU at 4.5% with tails depleted to 0.3%. Assumed life of MSR core is 30 years. Battery data is based on SSTAR Design Details: 20 MWe batteries, 30 year life, 17% of Pu/TRU in 6000 kg of HM[12]

[12] Jim Sienecki, "SSTAR Design Details," Argonne National Laboratory Presentation, September 7, 2005

The limited intrinsic resistance of any fuel cycle to country proliferation

Whichever scenario is considered, there would be few technical constraints on a country, once it had a nuclear infrastructure in place, from using its nuclear program to produce weapon-usable material. The character of the fuel cycle adopted by a country could, however, impact the time it would need to produce or to divert the material, and it could affect its ability to achieve a diversion clandestinely. In the next section, we address some of the implications of this realization for safeguards and institutional arrangements governing the construction and proliferation of nuclear reactors and fuel cycle facilities.

The special problem of centrifuge enrichment

Once fully established, the nuclear fuel cycles based on thorium technologies and the nuclear battery would not require a large capacity for uranium enrichment. Deployment of these fuel cycles will, however, take time, so in all five of the scenarios, there would have to be a very large increase in uranium enrichment over the next 50 years or longer. By 2050, in the once-through and hub-spoke scenarios, annual worldwide uranium enrichment capacity would be on the order of one-quarter million tons of separative work units (SWU). This would be about four times the current enrichment capacity worldwide. Required enrichment would be less in the other scenarios, but significant nonetheless.

In itself, a four-fold increase in uranium enrichment could be managed without a corresponding increase in the risks of proliferation. For example, the large enrichment enterprises today—the U.S. Enrichment Corporation, Russia's enrichment enterprise, Urenco, and Eurodif—could all certainly construct new plants and increase their output accordingly, supplying LEU to nuclear reactors worldwide, without any evident new risks. Nevertheless, in an expanding nuclear system, it is likely that some countries—for reasons of energy security, technological pride, or flexibility to produce weapons useable material should they ever decide to do so—will want to construct their own national enrichment facilities. Such facilities would in all likelihood be based on the gas centrifuge, which appears today the enrichment technology of choice for economic reasons. Centrifuges raise two serious proliferation concerns, especially compared to gaseous diffusion, the other principal enrichment technology today. They need relatively little electricity and have few emissions thus making clandestine facilities more difficult to detect. Moreover, a gas centrifuge cascade could be switched relatively quickly from producing LEU to the production of HEU.[13]

The economies of scale for centrifuge plants suggest that any plant less than about one million SWU per year capacity (or possibly more) would not be efficient. Such a plant could service about ten 1-GWe reactors. If we use this measure and the MIT

[13] See, for example, see International Panel on Fissile Materials, *Global Fissile Material Report 2006*, pp. 23-26, www.fissilematerials.org. The now almost universal movement of uranium enrichment to centrifuges in place of more proliferation resistant technologies is another reminder of how little attention the nuclear industry gives to proliferation resistance.

scenario for 2050, 20 countries would have at least this capacity, including Indonesia, Iran, and Pakistan. See Figure 4.3. Naturally, not all countries with over 10 GWe of capacity would necessarily build their own enrichment facility, and even a one million SWU plant might not be able to compete with LEU supplied by the main enrichment enterprises, such as Urenco. The cost penalty in most cases would, however, be low; even a doubling of the cost of enrichment would raise the cost of electricity only slightly – about 1.5 mills per kWh.[14] Therefore, the proliferation of centrifuge plants looms as one of the most significant challenges in a robust nuclear future.

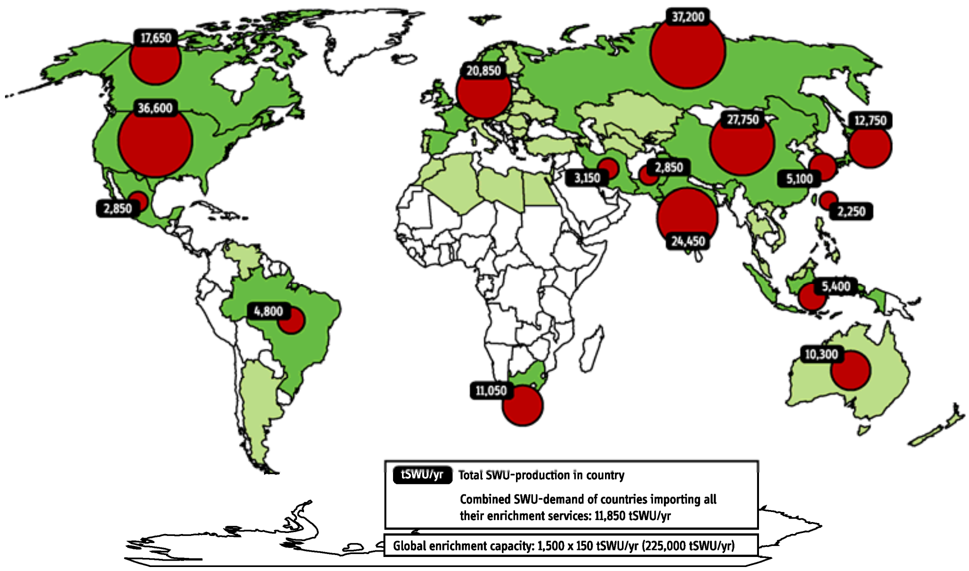

Figure 4.3: Hypothetical distribution of enrichment capacities for a 1500-GW(e) nuclear world, in which 56 countries operate commercial power reactors and 16 countries operate large-scale uranium enrichment facilities.

The special attractiveness of once-through fuel cycles

In the once-through fuel cycle, no nuclear-explosive material appears anywhere. While this does not preclude diversion paths to support country proliferation, it does provide a nearly intractable barrier to sub-state acquisition of fissile material. This is discussed in more detail in section 6 below.

A principal question is whether the once-through fuel cycle is sustainable in a robust nuclear future. The MIT study argued that there was sufficient uranium globally to support a nuclear system growing to 1500 GWe installed capacity by 2050. More recent studies indicate that even through 2100 as nuclear grew to 4500 GWe, it is very possible that the once-through fuel cycle will remain, as it is today, the most economical nuclear option. The cumulative uranium requirements through 2100 in that case would

[14] MIT, *op. cit.*, p. 146

be approximately 35 million tons. Recent studies suggest that at uranium prices of $200-300/kg, far more terrestrial uranium than that would be available, although more work in developing realistic supply curves for uranium should be done.[15] Kim-Edmonds, for example, shows a supply curve that estimates over 60 million tons of uranium available at $200/kg.[16] A price of $200/kg would raise the cost of the once-through fuel cycle only about 4 mills per kWh, which in all likelihood would keep the costs of the once-through fuel cycle below any closed cycle that has so far been suggested. These estimates of ultimate uranium resources do not include the possibility of extracting uranium from sea-water at comparable prices.[17] The uranium prices indicated here are meant to denote actual costs of the mining and processing of uranium ore over the long term. The spot prices for uranium, which rose rapidly over the past year due to limitations on current uranium mine production and rising short-term demand, are not a good indicator of the real costs of mining and processing. It should be a high priority of those concerned with the future of nuclear power to determine as carefully as possible the likely long-term supply curve for uranium.

The spent fuel discharge from a once-through fuel cycle at 1500 GWe capacity would be about 30,000 tons per year, with the spent fuel sent eventually to a geological repository. If we assume a thermal loading limit for a repository of 30,000 tons per square kilometer, which a Yucca Mountain-like repository appears capable of handling, the repository additions worldwide necessary to handle the spent fuel discharge in the once-through 1500 GWe scenario would be one square kilometer per year, which is probably manageable.[18] The requirements for a 4500 GWe scenario would be three times as great; but still, the worldwide addition of even 3 square kilometers per year by 2100 does not look impractical.

A Possible Advantage for Gas-Cooled Reactors

In our principal once-through fuel cycle scenario, we imagine a combination of LWRs and gas-cooled reactors. As discussed below, one could also imagine thorium reactors on a once-through fuel cycle. It is worth noting that gas-cooled reactors potentially could have significant advantages over LWRs if, as appears likely, they would be much more resistant to terrorist attacks designed to release large amounts of radioactivity. This is discussed further in Appendix A.

---

[15] Erich Schneider and William Sailor, *Long Term Uranium Supply Issues and Estimates*, *op. cit*.; also see Schneider and Sailor, "Nuclear Fission," *Science & Global Security*, Vol. 14, Nos. 2-3 (2006), pp 194-196.

[16] Kim and Edmonds, *op. cit.*, Figure 3-2.

[17] The lowest cost attainable now for mining uranium from seawater is ~ $200/kg U. See "Confirming Cost Estimations of Uranium Collection from Seawater," *Japanese Atomic Energy Agency (JAEA) R&D Review 2006,* p. 63.

[18] J. Kessler, "Room at the Mountain," *Technical Update*, EPRI, May 2006; the implications of the uniqueness in the Yucca Mountain case of its limited geographic extent were pointed out to authors by Steve Fetter, private communication.

Potential Attractions of Fuel Cycles Based on Thorium Reactors and Nuclear Batteries

Thorium reactors and nuclear batteries have potentially attractive proliferation and terrorism-resistant characteristics and could play a valuable role in any renaissance of nuclear power. It would be unwise to rush into a nuclear renaissance with the technologies that are the most developed now but which would not necessarily be the most suited to a large-scale expansion of nuclear power if other reactor technologies promise significant advantages.

Our principal illustration of thorium fuel cycles is a denatured sustainable molten salt reactor, i.e., a reactor that needs little further supplies of enriched uranium after startup, that requires isotope separation to obtain weapons-grade U-233, and that produces plutonium in significantly smaller quantity and poorer isotopic quality compared to an LWR. In addition, like the nuclear battery, no spent fuel is discharged during the reactor's operating lifetime, and this, plus the enhanced passive safety features and potential for underground siting of both batteries and molten salt reactors, lead to an enhanced level of both proliferation and terrorism resistance, including against radiological sabotage.

The advantage of the nuclear battery in a hub-spoke configuration is that some countries might be willing to import the batteries without seeking to establish a nuclear infrastructure, and any attempt by a country to break into the reactor once deployed would be readily discovered. We argue in the following section that an acceptable nuclear system cannot be constructed on the basis of the international community somehow demanding that certain countries *must* import nuclear batteries while others are allowed to meet their nuclear energy needs in other ways. But as an option for countries, the nuclear battery could be a valuable alternative.

5 – Proliferation Resistance for Countries

It is treacherous to imagine the institutional framework that would be relevant in fifty to one hundred years. But as an initial cut, let us consider three sorts of situations:

- a world where there has been a significant proliferation of nuclear weapons, to say 20 to 30 states, and where there no longer is an effective Nonproliferation Treaty constraining other countries from acquiring nuclear weapons;
- a world where there has been substantial nuclear disarmament, with most or all of the nuclear weapons under the authority of an international agency, possibly under the UN Security Council;
- a world more or less like the present, in which a few countries still have nuclear weapons and where most of the non-nuclear countries do not aspire to acquire them.

In the first case, the spread of nuclear power would have significance mainly if it led to proliferation to countries that the international community considered unfit to manage nuclear power or unfit to manage nuclear weapons. For countries such as those, states or combinations of states might try to prevent the proliferation of nuclear technology on an ad-hoc basis. In this situation, the dangers associated with nuclear power would flow from the great difficulty of assuring that nuclear power programs remain safe, and that terrorist groups are not able to get fissile material. Since some of the countries with nuclear weapons and nuclear power program could have shoddy safety and security systems, and could conceivably have ties to terrorist groups, these dangers would be evident. It is difficult to see how nuclear power could prosper in this kind of world and could be adequately safeguarded.

The second case would provide the best basis for a flourishing of nuclear power. Without question, if we wished to construct a future most compatible with a robust expansion of nuclear power worldwide, it would be one marked by very substantial nuclear disarmament. In such a world, the incentives for a few rogue countries to acquire nuclear weapons would be lessened, as would the myriad of discriminatory features that now dominate non-proliferation institutions. International authorities could oversee the safety and security of nuclear facilities, and, as explained further below, any move by a country to acquire nuclear material for weapons would be confronted by strong international measures to secure compliance with international agreements.

The third case is probably the most likely, and in any event the one requiring the most analysis. Much of what is discussed below would be relevant to the second case as well. Even if we focus only on the third case, a large range of alternative futures is still possible, and there is great difficulty in latching on to any one of these. Nevertheless, it is necessary to start somewhere. And so we assume the following as a first order approximation:

- That the world will not be free of nuclear weapons, and that something like the fundamental structure of the current nonproliferation regime as defined by the Non-Proliferation Treaty (NPT), will remain in place. In other words, there will remain two classes of states—declared nuclear weapon states allowed to keep nuclear weapon and non-nuclear weapon states that have forsworn them. The declared nuclear weapon states under the NPT are the U.S., Russia, China, France, and the UK. India, Pakistan, and Israel also have nuclear weapons and stand outside the treaty. North Korea also at present has nuclear weapons, but may be in the process of giving them up and rejoining the NPT. The nuclear states may be different and possibly more numerous in fifty years – but let’s assume that the number of nuclear states will stay limited to on the order of ten say, and more important that most countries will not be seeking a nuclear weapons capability.

- That all, or almost all, civilian nuclear facilities will be under international safeguards, such as those now implemented by the International Atomic Energy Agency (IAEA). Such safeguards will include inspections at declared nuclear facilities and the universal implementation of the so-called Additional Protocol, which authorizes the IAEA to look for undeclared, clandestine nuclear facilities.

Given the flows of material in a robust nuclear future, we would add the following stipulations for an international institutional framework necessary (though not necessarily sufficient) to safeguard nuclear energy.

- The nuclear power system is non-discriminatory. Any reactor or fuel cycle facility allowed in any country must be allowed in all.

- All enrichment and reprocessing will be under international authority; and that an international authority will guarantee fuel supply to all reactors. At present, the NPT is supplemented by agreements among suppliers not to export certain specified materials or technologies to non-nuclear countries, and to ensure that whatever nuclear material or equipment that is exported is under safeguards. This is a discriminatory arrangement and is not likely to be sustainable.

- All uranium mining and milling and possibly also all spent fuel will also be under international authority.

- Countries will not be able to withdraw from the NPT (or its functional follow-on), at least in the sense that they could withdraw and appropriate fissile material and facilities that they enjoyed while in the treaty; and that there will be clear provisions for enforcing compliance with all nuclear undertakings.

- Physical security standards for all nuclear facilities will be set and imposed by international authority. This is essential since a lapse of security anywhere will endanger every country.

- No research reactors will use nuclear-explosive materials. At present, many research reactors and some reactors producing medical isotopes are using highly enriched uranium (HEU) as fuel. But scores of reactors once running on HEU have already been converted to low enriched uranium, and it seems straightforward for the international community to work toward agreements that no reactors use HEU.

We elaborate briefly on the first two points. The issues here that most need clarification are: the character and scope of an international authority; the reasons for insistence on non-discrimination; and the emphasis on enforcement and compliance.

In this context, there has been renewed interest in restricting national access to enrichment and reprocessing via multilateral approaches to the nuclear fuel cycle. At present all enrichment and reprocessing are located in “safe” states — either countries that are already nuclear weapon states or industrialized countries that have forsworn nuclear weapons. While much of the envisioned expansion of nuclear power to mid-century would probably occur in states that already have reactors, some of the new growth and sustained growth after that would necessarily involve states that do not now have such facilities. It is conceivable that these states would be willing to rely upon existing market mechanisms supplemented by additional assurances of fresh fuel supply on favorable terms and (especially) by the willingness of other countries to accept spent fuel– that is, to rely on fuel cycle services done elsewhere. To the extent that this strategy is viewed by non-nuclear weapons states as adding an additional layer of discrimination to that inherent in the NPT’s division of the world into weapons and non-weapons states, though, it will certainly encounter significant opposition despite its practical advantages. Considerable skepticism already exists about the commitment of the NPT weapons states to fulfill their commitments under the NPT, and a discriminatory market-oriented strategy to make the world safe for nuclear power could be viewed as another attempt by the nuclear weapon states and their friends to maintain a nuclear status quo that largely favors the existing weapons states, their closest allies, and their nuclear industries.

The prospect that non-nuclear weapon states will willingly forgo a right that is inherent in Article IV while nuclear weapon states continue to retain, and in some cases enhance their arsenals with weapons seen to be developed for use rather than deterrence, is remote. The only way to persuade non-nuclear weapon states to accept tighter restrictions on their peaceful nuclear programs is through some kind of multi-lateralization of the fuel cycle — an arrangement that somehow levels the playing field with respect to tightening controls over the nuclear fuel cycle, but does so in a way that is non-discriminatory, placing the same obligations and constraints on all parties while assuring all of equitable and timely access to required nuclear fuel for a civil nuclear program. If the objective is to have states give up a right in a treaty, the result should not be further distinction between classes of states and discrimination, but rather the opposite.

For this reason, we think that the only way that nuclear power can achieve the level of political acceptability needed to permit its expansion on a significant scale for the long-term is to implement a non-discriminatory institutional framework involving multilateral ownership and operation of all enrichment, reprocessing, and possibly other fuel cycle facilities, especially for spent fuel or high-level disposal. The way to get this strategy off the ground is for the nuclear weapon states, especially the U.S., to commit to implementing a non-discriminatory, multilateral framework for nuclear power.[19]

No doubt, many in the U.S. and elsewhere in the nuclear industry take it for granted that a future nuclear system will in fact be discriminatory. For example, in a recent overview of the long-term future of nuclear power emanating from the U.S. Department of Energy, one of the authors of GNEP, Victor Reiss, notes that “the level of

---

[19] An important gesture in this regard would be for the U.S. to commit to operate its planned new centrifuge plants under multilateral auspices and as a test-bed for advanced safeguards procedures. See Marvin Miller and Lawrence Scheinman, “Israel, India, and Pakistan: Engaging the Non-NPT States in the Nonproliferation Regime,” *Arms Control Today*, December 2003.

engagement [with nuclear power] must be dependent upon the relative national trustworthiness" of countries. Thus he envisions South Korea with a full fuel cycle and full control of the fuel cycle, Iran with reactors only and leasing fuel made elsewhere, North Korea limited to leasing and nuclear batteries, and Sudan with no nuclear power at all.[20] This understanding that certain technologies will be out of bounds for some countries, but not others is a widely shared assumption in the U.S.

As already remarked, this paper assumes that the nuclear weapon regime will remain discriminatory, at least for the foreseeable future. But we believe that hoping to add another dimension involving nuclear power to this discrimination is illusory. In a future nuclear system, technical barriers alone cannot prevent countries from obtaining nuclear-explosive materials and eventually nuclear weapons.[21] Therefore, the critical safeguard to country proliferation will be the certainty of enforcement and the likelihood of enforcement will depend upon the strength of international consensus in support of the regime. If many countries view a nuclear power regime as discriminatory and illegitimate, it is difficult to imagine a sufficient consensus on enforcement being achieved. Still more telling, even if one adopted the thinking of those who do not wish to trust advanced and sensitive nuclear technologies to certain countries, one must realize that countries that might at one point be considered "safe" may not be considered safe at later times.

Since ready access to fissile materials could for some countries constitute a real threat, we should not allow national control over sensitive nuclear facilities. At various times in the past, the IAEA considered regional and other alternatives to national control of sensitive nuclear facilities. For example, in the 1970s, the IAEA endorsed the idea of regional nuclear fuel cycle centers, primarily with reprocessing in mind. This concept soon faded in the wake of a slowdown in the growth of nuclear power, a sharp drop in uranium prices, and the emergence of strong U.S. resistance to reprocessing the plutonium recycling. Similarly, in the late 1970s, countries considered for a time the idea of an International Plutonium Storage, a concept that also fell out of favor. The idea of the IPS is based on Article XII.A.5 of the IAEA statute that specifies circumstances in which the Agency can require that excess special fissionable materials from peaceful uses be deposited with the Agency to prevent stockpiling by states. In addition to the the same

[20] Vic Reis, "Vision, Strategy and Structure in the Global Nuclear Enterprise: Eisenhower and the Search for *Gesamtkonzept*," University of Texas, April 6, 2005.

[21] In the current world environment, the potential of a state to divert weapons materials from its civilian programs is not necessarily dismaying. For the most part, the countries with nuclear power programs are either already nuclear weapon states or countries that for whatever reason do not aspire to become nuclear weapon states. Japan, South Korea, and Taiwan have at one time or other considered nuclear weapons, but for the time being are deeply constrained from seeking weapons. Secondly, as already mentioned, the civilian program, even if it could be converted to weapons purposes, might not provide a quicker or easier path to nuclear material than a dedicated route. Countries could, if they wished, choose a dedicated route to nuclear weapons material. They do not have to depend upon the civilian fuel cycle (although such a cycle could provide a convenient cover). As a consequence, it is not essential that safeguards provide a foolproof barrier to diversion from the civilian fuel cycle. Rather, the principal task of safeguards must be to make diversion from civilian nuclear power substantially more difficult, time-consuming, and transparent than a dedicated route.

kinds of arguments that worked against the regional nuclear fuel cycle centers, the IPS foundered on the inability of countries to define the exact conditions under which contributing countries could withdraw fissionable material deposited with the Agency.[22]

Regional and multinational arrangements appear achievable and would represent a significant improvement over a multiplicity of national enrichment and reprocessing facilities, offering economies of scale and reduced risk of proliferation. In the longer term, to achieve a nuclear power system that is seen as truly non-discriminatory and even more supportive of nonproliferation, the establishment of an international authority to oversee and manage all sensitive nuclear fuel cycle facilities for all countries would be preferable. The initial attempt to sketch a framework for safeguarding nuclear power, the Acheson-Lilienthal Report, included these activities among the "dangerous" activities that an international authority would have to control. The Report also included uranium mining and milling as dangerous activities. Although the extent of uranium deposits are far wider spread than the authors of the Acheson-Lilienthal Report imagined, we believe it worth considering including these under the activities controlled by an international authority. We also would include spent fuel as part of the auspices of an international authority. See Appendix B for an overview assessment of several regional and international arrangements that have been suggested.

We do not here analyze the details of how an international authority would operate – how exactly it would control or manage enrichment, reprocessing, uranium mining, and spent fuel. Researchers have recently forwarded some ideas ranging from reliance on existing market mechanisms supplemented by additional assurances of fresh fuel supply and spent fuel return provided by governments and the IAEA, to co-ownership and operation of both existing and new fuel cycle facilities.[23]

Whatever the institutional arrangements, civilian nuclear power will provide a country the basis eventually for a dedicated weapons program – by allowing a country to train scientists and engineers, to build research facilities, and to learn techniques of reprocessing and enrichment that could later be turned to weapons uses. A civilian program could, in this manner, impel a country along a path of "latent proliferation," in

[22] Lawrence Scheinman, "The Nuclear Fuel Cycle: A Challenge for Nonproliferation," *Disarmament Diplomacy*, No. 76, March/April 2004. See also Appendix B.

[23] See, e.g., the comprehensive overview by a group of experts commissioned by the Director General of the IAEA, Mohammed El Baradei: *Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report submitted to the Director General of the International Atomic Energy Agency*, INFCIRC/640, February 22, 2005. Available on the IAEA web site: www.iaea.org. The option of relying primarily on existing market mechanisms is also explored (and advocated) by John Deutch, Arnold Kantor, Ernest Moniz, and Daniel Poneman, "Making the World Safe for Nuclear Energy," *Survival, vol. 46, no. 4, Winter 2004-05.* See also the article by Lawrence Scheinman in *Disarmament Diplomacy*, op. cit., for a discussion of approaches that involve co-ownership and operation of fuel cycle facilities.

which the country moves closer to nuclear weapons without having to make an explicit decision actually to take the final step to weapons, or at least to make transparent its intention to take such a step. Latent proliferation is particularly germane to consideration of the spread of civilian nuclear power to countries that do not now have any, and which, therefore, would not today have a ready infrastructure to support a dedicated route to nuclear weapons.

In our view, this situation cannot be helped. Civilian nuclear power will always present some degree of latent proliferation. For many countries today, this does not represent a serious concern, since the countries can always undertake a dedicated route to nuclear weapons, with no need to rely upon the civilian fuel cycle. In the future, with many new countries entering into nuclear power, we cannot so easily wave away the latent proliferation inherent in nuclear power programs. But, as we have also emphasized, in a world where most countries simply do not want nuclear weapons and where nuclear power is not constructed on a discriminatory basis, a complex of safeguards, international control of key fuel cycle elements, and well accepted compliance provisions could provide a reasonable degree of proliferation resistance.

6 – Proliferation Resistance and the Terrorist Threat[24]

One fundamental characteristic of any future nuclear power system must be that it does not provide opportunities for a terrorist group to obtain nuclear-explosive materials, or to release large amounts of radioactivity through attacks on nuclear facilities.

At the present and foreseeable state of nuclear technology, it does not appear feasible for a sub-national group to produce its own fissile material. Nor, even if it started with LEU or spent fuel could a sub-national group realistically produce HEU or separate plutonium. The principal prospect for diversion of weapons materials from civilian nuclear programs for sub-national groups is if they can steal or buy on a black market already separated fissile material – HEU or plutonium. These do not exist in the once-through fuel cycle, predominant in the world today; but some civilian research reactors use HEU, and plutonium is separated in programs that reprocess and recycle plutonium.[25]

[24] The following discussion is restricted to a consideration of the technical capabilities of terrorists. We do not speculate on such issues as their ability to attract individuals with relevant expertise based on the political, ideological, religious or other motivations that animate terrorist groups. Within this limited perspective, a terrorist group is essentially a sub-national group whose activities may or may not be supported by the countries where they operate. This obviously can have a significant impact on whether such activities are detected and terminated before they are successful. We discuss the detection issue briefly in the following.

[25] Even if a sub-national group could not realistically obtain fissile materials, it could conceivably acquire civilian spent fuel or high level wastes for a "dirty" bomb or radiological weapon. However, the prospect that a terrorist group could use spent fuel or high level wastes in a dirty bomb, while troubling, does not compare in severity to actual diversion of fissile material. A dirty bomb would not kill many people; and although if detonated in an urban concentration, it would cause a lot of economic dislocation, so could many other potential terrorist actions. With care, overseers of the nuclear fuel cycle could make it very difficult for a terrorist group to divert radioactive materials from nuclear facilities, especially compared to other routes terrorists could potentially take to acquire radioactive materials.

An additional concern is that a terrorist group could target a nuclear facility such as a large power reactor or reprocessing plant in ways that could lead to massive releases of radioactivity.

Can Terrorists Build Nuclear Weapons?

A 1988 paper co-authored by Carson Mark, the former head of the Theoretical Division at the Los Alamos National Laboratory (LANL) and four of his LANL colleagues, including the well-known weapons designer, Theodore Taylor summarized as follows:[26]

- Both crude designs, i.e., similar to the Hiroshima gun-type and Nagasaki implosion-type weapons, as well as designs that are more sophisticated, having, e.g., significantly larger yield-to-weight ratios, are considered. The emphasis is on the former, including ones that might utilize uranium and plutonium oxide, ($UO_{2)}$ and (PuO_2), respectively, rather than the metallic forms used in the Hiroshima and Nagasaki bombs. This is important because the uranium and plutonium used to fuel nuclear power and research reactors is more likely to be in the form of oxide powder than metal. On the other hand, the critical masses of the oxide forms are significantly greater, even at full crystal density. The oxide forms could be converted to metal using specialized equipment and techniques.

- A group not previously engaged in designing or building nuclear weapons can construct crude nuclear weapons provided they have the technical knowledge, experience, and skills in relevant areas, e.g., the physical, chemical, metallurgical and nuclear properties of the various materials to be used, as well as the characteristics affecting their fabrication, and the technology of high explosives and/or chemical propellants. Their number could scarcely be fewer than three or four, however, and might well have to be more. In any case, the necessary attributes would be quite distinct from the paramilitary capability most often supposed to typify terrorists.

- The use of reactor-grade instead of weapons-grade plutonium in a crude implosion-type Nagasaki design would reduce its expected yield because of the increased likelihood of pre-initiation of the chain reaction due to the higher concentration of plutonium isotopes such as Pu-240, which are copious emitters of spontaneous neutrons, in reactor-grade material. If the velocity at which the plutonium pit is compressed is comparable to that in the Nagasaki bomb, however, the lowest pre-initiation yield could still be in the 100 ton range. By contrast, the background spontaneous neutron source in enriched uranium, especially that containing very high concentrations of the fissile isotope U-235

[26] J. Carson Mark, Theodore Taylor, Eugene Eyster, William Maraman, and Jacob Wechsler, "Can Terrorists Build Nuclear Weapons?" in Paul Leventhal and Yonah Alexander, eds., *Preventing Nuclear Terrorism: Report and Papers of the International Task Force on Preventing Nuclear Terrorism* (Lanham, MD: Rowan & Littlefield, 1987).

> such as weapons-grade uranium (94% U-235), is much smaller, so that, unlike even high-purity plutonium, it can be used in a gun-type Hiroshima design with available projectile velocities. For this to be true, though, it is necessary to have rather pure uranium metal, since even small amounts of light element impurities such as oxygen or high element impurities such as isotopes of curium can add appreciably to the neutron source and hence to the likelihood of pre-initiation.

Given the comprehensive and authoritative nature of this LANL paper, the fact that there is no distinction made between the difficulty of making gun and implosion-type weapons is noteworthy, especially given the common view that building a uranium gun-type weapon, including obtaining the needed amount of highly-enriched uranium, is well within the capability of a small terrorist group.[27] Mark chaired a task force of weapons experts that published the Los Alamos weaponeers' view in a 1977 report on nuclear proliferation and safeguards with a statement on low-technology nuclear explosives:[28]

> It is widely believed that gun assembly is the simpler way to produce a nuclear explosive. Although the gun assembly may be conceptually simpler, the difficulty of actually constructing a nuclear explosive is roughly equivalent whether a gun or implosion assembly is used. The difficulties of the gun assembly often are not appreciated: a large mass of high density must be accelerated to a high speed in a short distance, putting quite unusual requirements on the gun design.

Not everyone agrees. Consider this statement by Robert l. Gallucci, who has spent many years in and out of U.S. government service dealing with nuclear proliferation issues:[29]

> It does not appear that there is a terrorist group on earth capable of assembling a nuclear weapon using an implosion system, even if it were given a sufficient quantity of plutonium and the help of a few refugees from nuclear weapons laboratories. Highly-enriched uranium in a gun-type device might be a different story, although perhaps not.

---

[27] See, e.g., Peter D. Zimmerman and Jeffrey G. Lewis, "The Bomb in the Backyard," *Foreign Policy*, November/December 2006, pp. 32-39. and William Langewieche, "How to Get a Nuclear Bomb," *The Atlantic*, December 2006, pp. 80-99.

[28] *Nuclear proliferation and Safeguards*, Congress of the United States, Office of Technology Assessment (New York: Praeger Publishers, 1977), p. 142. See also, Christoph Wirz and Emmanuel Egger, "Use of nuclear and radiological weapons by terrorists?" *International Review of the Red Cross*, 87(859), September 2005, pp.497-510 for a discussion of the problems that must be overcome by terrorists in order to construct a uranium gun-type weapon; and Mark Hibbs, "South Africa's Secret Nuclear Program: From a PNE to a Deterrent," *Nuclear Fuel*, May 10, 1993, pp. 3-6 for a description of the difficulties encountered by South African scientists and engineers in building such weapons.

[29] Robert L. Gallucci, "Nuclear Power and Nuclear Weapons Proliferation," in Paul Leventhal, Sharon Tanzer, and Steven Dolley, eds., *Nuclear Power and the Spread of Nuclear Weapons* (Washington, D.C.: Brassey's, 2002), p. 56.

In any case, it appears prudent to assume that a sophisticated terrorist group could construct a nuclear device if it obtained the requisite amounts of weapons-grade uranium or plutonium – all the more so, if we imagine the situation 50 years or more in the future.[30] With respect to plutonium, although the task would be made more difficult, we must also assume that the isotopic composition of the plutonium, including the possibility of high amounts of plutonium-238, will not be an insuperable barrier. Nor would the admixture of transuranics with the plutonium be a deterrent. As we noted earlier, such admixture would increase the critical mass by no more than a factor of two or so, and would not be self-protecting in the way in which spent fuel is, and it would not raise insuperable problems of pre-initiation or heat management.[31]

In a recent paper, von Hippel and Kang[32] find that the total radiation dose from a critical mass of a combination of plutonium and transuranics without the fission products would be a thousandth of the IAEA's threshold for self-protection, 100 rems/hr at 1 meter. Inclusion of either of the two lanthanide fission products, cerium-144 and europium-154, could increase the dose rate above the self protection threshold. However, Ce-144 has a half-life of only 0.8 years. Eu-154 has a longer half-life – 9 years; but it is not clear whether the Eu-154 will be recycled with the transuranics in the proliferation-resistant pyro-processing fuel cycles now under study.

Relatively high concentrations of Pu-240 and Pu-238 would complicate the work of using the material to make a nuclear device, but they would not render this impractical even for a terrorist group. While Pu-240, which spontaneously fissions thus creating a copious source of neutrons, will make pre-initiation of a chain reaction more likely, the resultant "fizzle yield" could still be on the order of one kiloton. The Pu-238 would add appreciably to the heat generated by the plutonium, and with Pu-238 concentrations at a few percent, which would be the case for some of the very high burn-up fuel cycles, a bomb designer would have to find ways to dissipate the heat.

With respect to uranium, the enrichment level would matter. The critical mass of uranium of different enrichments is shown below:[33]

---

[30] This underscores the need for a more nuanced approach towards the threat of nuclear terrorism as proposed recently by Michael Levi, "Stopping Nuclear Terrorism," *Foreign Affairs*, January/February 2008, pp. 131-140.

[31] If closed fuel cycles involving the reprocessing of spent fuel are implemented in the future expansion of nuclear power, it is likely that the reprocessing technology utilized will not produce the highly-purified plutonium characteristic of the PUREX process. However, since these more "proliferation resistant" separation technologies, e.g., pyro-processing, are still in the R&D stage, it is difficult to judge whether terrorists will be able to construct and operate "quick and dirty" plants based on them.

[32] Frank von Hippel and Jungmin Kang, "The Limited Non-Proliferation Benefits from Recycling Unseparated Transuranics and Rare-Earth Fission Products from Aged Spent Fuel," *Science & Global Security*, Vol. 13, Number 3, Winter 2005.

[33] Alexander Glaser, "On the Proliferation Potential of Uranium Fuel for Research Reactors at Various Enrichment Levels," *Science & Global Security*, Vol. 14, No. 1, 2006

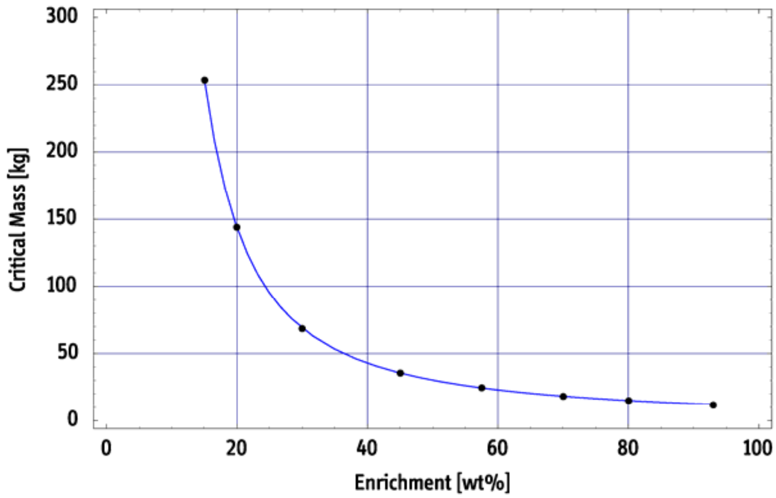

Figure 6.1. Critical mass of a beryllium-reflected uranium sphere as a function of the uranium-235 enrichment. MCNP 4C simulations at 300 K using ENDF/B-VI cross-section libraries. Reflector thickness is 15 cm. Assumed value of uranium density is 19 g/cm3. Enrichment is given in weight percent (wt%) for a simple binary mixture of U-235 and U-238.

Not only would the critical mass be high for uranium enrichments below weapon-grade levels (90% or greater U-235), roughly going as the inverse square of the enrichment, but the U-238 and other impurities would further complicate a weapons design. The difficulties of using 20% uranium for a weapon without further enrichment would therefore be formidable. Nevertheless, ensuring that there is no uranium of enrichment greater than 20% used in any fuel cycle would provide very significant proliferation resistance against terrorists.

Acquiring Highly-Enriched Uranium and Plutonium

In contrast to the above spectrum of views on the difficulties of building gun and implosion-type nuclear weapons, there is a widespread consensus that terrorists cannot produce fissile materials on their own "starting from scratch," i.e., by using natural uranium to feed an enrichment plant to produce HEU or feeding a plutonium production reactor and using a reprocessing plant to produce plutonium. Not only are the technologies, particularly enrichment, quite sophisticated, but the facilities required for both the enrichment and reprocessing routes are both much larger and have more detectable "signatures" than for bomb-making once the fissile material is in hand.[34] Hiding such facilities, both during construction and operation, would be difficult for terrorist groups, assuming that the state where they are operating vigorously opposes these activities, and thus deploys adequate means to detect them in a timely manner and mounts an intensive response if any effort is discovered.

[34] This is not to say that a country could not hide centrifuge enrichment and reprocessing. Both could be done with little signals to the outside – but the effort required would still be substantial. For example, a terrorist group would have to assemble hundreds or thousands of centrifuges.

Even if a terrorist group could not construct an enrichment cascade *de novo*, could it take over some number of centrifuges say and rewire them to produce HEU or replicate them somehow in secret? Either possibility appears unlikely. Nevertheless, this is a further reason why all enrichment should be under international authority, such that if a terrorist group or country sought to take over an enrichment facility, the effort would be immediately transparent and the facility destroyed if necessary.

The more probable route for terrorists to produce fissile material is with reprocessing. As with an enrichment plant, it does not look credible that a terrorist group could build its own production reactor. But would it be possible for such a group to divert power reactor spent fuel in storage and extract the contained plutonium in a so-called "quick and dirty" reprocessing plant?

Indeed, this possibility was raised during the Carter administration as a result of a 1977 study by a group of technical experts at the Oak Ridge National Laboratory that presented the design of such a plant together with a flow sheet and an equipment list.[35] The study sought to make the case that a country with a minimal industrial base could quickly and secretly build such a plant, and hence undermine the rationale for the Carter administration's opposition to commercial reprocessing.

The ensuing debate focused on the technical feasibility of the Oak Ridge design. Although some of the individuals who expressed their views were skeptical that the plant could be built as quickly and run as efficiently as specified, the consensus opinion was that it was feasible, *at least if done by individuals as skilled and experienced as the Oak Ridge-design team.*[36] [Emphasis added.]

The issue of the technical feasibility of a "quick and dirty reprocessing" plant was the subject of another study in 1996, this time by a team of experts organized by the Sandia National laboratory to assess the proliferation resistance of various alternatives for the United States' and Russia's disposition of excess stocks of weapons-grade plutonium.[37] While the process flow sheet is similar to that suggested by the Oak Ridge-team, the Sandia group was more explicit about the nature of the "adversarial group" involved in building and operating the plant. The study found that several skilled people would be required, and that previous experience in a nuclear industry would be valuable.

In the view of reprocessing experts today, the Oak Ridge and Sandia analyses likely underestimated the skills involved in operating the PUREX process, especially in

[35] D. E. Ferguson to F. L. Culler, Intra-Laboratory Correspondence, Oak Ridge National Laboratory, 'Simple, Quick Processing Plant," August 30, 1977.

[36] *Quick and Secret Construction of Plutonium Reprocessing Plants: A Way to Nuclear Weapons Proliferation?* Report to the Comptroller General of the United States, EMD-78-104, October 6, 1978.

[37] J. P. Hinton et al., *Proliferation Resistance of Fissile Material Disposition Program Plutonium Disposition Alternatives*: *Report of the Proliferation Vulnerability Red* Team, Sandia National Laboratory, SAND97-8201, October 1996.

view of the fact that these designs incorporate changes in the standard flow-sheet that were never utilized in practice.[38]

In addition to difficulties with reprocessing, acquisition of the spent fuel would also present great difficulties for any sub-state group. The spent fuel from any of the reactors described in this report would have an intense radiation barrier, which would make diversion by a terrorist group extremely difficult. Such a diversion would require the use of lifting equipment, the diversion of more than one ton of material for each critical mass, and a willingness to accept a very large radiation exposure. On the last requirement, a person one meter from a 15-year old spent fuel assembly would receive a dose of at least 2000 rem/hour.[39]

This also implies that even spent fuel must be physically secured.

In sum, while it is credible that relatively small groups can clandestinely build nuclear weapons and extract plutonium from spent fuel, a range of technical expertise not normally associated with terrorist groups is required.[40] Moreover, their chances of success depend critically on escaping detection, and this in turn depends on whether the state or states in which they operate have made timely detection and reaction to such activities a high priority.

Given the formidable difficulties of a terrorist group generating their own nuclear material, it is critical to block all other ways for them to obtain such material. At present, probably the greatest vulnerabilities are fissile materials generated by the nuclear weapon states for use in weapons. This is not an issue of the civilian fuel cycle; we assume that in our nuclear future all such material will have been destroyed or secured.

In the civilian fuel cycle, the most significant vulnerabilities are those associated with scores of research and isotope-production reactors that use HEU. The use of HEU in these reactors is unnecessary and could be phased out in any nuclear future. HEU is also produced in some countries for use in nuclear submarines. This also is unnecessary and could be eliminated – though this is not at present an issue of the civilian fuel cycle. At present, some countries are fabricating mixed-oxide fuel and recycling it into fresh fuel in LWRs, providing another potential source of fissile material acquisition by terrorist groups. Such use appears unacceptable in a robust nuclear future.

---

[38] Victor Gilinsky, Marvin Miller, and Harmon W. Hubbard, *A Fresh Examination of the Proliferation Dangers of Light Water Reactors*, The Nonproliferation Policy Education Center, Washington, D.C., September 2004, Appendix 2.

[39] For a PWR assembly, for a burn-up of 35 MWd/kg, the dose rate at one meter would be 2500 rem/hr (W.R. Lloyd, M.K. Sheaffer, and W.G. Sutcliffe, "Dose Rate Estimates from Irradiated Light-Water-Reactor Fuel Assemblies in Air," *UCRL-ID-115199*, Lawrence Livermore National Laboratory, January 31, 1994.) The Sandia Red Team report did note, that while extremely challenging, a diversion by an unauthorized group would not be impossible if members of the group were willing to accept very high, though not immediately incapacitating radiation doses [J .P. Hinton, *op. cit.*].

Vulnerability of Nuclear Facilities to Terrorist Attacks

Clearly, if nuclear power is to grow substantially, nuclear facilities – especially reactors that will be many and spread widely – must be made extremely safe from incidents that could release massive quantities of radioactivity to the public. The nuclear industry worldwide recognizes this, and has devoted considerable attention to increasing the safety of reactors, as witnessed by recent designs of LWRs and the efforts under the Generation IV initiative. It appears that new reactor designs do improve safety, partly by incorporating features of passive safety — i.e. design features such that an accident would automatically trigger safety measures, such as the flooding of the reactor core, without active intervention by reactor operators. These safety measures, however, have generally been developed and studied with respect to accidents – not to a deliberate terrorist attack.

Edward Lyman makes this point sharply when he emphasizes that the philosophy of "defense in depth" that is relied on to reduce the probability of major accidents in LWRs cannot be relied upon when it comes to terrorism.[41]

> It is true that a spontaneous occurrence of the multiple system failures necessary to cause a severe accident and large radiological release is typically a very improbable event. However, if one considers the possibility of sabotage or "deliberate" accidents, the low-probability argument that NRC uses to justify continued operation of nuclear plants completely breaks down. Terrorists with basic and readily available knowledge of how nuclear plants operate can design their attack to maximize the chance of achieving a core melt with large radiological release…With modest inside assistance, saboteurs would be able to identify a plant's specific set of components known as a "target set." If all the elements of the target set are disabled or destroyed, significant core damage would result. Thus, by deliberately disrupting all redundant safety systems, saboteurs can cause a severe event that would have had only a very low probability if left to chance.

While identifying the target set and disabling it may be extremely difficult, more so than the above quote suggests, certainly the prospect of a terrorist attack on reactors must be considered in gauging their safety. Any safety analysis would have to look also at spent fuel pools at the reactor sites, although in this case, there may be readily available technical fixes to lessen the dangers. Unlike reactors, a containment dome does not protect such pools. This makes it easier to attack them from both the air and the ground. Such an attack could cause a loss of the water coolant that potentially could lead to a propagating zirconium cladding fire and a large radioactive release to an open environment. While an assessment of this risk by a group of independent nuclear

[41] Edward S. Lyman, "Chernobyl on the Hudson? The Health and Economic Impacts of a Terrorist Attack at the Indian Point Nuclear Power Plant," *Union of Concerned Scientists*, September 1994, p. 21.

scientists has been challenged by the U.S. Nuclear Regulatory Commission (NRC),[42] a study of the issue by the National Academy of Sciences supports both its conclusion that such releases are possible and its recommendations about ways to reduce the risk of such events.[43]

Even without the threat of terrorism, in a world of 1500 GWe or more nuclear power with nuclear reactors spread over the world, some in countries without a formidable safety culture, there would be great value in nuclear reactor designs that had extremely high degrees of safety. In such a world, passive safety measures alone may not be sufficient. Far better, if achievable, would be reactor systems where the release of large amounts of radioactivity is practically impossible – let us call this intrinsic safety.

In this regard, the modular pebble bed reactor in which the pebbles are not expected to melt even if the coolant is completely and permanently lost, would look very attractive. Graphite fires may still occur and could in some circumstances lead eventually to a release of radioactivity, though this possibility needs further study. But the principle suggested by this example is clear. In a robust nuclear future, one should give considerable weight to the intrinsic safety of reactor systems. The nuclear industry could also consider underground siting of reactors. This would reduce the risk that terrorists could cause a core melt by either land or air attacks, and would also limit the release of radioactivity even if they are successful. Designers of both molten salt and battery reactors have suggested such siting.

Since, as noted, in a world of much nuclear power, reactors will be located potentially in countries without a rigorous domestic safety culture, there may be institutional as well as technical implications – to place reactors under some kind of international authority that would ensure the highest levels of safety.

Naturally, any assessment of how much cost and effort should be put into increased reactor security with respect to radiological terrorism will have to be balanced against various factors including comparison with other vulnerabilities to terrorist attacks such as, for example, chemical plants of various kinds. Also, it should be recognized that as serious as would be the consequences of any large-scale release of radioactivity from a reactor, the consequences of any use of a nuclear weapon on an urban target is likely to be far more catastrophic.

Summary of Implications of Terrorist Threat

The implications of these conclusions for minimizing the nuclear terrorist bomb threat in a world with much more nuclear power are these:

---

[42] Robert Alvarez et al. "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States," *Science & Global Security*, Volume 11, 2003, pp. 1-51, and "Response by the Authors to the NRC Review of 'Reducing the Hazards …'," *Science & Global Security*, Volume 11, 2003, pp. 213-223.

[43] Unclassified executive summary of study on the safety and security of spent fuel in the United States, National Academy of Sciences, May 2006.

- There should be no use of HEU in the nuclear fuel cycle, including in research and isotope-production reactors, and in naval reactors.

- Separated fissile material should not be located anywhere in the fuel cycle where terrorists could plausibly appropriate it. Possibly such separated materials could be tolerated in a center controlled by an international authority or embedded in a sealed fuel assembly such as envisioned for the nuclear battery. But separated weapons-usable materials should not be used in fuel elements that would routinely be sent to hundreds of nuclear reactors, as would be the case in some of the scenarios described.

- An international norm needs to be established that requires states to take strong action against individuals and entities engaged in nuclear terrorist activities.[44]

- Reactors with features of intrinsic safety should be given extra weight in consideration of future nuclear power.

7 – Summary

If nuclear power is to make a dent in global warming, it will have to grow substantially. We take as nominal illustrative capacities, the following:

- 1500 GWE in 50-plus years, 4500 GWe by 2100. This would be roughly a four-fold increase to 2050 and a 12-fold increase to 2100 from today's 370 GWe. It represents a "savings" of 1.5 to 4.5 gigatons per year in 2050 and 2100 respectively of carbon emissions compared to business as usual if the nuclear plants replaced modern coal plants of equivalent capacity.

- We can imagine two periods: one for the next 50 years or so, when nuclear power could expand, based initially on current technologies and after 2025-2040 on technologies now under study; and two, a period after that where nuclear reactors and fuel cycles designed in the next decades could actually be employed.

Certainly, such a dramatic expansion of nuclear power could only happen if it is economically competitive with other carbon-free energy alternatives, is safe, and has a strong degree of sustained public support. But in addition, any nuclear power system of the scope posited would have to be highly proliferation resistant.

In this respect, the first critical requirement is that the nuclear fuel cycle not give a terrorist group access to fissile material or the capability to cause a severe release of radioactivity. This means at least the following:

[44] A promising start is Security Council Resolution 1540 (2004) under which the Council decided, inter alia, that all states would establish domestic controls to prevent the proliferation of weapons of mass destruction and their delivery systems, in particular for terrorist purposes.

- No fissile material is isolated in the fuel cycle in a form where a terrorist group could plausibly appropriate it. Keeping plutonium mixed with the other TRU, but with fission products largely separated, is not a sufficient protection. Such separation would be less dangerous if it took place at centers under control of some international authority.

- Research reactors should not use fissile materials – certainly including highly enriched uranium. Critical assemblies would be shut down.

- Large releases of radioactivity through attacks on civilian nuclear facilities are impossible or nearly so. This would give privilege to reactors where loss of coolant would not lead to a melt-down and release of radioactivity. Consideration should be given to siting reactors underground.

- Binding international arrangements assure that every country with nuclear power imposes stringent physical security on all its nuclear facilities. At present, physical security arrangements are left to individual countries. To ensure that all countries have stringent security, it may be necessary for the international community to own or manage any facility where appropriation of fissile material is possible.

- Countries with suspected ties to terrorists do not have any ready access to fissile materials. Since governments change over time, this could be a difficult criterion to monitor. It leads to some of the conclusions in the next item below, pertaining to country proliferation.

With respect to country proliferation:

- Any country with nuclear power and a nuclear power infrastructure could get fissile material if it wished – within months or a year – barring international action to prevent this. If it had a commercial reactor, it could build a reprocessing plant to separate out plutonium; or it could build a dedicated reactor and reprocessing plant in a somewhat longer period. It could also enrich uranium over time, but as long as the country did not have any enrichment facilities to begin with, such a route would take longer than would a plutonium path.

- However, in the scenarios considered, it should be possible to have a safeguards regime such that any diversion of facilities and materials would be quickly detected, giving time for an international response (see the following bullet). In this respect, the once-through fuel cycle, the hub-spoke arrangements with sealed reactors, and possibly certain thorium cycles appear particularly attractive in making immediately visible an attempted diversion and lengthening the time for a diversion to be consummated.

- Since technically most countries will be able to get nuclear weapons, enforcement and compliance provisions of any international control regime are crucial.

- Compliance will be stronger and more accepted if nuclear power is non-discriminatory. That is, for example, if countries such as the United States wish to have breeder reactors, it will be hard to argue that other countries should not be allowed these.

- Secondly, compliance will be surer and more effective if ventures to produce fissile material for weapons can quickly be seen and monitored by multinational or international authorities and if the acquisition of significant quantities of fissile material by a country, clandestinely or overtly, will take months or longer. For this reason, we believe that all "sensitive" or "dangerous" nuclear facilities should ideally be put under multinational or international control. This includes reprocessing and enrichment plants. It might include also all uranium mining and milling and spent fuel. In time, the fuel could be "owned" by an international authority.

With respect to the scenarios examined:

- The once-through fuel cycles based on LWRs and gas-cooled reactors do not involve any separation of fissile material, and they are based mostly on technologies reasonably well developed. They require very large amounts of uranium mining and enrichment, however, and they put into repositories large quantities of plutonium and TRU. Increased burn-up in LWRs or gas-cooled reactors would reduce the amounts of heavy metal put into repositories, but would not much change the enrichment or natural uranium requirements. Increased burn-up would make the plutonium in the spent fuel less attractive for weapons, especially for terrorist groups; but the isotopic composition of the plutonium does not appear an insuperable barrier to its use in weapons. Possibly, gas-cooled reactors would be less vulnerable than LWRs to terrorist attacks designed to release massive amounts of radioactivity.

- The actinide (plutonium, uranium, and transuranic) burning schemes envisioned under GNEP could in principle increase effective space for repositories like Yucca Mountain by a factor of 5-10 or greater. The advantages of doing so are unconvincing, though, and the general architecture set out under GNEP looks shaky. It requires so far untested separations of actinides, the fabrication of these into fuels, and a fleet of fast reactors to burn the plutonium and the TRU. There would have to be continued separations and recycling to reap significant advantages. Under the schemes examined, the fuels delivered to the reactors would not meet the spent fuel standard of 100 rem/hr at one meter; even for aged fuel, they would be a tenth or one hundredth of that standard at best. The fuels would have critical masses at most two times greater than pure reactor-grade plutonium, and the fuel compositions being considered do not raise insuperable problems of pre-initiation and heat management for bomb designers. A concern with actinide burning schemes is that the process might be truncated prematurely, in which case the advantages of the schemes would be largely negated, and the costs multiplied.

- The breeder scenarios, once equilibrium is established, require little uranium enrichment and little natural uranium. They do involve separation of fissile materials and very large transfers of these materials to reactor sites, though. The pyro-processing products being most investigated would not prevent their incorporation into weapons. It is difficult to see how such systems can be made proliferation resistant. Also the technical developments required are substantial.

- The denatured sustainable molten-salt reactor has many attractive features. Access to weapons-grade U-233 requires a difficult isotope separation, and compared to an LWR on a once-through cycle: (1) the relatively small amount of plutonium is of poor isotopic quality; (2) the quantity of actinides going to a repository would be reduced by a factor of 10 or more; and (3) after startup, little further enriched uranium is required, thereby reducing the amount of uranium and separative work needed by about a factor of eight. But no molten salt reactor has ever operated on a commercial basis, and even the limited pilot plant experience dates from the 1960s and 1970s. Thus, molten salt technology in general and the feasibility of the denatured sustainable cycle in particular would need to be validated by an extensive research and development effort. This is true for thorium cycles in general; and unless uranium resources prove to be more limited than now appears likely, and the uranium-plutonium breeder fuel cycles come to be seen as unacceptable on technical, economic, or nonproliferation grounds, there will be little incentive for further development of thorium cycles except in countries where thorium resources are abundant, such as India.

- Hub-spoke arrangements employing sealed nuclear batteries not requiring refueling for a long period would probably not significantly reduce uranium or enrichment requirements for half a century or longer, and could actually increase these requirements in the next fifty years. Such arrangements would have certain proliferation-resistant advantages, though. Most important, in principle, they would obviate the need for a nuclear infrastructure in battery-importing states. They do raise questions. First, it appears that until equilibrium is reached in the nuclear power system, the arrangements would require that a substantial part of world nuclear energy is produced at the hubs – presumably regional or international centers. Second, the economics of the nuclear battery are unclear. The initial loadings if done by LWR plutonium would be very expensive; if done by 20% uranium, they would be more economic, but would then require substantial enrichment, thus partially offsetting the advantages of the hub-spoke over the once-through fuel cycle. Serial production of nuclear batteries could conceivably compensate for the loss of economies of scale for the reactors themselves, but it is too soon to say for sure. Also, hub-spoke arrangements deploying sealed reactors must be compared to those where at the international center, electricity or hydrogen is sent out to the spokes, instead of reactors.

> In general, if all dangerous activities are under international authority, then the LWR or gas-cooled reactor on a once-through fuel cycle would appear equally proliferation-resistant or nearly so to that of the nuclear battery under a hub-spoke configuration. Instead of a sealed reactor not needing refueling for a long period, the LWR or gas-cooled reactor would have to be refueled. In the case of the LWR, this would occur every 1.5 to 2 years, when the reactor would be shutdown and carefully monitored. Refueling would occur continuously in the case of the gas-cooled reactor, but under continuous inspection by an international safeguarding agency. In either case, it appears possible that an international inspectorate could maintain high confidence that there was no diversion of fissile materials.

In sum, a nuclear system of 1500 GWe will require either a four-fold expansion of enrichment or substantial reprocessing or both. Given plausible economies of scale of enrichment – almost certainly based on centrifuge technology – scores of enrichment plants could operate worldwide. These would have to be under multinational or international control. Likewise, all reprocessing would have to be under such control. We imagine that at least 20-30 reprocessing plants will be required if countries move away from the once-through fuel cycle which now dominates. If all enrichment, reprocessing and uranium mining were under international authority, the dangers of country proliferation could be minimized, though not eliminated. The once-through fuel cycle would more clearly suppress the risks of terrorist acquisition of fissile materials than any closed fuel cycle so far advanced. Risks of terrorist attacks on the reactors and spent fuel holdings would remain under most scenarios, though it is possible that some advanced reactor concepts would make such attacks less possible.

Schemes of fuel cycle assurances and ways to supply nuclear technology to certain countries without the countries needing to build a domestic nuclear infrastructure are worth exploring. In some interim period, we can imagine a country foregoing its own nuclear industry and importing instead small, sealed reactors that would not need refueling for decades. It would be valuable to develop such reactors, but it would be an illusory goal to build a nuclear future on the basis that nuclear technologies in use in some countries could be kept indefinitely away from other countries.

The challenge of a 4500 GWe system would be still more daunting. It would most importantly entail the spread of nuclear technology to scores of countries that do not now have nuclear power, and it could also lead to a further spread of centrifuge plants. If such an expanded nuclear system drove nuclear to closed fuel cycles as is imagined by the Generation IV studies, the proliferation risks would be multiplied.

Even in a world of 4500 GWe, it is very possible that the once-through fuel cycle will remain, as it is today, the most economical nuclear option. The cumulative uranium requirements through 2100 in that case would be approximately 35 million tons. Current estimates of terrestrial uranium indicate that at uranium prices of $200-300/kg, far more uranium than that would be available. A price of $200/kg would raise the cost of the once-through fuel cycle only about 4 mills per kWh, which in all likelihood, would keep the costs of the once-through fuel cycle below any closed cycle that has so far been suggested.

Acknowledgements

We wish to express special thanks to David Wade, Robert Hill, and James Sienecki of Argonne National Laboratory; William Halsey and Ralph Moir of Lawrence Livermore National Laboratory; Robert Budnitz of Lawrence Berkeley National Laboratory; Michael Driscoll, Andrew Kadak, and Neil Todreas of the Massachusetts Institute of Technology; and Steve Fetter, John Steinbruner, and Nancy Gallagher of the University of Maryland.

Appendix A – Five Scenarios

In this Appendix, we explore five scenarios for a nuclear power system growing worldwide to 1500 GWe by 2050 and to 4500 GWe by 2100. The scenarios are as follows:

- Advanced LWRs and/or gas reactors on a once-through fuel cycle
- Actinide burning based on fast reactors – this is the vision of the Global Nuclear Energy Partnership (GNEP)
- Fast breeder reactors in a closed fuel cycle
- Thorium fuel cycles with molten-salt reactors being the principal illustration
- Nuclear batteries in a hub-spoke configuration

We focus on how the 1500 GWe scenario might look in 50 or so years, describing the scenarios beyond 2050 much more sketchily. Table A.1 quantifies the annual requirements of nuclear materials, enrichment and reprocessing capacities, and total amounts of materials discharged or separated for 500 GWe "sub-scenarios" based on the five scenarios defined above, assuming that simultaneous deployment of several main technologies is likely to occur. The table illustrates that each scenario has its advantages and disadvantages with respect to front-end and back-end characteristics and requirements.

As anticipated, uranium requirements are largest for the standard once-through cycle as it is widely deployed today—a fact that has driven the research on alternative reactor technologies and fuel cycles. By comparison, the thorium-based reference scenario would reduce the uranium requirements by 75%, the fast breeder scenario still more. These "self-sustaining" systems, however, need significant amounts of fissile materials for the initial cores. Here, either we can assume that these stocks already exist (e.g. extracted from spent fuel) or that they would have to be specially produced, which would then offset these savings to some extent.

For 500 GWe installed capacity, the spent fuel discharged from the five systems discussed here ranges from 2500 tons to 10,000 tons per year. The amount of fissile material contained in this material varies more markedly. Whereas 850 tons of plutonium and TRU are discharged *and* separated per year in the breeder and nuclear battery scenarios, only 12.5 tons are discharged annually in the case of the thorium-based concept. The standard once-through and the thorium-based concepts do not require separation of fissile materials from the spent fuel.

	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4	SCENARIO 5
	LWR (once-through)	GNEP (MIT) LWR + Burner	FBR	Thorium MSR	Nuclear Battery
Initial Core	30,000 MT of LEU at 4.5%	16,500 MT of LEU at 4.5%	2000 MT of plutonium	8750 MT of 20% LEU	25,000 MT of Pu/TRU
Front end: Externally supplied services and materials					
U(nat) requirements	100,000 MT/yr	55,000 MT/yr	500 MT/yr	25,000 MT/yr	—
Enrichment	62,500 tSWU/yr	35,000 tSWU/yr	—	20,000 tSWU/yr	—
Fresh Fuel	10,000 MT/yr of 4.5% LEU	5500 MT/yr of 4.5% LEU	—	500 MT/yr of 20% LEU	—
Front end: Self-generated fuel					
Fresh Fuel (recycled)	—	390 MT/yr of Pu and MA	750 MT/yr of plutonium	—	850 MT/yr on average
Back end					
Total Discharge Spent fuel	10,000 MT/yr	7000 MT/yr	7500 MT/yr	> 2500 MT/yr on average	5000 MT/yr on average
Total Discharge Fissile Material	100 MT/yr of plutonium	390 MT/yr of Pu and MA	850 MT/yr of plutonium	12.5 MT/yr on average	850 MT /yr on average
Separation Fissile Material	—	390 MT/yr of Pu and MA	850 MT/yr of plutonium	—	850 MT /yr on average

Table A.1. Annual Requirements for various 500 GWe sub-scenarios.

Scenario 1 – LWRs and Gas Reactors on a once-through fuel cycle

We assume for illustration that a once-through cycle would be based on today's light-water reactors or high-temperature reactors.

Front-End of the Fuel Cycle

A typical 1,000 MWe LWR requires about 20 metric tons of fresh fuel per year if the average burn-up is 50 megawatt-days-thermal(MWd) per kilogram of uranium in the fuel (about 5 percent fission). For an initial uranium enrichment level of 4-5%, separative work of 120,000-150,000 kilogram of SWU/yr would be required to enrich the fuel needed for one LWR. About 160 tons of natural uranium is needed.

Again for illustrative clarity, we assume that all countries with an installed capacity of at least 10 GWe would seek to establish a domestic enrichment industry with or without foreign assistance. Up to 1.5 million SWU per year are needed to support 10 GWe, which is somewhat less than a typically sized commercial centrifuge plant in operation today. In addition, there would be a strong incentive for the major suppliers of uranium ore, i.e. Australia, Canada, and South Africa, to provide enrichment services. We further assume that the U.S. and Europe would continue to import up to 50% of the needed enrichment services, while Russia would continue to be a major exporter.

Based on these assumptions, the distribution of SWU-capacities is illustrated in Figure A.1 for a 1500 GWe Scenario. This example shows large enrichment facilities operating in 16 countries, including the nine non-weapon states: Australia, Brazil, Canada, Indonesia, Iran, South Korea, Mexico, South Africa, and Taiwan. Note that 5,000 SWU/yr are sufficient for a small nuclear weapons program (30 kg/yr of weapon-grade HEU using natural uranium feed; more than 100 kg/yr of HEU if LEU stocks are available). Even a single 1.5-million SWU plant could make about 300 bombs per year starting with natural uranium. It could make 2000 bombs per year starting with 8% uranium, the nominal fuel enrichment of the gas-reactor fuel. For the world as a whole, more than 200 million kilograms of SWU will be required annually.

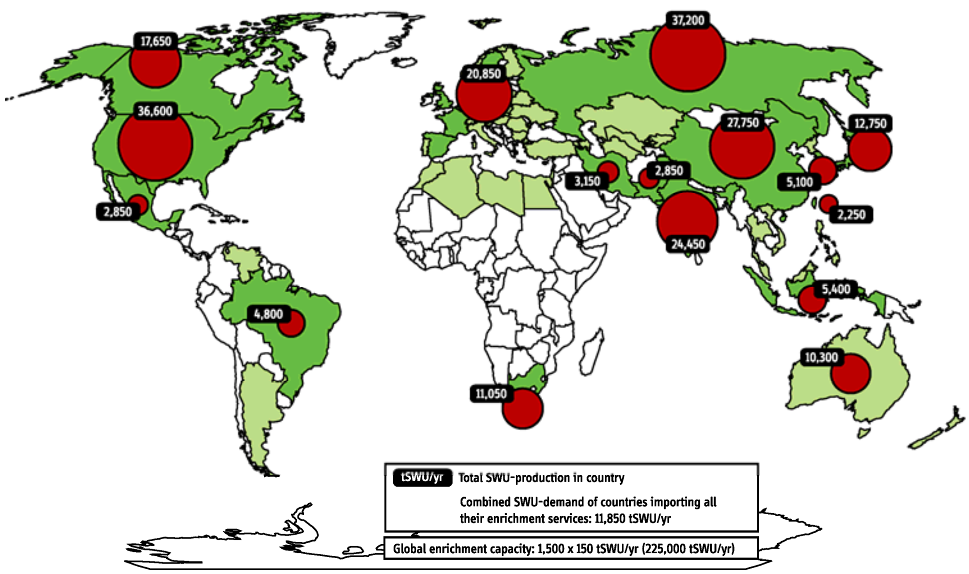

Figure A.1. Enrichment Capacities for a Once-Through Fuel Cycle, 1500 GWe Global Capacity.

We can draw three alternative conclusions: (1) a large scale expansion of nuclear energy may be impossible without further spread of uranium enrichment capability; (2) a new global arrangement may be needed, in which the states currently with enrichment capability would build the very much larger capacity required to supply greatly expanded nuclear power programs at home *and* in other countries, and that leaders and publics in both sets of countries would accept this; or (3) international agreement may have to be reached on averting the proliferation consequences of a large nuclear expansion through non-discriminatory, equitable, multinational provision of enrichment services that assure supply.

The enrichment and uranium requirements would be somewhat larger if, say after 2025, the LWRs were complemented by high-temperature gas reactors, such as the pebble-bed modular reactor (PBMR). We take as our nominal reactor here the PBMR design that is being considered in South Africa and China and investigated at MIT. We assume a 100 MW reactor using 8% enriched uranium as fuel and a burn-up of 80 MWd/kg HM. If half of the 1500 GWe capacity were achieved by LWRs and half by PBMRs, the nuclear system would be comprised of 750 of the former and 7500 of the latter. The corresponding annual enrichment capacity required would be 250 million SWU, the natural uranium required 270,000 tons, and the annual spent fuel discharge 24,000 tons.[45]

It should be possible over time to increase the burn-up of both reactors. For example, the LWR could conceivably achieve a burn-up of 100 MWd/kg and the PBMR at least that. But roughly speaking the uranium and enrichment requirements would change little.

Back-End of the Fuel Cycle

The spent fuel discharge for an installed capacity of 1500 GWe based on light-water reactor technology on a once-through fuel cycle would be about 30,000 tons per year, containing 300 tons of plutonium and TRU. The spent fuel would be sent eventually to a geological repository. While 30,000 tons is nearly half of the *current statutory limit* on Yucca Mountain of 70,000 tons thereby meaning that the limit would be reached every two years or so, this is misleading. First, the actual technical limit at Yucca Mountain is almost certainly far higher than the statutory limit, with for example a recent EPRI study suggesting that the true Yucca capacity to be between 260,000 and 570,000 tons. Still more telling is the realization that, while Yucca Mountain is limited by its natural geographic boundaries (about 7 square kilometers), repositories in principle certainly do not have to be. If we take a thermal loading limit for a repository of say 30,000 tons per square kilometer, which a Yucca-like repository appears capable of handling, the repository additions worldwide necessary to handle the spent fuel discharge in the once-through 1500 GWe scenario would be roughly one square kilometer per year.[46] Still, siting final repositories for nuclear waste is a complex process that goes beyond technical or scientific considerations, but has to take into account important socio-political dimensions.[47]

---

[45] To go from natural uranium to 8% uranium (and with 0.2% tails) will require 15.6 kg of natural uranium feed and 17 SWUs per kilogram of product. The loading and spent fuel per GWe would be about 12.5 tons based on 80 MWd/kg burn-up. So about 12.5*1000*17 = 212,500 SWU will be required per GWe of pebble bed, compared to 140,000 SWU per GWe of LWR.

[46] J. Kessler, "Room at the Mountain," *op. cit.*; the implications of the uniqueness in the Yucca Mountain case of its limited geographic extent were pointed out to authors by Steve Fetter, personal communication.

[47] For a discussion of the German site-selection process, see Arbeitskreis Auswahlverfahren Endlagerstandorte, *Site Selection Procedure for Repository Sites, Recommendations of the AkEnd – Committee on a Site Selection Procedure for Repository Sites,* Cologne, Germany, December 2002, www.ipfmlibrary.org/ake02.pdf.

Again, in the longer term, the typical fuel burn-up for an LWR and the PBMR could be expected to increase to 100 MWd/kg. The spent fuel discharges could be cut in same proportion to the increase in burn-up;[48] and the plutonium and TRU discharge in the spent fuel would be reduced but by a lesser degree. The isotopic composition of the plutonium in the spent fuel would be changed, with a much higher Pu-238 content and a lower Pu-239 content, but how significant this is with respect to proliferation resistance is less clear.

Nonproliferation and Safety

A 1500 GWe system based on the once-through fuel cycle will involve a four-fold increase compared to today of uranium mining, uranium transport, uranium enrichment, and transport of low-enriched uranium. Although such an increase does not represent a direct danger of diversion, it could have proliferation-resistant consequences in the long-run. As already noted, it will in all likelihood, lead to many more enrichment plants in several additional countries. It could also provide powerful economic incentive for innovation to make isotope separation cheaper and quicker.[49]

For the spent fuel, the LWR and the PBMR have different advantages and disadvantages. In the case of the LWR, refueling can only take place when the reactor is shutdown. During the shutdown period, the spent fuel pool and reactor could be rigorously safeguarded and secured. The spent fuel contains an intense radioactive field (meeting the "spent fuel standard"). Naturally, in a breakout scenario a country could seize the spent fuel, build a reprocessing plant, and separate plutonium. Though with rigorous safeguards at the reactor site as well as extensive monitoring to detect the possible construction and testing of secret facilities throughout the country, it should be possible to assure that this could not be done clandestinely. Acquisition of spent fuel assemblies by terrorist groups and their subsequent reprocessing does not look credible.

For the PBMR, the refueling is done on-line, which would in theory allow the diversion of spent pebbles without detection while the reactor is operating. However, the pebbles would be high burn-up material encased in thousands of tiny carbon-coated spheres making it a comparatively unattractive source from which to recover plutonium. At any given time, the core of the reactor (nominally 100 MW) would consist of 360,000 pebbles (60mm in diameter), each containing about 9 grams of uranium (at about 8 percent U-235) in the fresh fuel in 11,000 micro-spheres (0.9 mm diameter).[50] But at low burn-up, when the weapon-grade quality of the plutonium is relatively high, its content will be very low. At the design burn-up, there will be more plutonium, but it will be far

---

[48] For an LWR at 100 MWd/kg burn-up, the spent fuel discharge is about 10 t/y per GWe. At 0.2% tails, the enrichment required would 20.3 SWU/kg of 9.75% U.

[49] For example, there has been renewed recent interest in laser-isotope separation techniques. In 2006, General Electric acquired the SILEX process, originally developed by a privately-owned Australian company. The details of the process had already been classified by the U.S. Government in 2001.

[50] This is based on "PBMR: Still in the Running," *Nukem*, August 2005.

from weapon-grade quality with regard to both pre-initiation and internal heating due to high concentrations of both Pu-240 and Pu-238 (almost 6 percent). The total content of the plutonium in this case would be about 5 kilograms per ton of uranium fuel, so that perhaps two hundred thousand pebbles would have to be diverted to obtain a critical mass. As with the LWR spent fuel, the PBMR spent fuel would be self-protecting.

As previously noted, the PBMR has a higher safety margin against radiological releases compared to an LWR because, unlike the latter, the fuel will not melt following a complete and permanent loss of coolant. One can only achieve this safety feature by limiting the capacity of an individual PBMR to ~100 MWe since it depends on both the design of the fuel and the fact the decay afterheat can be conducted efficiently to the periphery of the core in a small reactor. Although the capital cost disadvantage of such small reactors compared to large LWRs might be compensated by serial factory production of the former with subsequent transport of reactor modules to the reactor site, it might also be advantageous to develop a high temperature gas reactor that retains the non-melting of the fuel at large capacities. Recently, researchers have proposed several such designs that use liquid salt instead of helium as the coolant.[51]

Scenario 2 – Actinide Burning and the GNEP Vision

In the spring of 2006, the U.S. Department of Energy launched the so-called Global Nuclear Energy Initiative (GNEP). The GNEP vision for the United States featured the deployment of a fleet of fast reactors that, with repeated recycling, would burn up the plutonium and TRU) in the spent fuel of all reactors, and reprocessing plants that would employ novel technologies to keep the plutonium in the spent fuel always mixed with the TRU. To achieve this vision, GNEP advocated an accelerated program to develop and then deploy the required fast reactors and reprocessing technologies. The reprocessing would be based both on a new aqueous process termed UREX, and later on pyro-processing. Internationally, GNEP imagined a nuclear world where all the reprocessing and use of fast reactors would take place in a few or several “fuel-cycle countries” (implicitly, nuclear weapon states and other developed countries that would appear not to present a risk of nuclear proliferation), and that other countries wishing the bounty of nuclear power would be willing to forego fuel cycle facilities and send their spent fuel to the fuel-cycle countries for processing. The GNEP concept is illustrated in Figure A.2.

[51] See, e.g., Charles W. Forsberg, P. F. Peterson, and R. A. Kochemdarfer, “Design Options for the Advanced High Temperature Reactor,” paper to be presented at the *2008 International Congress on the Advances in Nuclear Power Plants (ICAPP’08),* Anaheim, CA June 8-12, 2008.

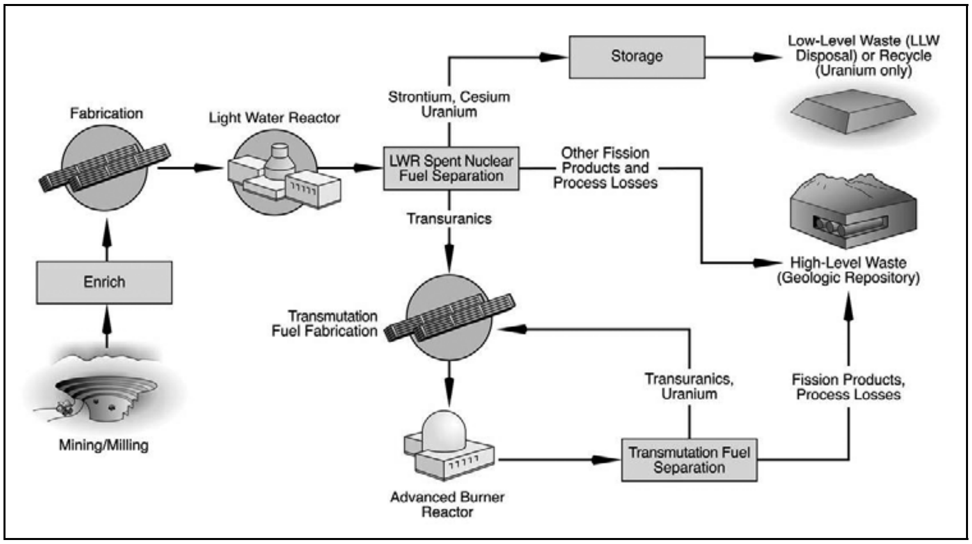

Figure A.2. Diagram showing a Department of Energy proposal for reprocessing U.S. spent fuel and fissioning the transuranics with fast-neutron reactors, shown here as “Advanced Burner Reactors.” After reprocessing, the 30-year half-life isotopes, cesium-137 and strontium-90, which dominate the radiological hazard until they decay away, would be placed in interim surface storage for some hundreds of years. Graphics from Report to Congress: Spent Nuclear Fuel Recycling Program Plan, U.S. Department of Energy, May 2006, www.ipfmlibrary.org/doe06.pdf.

GNEP has so far not made public the number of burner reactors and number of recycling steps that would be required to burn the actinides. However, the basic architecture of a burner strategy was shown in the MIT study—and we use that here. The MIT study assumed that the LWRs worked at 90% capacity factor, a burn-up of 50 MWd/kg, and an electric efficiency of 0.33; and that the total actinides produced annually by the LWRs was at a rate of 0.0145 of the spent fuel. The corresponding assumptions for the burner reactors were 90% capacity factor with a burn-up of 120 MWd/kg, and 0.4 electric efficiency; and that the total quantity of actinides was reduced by 20% each year in each cycle. It was assumed that the plutonium plus TRU loading in the burners would be 25% of the core. With these assumptions, the ratio of burners to LWRs is 0.84. For a 1500 GWe capacity this means that 815 GWe would be in LWRs and 685 GWe in burners. This is the equilibrium condition where there is no net increase in actinides. To burn up the accumulated actinides in spent fuel now stored worldwide would of course take a still greater number of burners and more time.

Proponents of GNEP advanced three presumptive advantages: one, the GNEP scheme of burning actinides could vastly expand the effective repository space for final geological disposal at Yucca Mountain or other similar repository sites. Two, the process could be made significantly proliferation resistant. And three, if the reactors used to burn the actinides were fast reactors, the enterprise could gradually segue into a full breeder system of the type looked at in the next scenario examined.

GNEP Fuel Cycle

With respect to repository loading, the GNEP analysis is consistent with a recent Argonne study, which estimated the limits on loading at Yucca Mountain based on two constraints: the wall temperature in each drift must remain below 96 degrees centigrade, and the temperature between drifts must remain below 200 degrees.[52] The study found that a 99% separation of the plutonium and TRU from the wastes put into the repository would allow a 4-6 fold increase in repository loading potential if there is no removal of the cesium and strontium (Cs and Sr) fission wastes. If the Cs and Sr fraction in the wastes was reduced by 90%, then a 99% reduction in the plutonium and TRU could increase repository space by as much as 44 times. This has led the GNEP architects to propose that the Cs and Sr be kept above ground for hundreds of years until they largely decay away.[53]

The repository gains from the partition and transmutation thus appear somewhat contrived, with the gains dependent on a century or so of recycling and burning of the actinides while the separated fission products are kept out of the repository for hundreds of years. The plan seems the more dubious if a recent study by EPRI on the ultimate capacity of Yucca Mountain without removal of the actinides holds up upon peer review.[54] According to this study, it is possible to dig an increased number of drifts in the mountain, so that, even keeping to the drift and inter-drift constraints on temperature, the mountain's capacity could be increased from its nominal legal limit of 70,000 metric tons by a factor of 4 to 9 – or to 260,000-570,000 metric tons. And finally it should be noted that repositories need not be thermally limited in the same way as Yucca or as constrained in geographic area.

To address proliferation resistance concerns, GNEP proposes reprocessing schemes whereby the plutonium is kept together with most or all of the other actinides in the first separation process. This could be done by an aqueous process, termed UREX, or eventually through pyro-processing. But, unfortunately, the UREX product would not be self-protecting. Consider the dose rate of a typical 4.4 kg container of separated transuranics illustrated in Figure A.3. If the plutonium is mixed with neptunium and americium only the dose rate (mainly from neutrons) from such a container at one meter would be less than 0.01 rem/hour. Even if all the TRU were included, the dose rate would still be less than 0.1 rem/hour. These rates should be compared to the IAEA threshold for self protection of 100 rem/hr.[55] The lack of self protection is troubling

[52] R. Wigeland, T. Bauer, T. Fanning, and E. E. Morris, "Separations and Transmutation Criteria to Improve Utilization of a Geologic Repository," *Nuclear Technology*, Vol. 154, No. 1, April 2006, pp. 95-106.

[53] Robert Hill, "Advanced Fuel Cycle Systems: Recycle/Refabrication Technology Status," September 7, 2005, slide 10.

[54] J. Kessler, "Room at the Mountain," *op. cit*.

[55] Robert Hill, *op. cit.*, slide 17. See also Frank von Hippel and Jungmin Kang, "The limited non-proliferation benefits from recycling unseparated transuranics and rare-earth fission products from aged spent fuel," *op. cit*.

because the critical masses of these actinide mixtures would not be substantially greater than for reactor-grade plutonium.[56]

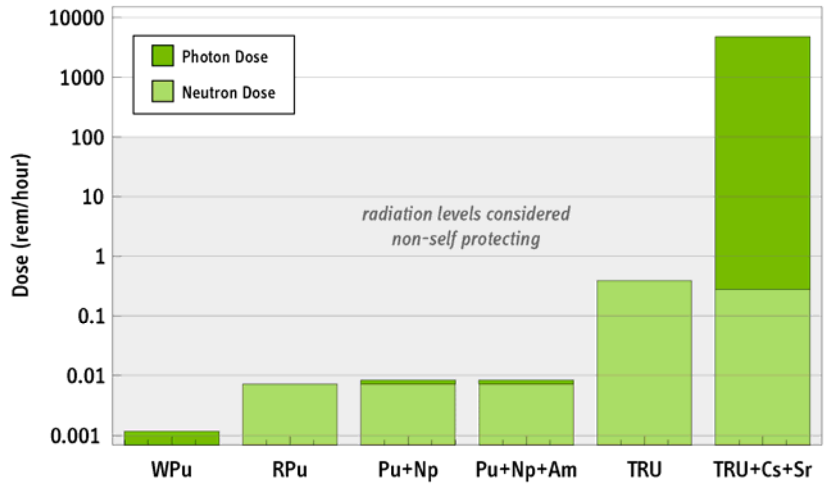

Figure A.3. Dose rate of typical 4.4 kg container of separated transuranics. Peak dose rate only approaches spent fuel standard (100 rem/hour) if high-activity fission products are included (cesium in 100 year time period, possibly europium for shorter time periods). Note that neutron dose is significantly harder to shield against. Data from R. Hill, "Advanced Fuel Cycle Systems," *op. cit.*

GNEP designers have recognized this problem and at one point contrived a two-stage separation scheme. In the first separation, the lanthanide fission products, europium and cerium, would be kept mixed with the actinides when they are transported to the actinide fabrication facilities, at which time the lanthanides would be removed. Since the actinide fuels would then still have to be sent to the burner reactors, this scheme appears to imply that each burner reactor will have associated with it, both a separation and fabrication facility.

A second alleged advantage of actinide burning is that it could prevent the proliferation of "plutonium mines" – large quantities of plutonium that, over time when the radiological barrier of spent fuel is much reduced, could be gotten to by countries or others digging into a repository. Indisputably, recycling plutonium and other actinides and burning them in reactors sharply reduces the build-up of plutonium in spent fuel compared to the once-through fuel cycle. This could be important because one potential (though long-term) risk of the once-through fuel cycle is that the plutonium contained in the spent fuel could eventually become accessible to potential proliferators as the radioactive barrier provided by the fission products decays away – roughly by a factor of ten every 100 years. Thus potentially the geologic repositories to which the spent fuel is destined could become "plutonium mines." But the specter of plutonium mines 200 years from now should not provide reason for increasing sharply the flows of plutonium today. This is self-evident with respect to sub-state threats. And with respect to country

[56] Robert Hill, *Ibid*, slide 15.

proliferation, as long as a country has an operating nuclear power program, diversion of plutonium appears far easier than it would be in a mining operation.[57]

Actinide burning will require continuous separations, the fabrication of the separated actinides into fuel, and then a scheme to burn the fuel in reactors through continued recycling. If this process were truncated prematurely, the advantages of the actinide burning would be largely negated, and the costs multiplied.

Scenario 3 – Closed Fuel Cycles

In a growing nuclear power system, the fast reactors would not be used as burners. They instead would be used to breed plutonium with a relatively high breeding ratio. All the spent fuel would be reprocessed, using pyro-processing for metal fuel or an aqueous process if an oxide fuel, in which the plutonium would never be completely separated from the other actinides.

Because of the high burn-up, the plutonium in the core of the spent fuel of the fast reactors will be of relatively low quality for weapons purposes. The plutonium in the blanket, however, would be of weapon-grade quality, and the blanket spent fuel could in principle be reprocessed separately from that of the core. About 300 kg of plutonium are generated in the blankets of a fast breeder reactor per year per gigawatt electric.

The recycling of mixed oxide fuel (MOX) into LWRs is sometimes justified as a prelude to a breeder economy. Some countries have already embarked upon this path, which also raises concerns, especially if it is an interim step that an increasing number of countries will adopt. With the MOX recycling activities so far restricted to Europe, the standards of security and safeguards applied to the MOX are probably high – but may not always remain so. Third, whatever the risks today, they will be multiplied if ever a real market develops for MOX, with middlemen and agents arranging for the purchase and sale of MOX to more customers worldwide. Finally, safeguards at bulk-handling facilities such as reprocessing plants and MOX fabrication plants are much more difficult to apply than at reactors, with far more diversion paths potentially available to a country.

It is because of the obvious risks associated with separated plutonium that GNEP and the developers of the Gen-IV technologies more generally have sought reprocessing options where the plutonium is never separated completely from the other actinides, as we have pointed out above. In addition, some advanced reactor designs envision integrating the reprocessing and reactor operation at a single site. This could be especially attractive if the separations are done by pyro-processing (electro-refining). In the view of its advocates, pyro-processing has a superior level of proliferation resistance by virtue of its compact nature that better allows co-location with the reactor, its practical

---

[57] Per Peterson, "Long-term Safeguards for Plutonium in Geological Repositories," *Science & Global Security*, Vol. 6, No. 1, 1996; Edwin Lyman and H.A. Feiveson, "The Proliferation Risks of Plutonium Mines," *Science & Global Security*, Vol. 7, No. 1, 1998

inability to separate out pure plutonium, and the poor weapon quality of the separated plutonium.[58]

In general, scenarios to divert plutonium from these fuel cycles will require off-normal operation and specialized equipment, which in principle could be detectable by an inspection agency. On the other hand, even where pyro-processing is used, fuel recycling equipment could be operated in a manner that would allow the extraction of large amounts of plutonium fairly quickly by adding a cleanup stage. In addition, safeguards that relied upon materials accountability would be difficult to apply and therefore more than customary reliance would consequently have to be placed on containment and surveillance. A group of technical experts led by Ray Wymer of the Oak Ridge National Laboratory commissioned by the Departments of State and Energy in 1992 studied these and other safeguards issues.[59] In addition, as noted above, even if the plutonium is not separated from the TRU, the product of reprocessing would still be weapons usable.[60]

Partly for these reasons, the expert group concluded that "in the absence of compelling circumstances to the contrary, access to IFR technology should be preferentially limited at the outset to countries that have good nonproliferation credentials."

This last point is the most troubling. Those countries that are considered "safe" or to have "good nonproliferation credentials" will depend on who is making the judgment. It is illusory to think that the world can build a secure nuclear future that depends on two classes of countries – one where certain activities and fuel cycles are barred and one where anything, or almost anything, goes.

In this scenario, after 2050, the LWRs will gradually be phased out; and by the end of the century, we imagine a closed fuel cycle consisting solely of fast reactors. If nuclear power were still growing at that time, the reactors would continue to breed. But for illustration, we assume that by 2100, nuclear power has reached a plateau and the reactors are then operated in a breakeven mode. In steady state, fast reactors would dramatically reduce the requirements for natural uranium (by a factor of 200 compared to LWRs), but imply tremendous flows of fissile material to support operation: as illustrated in Table A.1, at least 750 tons of plutonium are separated and recycled annually for every 500 GWe of capacity installed.

[58] Yoon I. Chang, "Pyro-processing," presented at the *Workshop on the Security Implications of Increased Global Reliance on Nuclear Power*, CISAC, Stanford University, September 19-21, 2007.

[59] "An Assessment of the Proliferation Potential and International Implications of the Integral Fast Reactor," prepared for the U.S. Departments of State and Energy, April 1992.

[60] Frank von Hippel and Jungmin Kang, "The limited non-proliferation benefits from recycling unseparated transuranics and rare-earth fission products from aged spent fuel," *op. cit.*

Scenario 4 – Thorium Fuel Cycles

Thorium fuel cycles, i.e., cycles in which thorium is wholly or partially substituted for uranium, have been extensively studied over the past 40 years, and much experience also has been gained in using thorium fuel in power reactors.[61] Although no thorium-fueled power reactors operate today, there has been a recent revival of interest in such reactors because of their potential for greater proliferation resistance, smaller production of long-lived actinides, and decreased requirements for mined uranium compared with conventional LWRs on the once-through cycle as illustrated in Table A.1.

Natural thorium, which is approximately three times as abundant in the earth's crust as uranium, consists almost entirely of the isotope Th-232. This isotope is a close neutron analog of U-238, in that it produces via neutron capture and subsequent beta decay a fissile isotope, U-233 in this case. In a thermal reactor, U-233 is superior to the other principal fissile isotopes, U-235 and Pu-239, because it has the largest fission neutron yield per neutron absorption of the three at thermal and epithermal energies. This is good enough to achieve a breeding ratio slightly greater than one in thermal reactors with good neutron economy in which thorium is wholly substituted for uranium and the fuel containing the bred U-233 is periodically reprocessed and recycled.

The production of actinides is smaller than in uranium cycles since many more neutron absorptions are needed to produce such isotopes starting from Th-232 than from U-238. Because of the higher fuel burn-ups possible in thorium fuel cycles less spent fuel is produced compared with uranium cycles. And thorium spent fuel would also behave better in an oxidizing geologic disposal environment like Yucca Mountain since, unlike UO_2, which forms U_3O_8 in such an environment, ThO_2 is stable.

Since U-233 does not occur in nature, startup of a reactor on such a "pure" thorium cycle still requires either enriched uranium, typically 20% U-235, or plutonium previously produced in other reactors. However, after startup no further enriched uranium or plutonium is required, and any U-233 produced in excess of that needed to refuel the reactor could be used to startup other reactors.

Alternatively, thorium could be partially substituted for natural uranium and the reactor operated on a once-through fuel cycle. In this case, breeding is not possible so that the reactor must be continuously refueled with enriched uranium. However, the requirements for mined uranium are smaller, in some cases much smaller, in such "mixed" thorium/uranium cycles compared with a uranium-fueled LWR on the once-through cycle. For example, in the Radkowsky Thorium Reactor (RTR) where 20% enriched uranium seed and thorium blanket fuel is substituted for the 3-5% enriched uranium fuel in a standard LWR, the savings in mined uranium is ~ 15%. The Denatured Molten Salt Reactor (DMSR), in which liquid fuel is dissolved in a high temperature molten fluoride salt, which is chemically processed on-line to remove the noble gas

[61] For a summary of past R&D on thorium fuel cycles, the use of thorium in power reactors, and advanced thorium reactor concepts, see the World Nuclear Association's June 2006 Issue Brief on Thorium, available on the web at www.world-nuclear.org/info/inf62.htm.

fission products, also requires periodic refueling with 20% enriched uranium.[62] However, because of its greater thermal efficiency and higher conversion ratio, much larger uranium savings of up to 70% are possible. The amount of thorium required in mixed cycles is also small, typically 1/10 of the uranium, which is mined primarily for its U-235 content. Taken together with the large thorium resource base, this indicates that supplies of thorium would not be a constraint on the expansion of nuclear power based on the use of thorium fuel cycles.[63]

For illustrative purposes, we adopt the 1,000 MWe DMSR discussed in the articles by Moir and Teller and Engel, et al. Such a DMSR requires 17.5 tons of 20% enriched uranium and 110 tons of thorium for startup and ~ 1 ton/yr of 20% enriched uranium thereafter as makeup. As illustrated in Table A.1, this corresponds to a four-fold reduction in natural uranium requirements compared to the standard LWR and to a more than three-fold reduction in enrichment capacities. Most significantly, eight times less fissile material is discharged from a DMSR and, as in the case of the LWR once-through cycle, none is separated from the spent fuel. This reactor is commonly called "denatured" because the U-233 produced by neutron absorption in Th-232 always remains mixed with enough residual U-238 so that enrichment is required to produce weapon-grade U-233 from uranium removed from the reactor.[64] By contrast, without the addition of uranium, i.e., in a pure thorium cycle, only a chemical separation would be required to obtain weapon-grade U-233, which is excellent weapons material.

---

[62] The Radkowsky Thorium Reactor (RTR) is described in detail in Alex Galperin, Paul Reichert and Alvin Radkowsky, "Thorium Fuel for Light Water Reactors-Reduced Proliferation Potential of the Nuclear Power Fuel Cycle," *Science & Global Security*, Volume 6, 1997; also see A. Radkowsky and A. Galperin, "The nonproliferative light water reactor: a new approach to light water reactor core technology," *Nuclear Technology*, 124, 1998, and Mujid Kazimi, "Thorium Fuel for Nuclear Energy," *American Scientist*, September-October 2003. A comprehensive critique of the RTR by Paul R. Kasten was subsequently published in the same journal, Volume 7, 1998, pp. 237-269. More recently, a variant of the RTC in which the seed and blanket reside in separate assemblies has been analyzed at MIT. See, e.g., D. Wang, M. J. Driscoll, and M. S. Kazimi, "Design and Performance of a PWR Whole-Assembly Seed and Blanket Thorium Fuel Cycle," *Nuclear Fuel Center, MIT Department of Nuclear Engineering*, MIT-NFC-TR-026, October 2000. The Denatured Molten Salt Reactor (DMSR) is discussed by Ralph Moir and Edward Teller, Thorium-Fueled Underground Power Plant Based on Molten Salt Technology, *Nuclear Technology*, Vol. 151, September 2005 and in more detail by J. R. Engel et al., "Conceptual Design Characteristics of a Denatured Molten-Salt Reactor with Once-Through Fueling," *Oak Ridge National Laboratory*, ORNL/TM-7207, July 1980. The Moir and Teller article also has a brief description of the molten salt breeder reactor (MSBR). A comprehensive assessment of the proliferation resistance and physical protection characteristics of molten salt reactors, including the MSBR and the DMSR, has recently been made by Charles W. Forsberg, "Proliferation Resistance and Physical Protection Characteristics of Molten Salt Reactors," *Draft White Paper*, Oak Ridge National Laboratory, September 14, 2006.

[63] Existing estimates of thorium resources, more than 4.5 million tons, are considered conservative because data from China, Central and Eastern Europe and the former Soviet Union are not included, and also because the historically weak market demand has limited thorium exploration.

[64] Other uranium isotopes that thorium-fueled reactors produce, especially U-232, also complicate the process of obtaining weapons-useable U-233 from uranium in the blanket. We discuss this issue in the next section.

Weapon-relevant characteristics of U-233 compared to U-235 and Pu-239

From a weapons physics perspective, U-233 is superior to U-235, and in some respects, is also superior to Pu-239. As indicated by their bare sphere critical masses, ~ 50, 17, and 16 kg for U-235, γ-phase Pu-239, and U-233, respectively, U-233 is superior to U-235, and comparable to Pu-239 in reactivity.[65] Like weapon-grade U-235, the rate of spontaneous fission in weapon-grade U-233 due to the residual U-238 is small enough to permit its use in gun-type fission weapons provided the uranium is first processed to remove the light-element impurities that give rise to a neutron background via (α, n) reactions.

Chemically and metallurgically, both U-235 and U-233 are much more tractable than the plutonium isotopes, and their inhalation toxicity is also much lower. The only significant disadvantage of U-233 is that its production is generally accompanied by the production of U-232 via (n, 2n) reactions with Th-232, U-233, and U-235.[66] While U-232 itself does not emit troublesome radiation, some of its daughter products do, especially Tl-208, which decays with the emission of penetrating 0.6 and 2.6 MeV gamma rays. The resultant gamma dose depends on the amount of U-232 contained in the uranium chemically separated from the spent fuel, which in turn depends on the fuel burn-up and the reactor's neutron spectrum.[67]

For example, the amount of U-232 in the uranium of a DMSR after 15 years of operation is ~ 0.02% or 0.2 gm per kg total uranium, while the U-232 concentration in the blanket fuel of a RTR after 10 years of operation is ~ 0.2% or 2 gm per kg total uranium.[68] The gamma dose of such material increases continuously after discharge reaching a maximum about 10 years after separation. For example, the dose 1 meter from a sphere one year after separation is about 1 rem/hr and 10 rem/hr per kilogram uranium for the molten salt reactor and the RTR, respectively.[69] Support for the conjecture that the main impact of the U-232 as far as U-233-based weapons are

---

[65] As is well known, these critical masses can be reduced significantly by reflection and compression in implosion designs. Because of its higher reactivity, the 20% U-235 dividing line between LEU and HEU in mixtures of U-235 and U-238 should be taken at 12% U-233 in mixtures of U-233 and U-238. In uranium that contains both U-233 and U-235, the appropriate criterion for LEU is (U-233 + 0.6 U-235)/ total U < 12%. See Charles Forsberg et al., "Definition of Weapons-Useable Uranium – 233," *Oak Ridge National Laboratory*, ORNL/TM-13517, March 1998.

[66] Manson Benedict, Thomas Pigford, and Hans Levi, *Nuclear Chemical Engineering,* 2nd Ed, McGraw Hill, New York, 1981, p. 378.

[67] In particular, since the (n,2n) reaction with Th-232 has a threshold of 6.8 MeV, a harder neutron spectrum would increase the production of U-232. For a detailed discussion of the factors influencing the production of U-232, see Jungmin Kang and Frank von Hippel, "U-232 and the Proliferation-Resistance of U-233 in Spent Fuel," *Science & Global Security*, Vol. 9, 2001, pp. 1-32.

[68] See Moir and Teller, *op. cit.*, p. 337, footnote e, and Galperin, Reichert, and Radkowsky, op. cit., Table 4, p. 281, respectively. The major factors leading to a smaller level of U-232 in the DMSR is that the neutron flux in such a reactor is reduced in order to decrease losses of U-233 due to neutron absorption in Pa-233 and the softer neutron spectrum in such a graphite moderated reactor compared with an LWR.

[69] See, e.g., Manson Benedict, Thomas Pigford, and Hans Levi, et al., *op. cit.*, Figure 8.13, p. 383.

concerned is to require remote or semi-remote operations during manufacture rather than compromising the actual performance of the weapons themselves is provided by the following statement in the 1980 Nonproliferation Alternative Systems Assessment Program (NASAP) report:[70] "The U-233 would be accompanied by radiation from U-232, an industrial disadvantage, but a minor nonproliferation advantage."

Nonproliferation Aspects

In a once-through denatured thorium cycle, there are three potential sources of weapon-usable materials: the plutonium and U-233 in the spent fuel or in the in process inventory, and the U-235 in the fresh fuel.

With respect to the plutonium, due to the partial substitution of thorium for uranium as fertile material and the higher burn-ups possible with the more highly-enriched uranium fuel, both the total quantity and the isotopic quality of the plutonium in the spent fuel of the RTR and the molten salt of the DMSR would be inferior to that in the spent fuel of a standard LWR. For example, after 15 years, the plutonium in the DMSR would consist of 7% Pu-238, 21% Pu-240, 20% Pu-242, 15% Pu-242, and 36% Pu-239. It would be similar for the RTR.[71]

A second route to weapons material is via chemical separation of the uranium in the discharged blanket fuel of a reactor such as the RTR or the molten salt in a DMSR and its subsequent enrichment to weapon-grade U-233. Since the separative capacity of a centrifuge varies as $(\Delta m)^2$, the separative capacity for the separation of U-233 from U-238 would be a factor of $(5/3)^2$ larger than for the separation of U-235 from U-238. This means that the number of centrifuges required to perform a given separation task would be reduced by ~2/3 in the case of U-233 compared with U-235 enrichment. And so, in this regard, the denatured product may look somewhat less proliferation resistant than spent fuel from a uranium reactor with a similar U-235 isotopic fraction.

However, the presence of U-232 complicates the task of enriching the LEU-233 to weapon-grade. As indicated in Table 4 on p. 281 of Galperin et al., besides U-232, U-233, and U-238, small amounts of U-234, U-235, and U-236 are also present in the blanket fuel. In a "matched U-233/U-238" ideal enrichment cascade, i.e., a cascade in which the abundance ratio of U-233 and U-238 doesn't change when streams are mixed in the cascade, the U-232, U-234, and U-235 will tend to concentrate with the U-233 in the product stream while the U-236 will tend to concentrate with the U-238 in the waste stream.

A simplified calculation in which all the U-234 and U-235 was lumped with the U-233 and all the U-236 was lumped with the U-238 so as to approximate the actual situation as a mixture of three components - U-232, U-233 and U-238 - confirms the

[70] Nonproliferation Alternative Systems Assessment Program (NASAP) report, Vol. II, Proliferation Resistance, US Department of Energy, Washington, DC, 1980, p. 2-14.

[71] Galperin, Reichert, and Radkowsky, *op. cit.*, Table 3, p. 280.

expectation that if the product U-233 concentration is high, e.g., 90%, practically all the U-232 contained in the feed will go to the product stream, especially in the case of centrifuge enrichment, thus greatly increasing the U-232 radiation problem.[72] Thus, to obtain relatively pure U-233, a proliferator would have first to enrich the U-233 to weapon grade in one cascade and then strip the U-232 to tolerable levels in a second cascade.

Another potential source of relatively pure U-233 is the protactinium isotope Pa-233, which β decays with a 27-day half-life to U-233. This would require chemically separating the protactinium from the spent blanket fuel in an RTR soon after the fuel is discharged from the reactor, or from the fuel salt in a DMSR during reactor operation. However, the amount of U-233 that could be obtained in this manner is limited in the case of the RTR by the need to wait for the high burn-up fuel to cool for a period of ~150 days or more by which time most of the Pa-233 has decayed, and by the need for significant and easily detectable modifications in the normal operation of the DMSR if more than a small quantity of salt is removed at one time.[73]

Thus, the spent fuel in the RTR and in the in-process inventory in the DMSR are more proliferation resistant than that of LWR spent fuel. At the front-end, the situation is less clear. While the 20% enriched uranium required for the denatured thorium cycle requires less separative work per unit mass to enrich it to weapon-grade than the 5% enriched fuel used in a modern LWR, the amount of 5% fuel required annually is much greater than the annual 20% makeup in the thorium cycle. If, for example, the available enrichment capacity is not a constraint, then more weapon-grade material can be made from the 5% than the 20% material.[74]

Thorium Fuel Options vs. Standard Uranium Once-Through Cycle

The preceding discussion suggests that denatured thorium cycles, such as the RTR and the DMSR considered here, have a higher degree of proliferation resistance than standard LWRs operating on the once-through cycle. They could also stretch uranium resources and reduce the production of long-lived waste actinides. However, it is questionable whether these benefits alone are sufficient to motivate the substantial costs involved in introducing a new fuel cycle on a large scale. In particular, the fact that the RTR utilizes existing LWR reactor technology is an advantage in terms of reducing the

---

[72] Manson Benedict and Marvin Miller, "Nonproliferation Alternative Systems Study: Progress Report for the Period September 1, 1977 – January 1, 1978," *MIT Energy Laboratory*, MIT- EL 78-001, February 1978, pp. 19-25.

[73] J. R. Engel et al., op. cit., pp. 95-96 discusses this diversion scenario for the DMSR. While periodic chemical separation of the protactinium to prevent loss of U-233 due to neutron absorption in Pa-233 is incorporated in the molten salt breeder reactor (MSBR), it is eliminated in the DMSR because of its proliferation potential.

[74] For example, assuming a product and tails assay of 90% and 3%, for both the 5% and 20% enriched feed streams, ~ 200 kg of product could be produced from the ~ 1 ton of 20% annual makeup required in the 1000 Mwe DMSR illustrated in Figure 3-6, while ~ 380 kg could be produced from the ~16.7 tons of 5% enriched makeup for a modern LWR operating at the same capacity factor.

need for further R&D, but is also a disadvantage with regard to the consensus view that future reactors must have a much higher degree of inherent safety with regard to major radioactive releases than LWRs. Their uranium savings are also modest, and the higher fuel burn-ups potentially achievable in both modular gas reactors and future LWRs would also result in plutonium of poorer isotopic quality in their spent fuel than in today's LWRs.

By contrast, the uranium savings potentially available with the DMSR are substantial, and some of the characteristic features of all molten salt reactors, especially their small fissile inventory, which can be continuously monitored and the presence of U-232, facilitate the application of safeguards. They also are designed with a high degree of passive safety, which could limit the likelihood and potential consequences of accidents and sabotage,[75] especially when combined with underground siting. While a substantial effort would be required to revive the molten salt reactor concept, which has languished since the operation of two experimental reactors in the 1950s and 1960s, such an effort should be seriously considered, but not for the goal of validating the DMSR per se.

Rather, through modification of the chemical processing system in a DMSR to remove more fission products, it may be possible to combine the proliferation resistance features of the DMSR with the potential for breakeven breeding of a molten salt reactor operated on the pure thorium cycle.[76] After startup, such a sustainable denatured molten salt reactor (SDMSR) wouldn't require any more enriched uranium, and the total amount of mined uranium would be reduced by a substantial factor, ~ 90%. Such a reactor would provide a more proliferation-resistant, and potentially also a safer and more economic alternative to the standard plutonium fast breeder in a situation where there isn't a need for a rapid growth in installed nuclear capacity unconstrained by a lack of uranium.

Scenario 5 – The Hub-Spoke and Nuclear Battery

This refers to schemes that restrict nuclear power to large, international or regional energy parks that would then export to individual countries, small, sealed reactors. The reactors would be fueled at the central nuclear park and then sealed and sent out to client countries. The reactors would have lifetime cores, not requiring re-fueling, and at the end of the core life (say 20 years) would be sent back to the central facility unopened. Let's call this a hub-spoke configuration. In Figure A.4 below, we illustrate such a scheme, in which we arbitrarily define six global hubs and assume that these operate independently. We also assume that the fractions of nuclear batteries deployed strongly vary across these regions.

To some advocates of the battery, it could represent the core of a nuclear future with essentially all nuclear power revolving around the battery, and whatever nuclear

[75] For further discussion, see C. W. Forsberg, *Draft White Paper, op. cit*.

[76] For a description of such a reactor, see J. R. Engel et al., "Molten Salt Reactors for Efficient Nuclear Fuel Utilization Without Plutonium Separation," *Oak Ridge National Laboratory*, ORNL/TM-6413, August 1978.

power is required in the central nuclear parks. To others, the battery is seen more as a niche technology, to be welcomed by countries that would not want necessarily to develop a domestic nuclear industry or infrastructure. In the GNEP vision discussed above, batteries would be available only to countries that in fact foreswore any domestic nuclear industry – and indeed the GNEP proponents imply that nuclear technologies other than batteries from abroad would be denied to certain countries. Our view is closer to the niche view of the battery – a potentially valuable alternative that many countries might find attractive in a robust nuclear future, but not one where it would dominate all nuclear power. The discussion below assumes that the battery would be dominating only in a few regions and, overall, would provide only a smaller fraction of the total nuclear capacity installed worldwide.

Scientists at the Argonne National Laboratory, the Lawrence Livermore National Laboratory, the Pacific Northwest Laboratory, and colleagues elsewhere have designed on paper various versions of a battery.[77] Designs were developed for a 20 MW reactor with a 30-year core life and a 180 MW reactor with a 15-year core life – these reactors fueled by plutonium. But for convenience of illustration we take a 100 MW reactor and assume a 20-year core life. The reactor would be lead cooled and have a burn-up of 80 MWd/kg. We assume that the reactor would be fueled either by 20% U or 18% plutonium. The Argonne scientists are in the process of designing a uranium-fueled reactor but have not at this writing completed the analysis; and so our illustrative scenario will no doubt have to be updated.

Such a reactor would have an initial inventory of about 4 tons of fissile material (U-235 or plutonium).[78] The presumed fuel is a nitride matrix of density 14 g/cc. This fuel loading could impose a very high cost on the battery, though there are many uncertainties involved. It appears, however, that fueling initially with enriched uranium would be less expensive than fueling with plutonium derived from LWR spent fuel.[79]

---

[77] D.C. Wade, "The STAR Concept: A Hierarchal Hub-Spoke Nuclear Architecture ...," *TEC Doc-1457*, June/July 2005; D.C. Wade, "Overview of Advanced Nuclear Development Activities on Small Reactors of Long Refueling Interval Supported by Centralized Fuel Cycle Infrastructure," September 7, 2005; Jim Sienecki, "SSTAR Design Details," September 7, 2005; Jim Sienecki, "SSTAR Portfolio R&D Needs and Time Phased Deployment Schedule," September 7, 2005; Jim Sienecki and D.C. Wade, "Nonproliferation Features of the Small Secure Transportable Autonomous Reactor (SSTAR) for Worldwide Sustainable Nuclear Energy Supply," Argonne National Laboratory, undated; D.C. Wade, et al, "A Multi-Regional Analysis of Nuclear Energy Systems: Synergies Between Regions, Reactors, and Fuel Cycles," Proceedings of the Global 2005, Takuba, Japan, October 9-13, 2005; Chad Painter, "The Atoms for Peace Reactor," presented at Workshop on the Future of Nuclear Power and Nonproliferation, School of Public Policy, University of Maryland, January 15, 2008.

[78] This assumes a 20-year life, a 0.9 capacity factor, an efficiency of 0.40, and a burn-up of 100 MWd/kg. The total MWd over the 20 year period would then be 2.5*365*0.9*20 = 16425 MWd. At 80 MWd/kg, this implies a heavy-metal inventory of 200 kg/MW installed capacity. A 100 MW reactor would then have a heavy metal inventory of about 20 tons. If the TRU content is 20%, the TRU loading would be about 4 tons.

[79] As noted, we assume a loading of about 20 tons of 20% uranium for a 100 MW reactor (containing 4 tons of TRU). We also assume that the battery will be a near breeder, producing as much TRU as it consumes – so that at the international center, the fuel for each successive core can be derived from the spent fuel of the

Overall, the economics of the battery will depend on several factors, including the cost of the reactor itself, the cost of the initial fueling, and the costs of the refueling at the fuel-cycle centers. With respect to the first, there will be a tradeoff in economic savings due to serial production possible with the large-scale production of the batteries compared to the economic losses in going to a smaller scale. In this regard, the tradeoff in favor of the battery might be less than would otherwise be expected if the industrialized countries for the most part built large reactors, say LWRs, so that the learning attendant on development and mass production of a new reactor type would be limited. Analysts at the Lawrence Livermore Laboratory have done a preliminary economic analysis of the battery, which shows that without account of various improvements including those associated with serial production, the capital costs of the battery would 3 c/kwh higher than a reference lead-cooled reactor, which had previously been studied. With improvements, which the authors believe possible, this gap could be lowered in a way to make the battery competitive with other nuclear technologies. It appears too soon to make any definitive judgment on the economic feasibility of the battery.

In a steady state of 500 GWe installed, the annual production of nuclear batteries of 100 MW and 20-year life would be about 230 batteries per year. If the batteries produced as much fissile material as burned, then no new production of fissile material would be required.

This would not be the case, of course, during the period of growth of the batteries. During this period, the reactors would have to be initially fueled by enriched uranium or plutonium derived either from LWR spent fuel or fast reactor spent fuel. If from LWRs, the cost of the initial core would be very high; and so the battery scheme might require instead breeder reactors at the hub to produce the plutonium fuel for the new batteries. If

---

old core. The costs then will depend on the source of the initial loading and the costs of reprocessing and fabrication of fuel elements at the centers.

At an enrichment cost of $100/SWU, a uranium cost of $50/kg, 1 kg of 20% uranium will be about $6000, or $1200/KW. Taken as a capital cost, this would add about 2.3 cents per kilowatt-hour to the cost of electricity – possibly a tolerable amount even without considering the value of the spent fuel after 20 years.

If the initial loading were plutonium derived from LWR spent fuel, the costs would be far greater. To provide the TRU for a battery (~18% TRU in one kilogram of fuel), about 24 tons of LWR spent fuel will have to be reprocessed. If one takes a reprocessing cost of $1000 per kilogram of heavy metal, the contribution of reprocessing to the cost per kilogram would be about $24,000. To this must be added the cost of fabrication. For mixed oxide fuel for LWRs, this cost is about $1500/kg. Here the TRU composition would be 4 or so times greater than for MOX – but let's assume that the fabrication costs would not be much increased. The total cost of the TRU fuel then would be approximately $25,500 per kilogram. As before, the loading would be about 1/5 kg per kilowatt-electric; and the cost per kilowatt-electric would then be $5000/KWe.

However, this does not attribute any value to the spent fuel. If we assume that the battery is a near breeder, the TRU for the makeup core could be obtained from the spent fuel of the old core. Reprocessing costs would be much lower than for the initial fuel loading because the TRU content of the spent fuel would be much greater than for LWR spent fuel – by a factor of 20 or so. If we take reprocessing cost to be $2000-3000/kg HM and fabrication costs to be $1500-3000/kg, the costs for the replacement core could be comparable to that of a 20% U core – on the order of $6000 per kilogram or less.

enriched uranium is used, the cumulative global requirements could be very high. The annual requirements once equilibrium is achieved, however, would be zero if all the replacement fuel was plutonium and TRU recovered from the spent battery fuel.

To get some initial feeling for the flows of materials implied, we make some arbitrary assumptions. For North America and Europe, we assume that 90% of the reactors deployed will be LWRs and 10% batteries. For the South American, Oceanic, and Asian hubs, we assume a 50-50 split between LWRs and batteries. And for Africa, we assume a 20-80 split between LWRs and batteries. We assume that the initial loads of all the batteries will be 20% uranium, and that all replacement cores will be fueled either by the plutonium and TRU in the spent fuel or enriched uranium. Figure A.4 gives some of the implications of these assumptions. Under these assumptions, separative work requirements compared to an all LWR future would be higher for a long period. The total SWU capacity needed for the initial cores of the batteries is about 4.2 million ton SWU – and spread over say 20 years this would be approximately 200,000 tons SWU per year. Added to the 155,000 tons of SWU for the LWRs gives a total of 350,000 tons SWU, which is about 50% higher than for an all LWR world.[80] The example illustrated in the map also shows that even if batteries played dominant roles in several regions of the world, and even if their total number were significant (more than 4,600 operational nuclear batteries and 230 batteries replaced annually), the major fraction of nuclear power generation would still be provided by other reactor technologies because electricity demand is likely to be dominated by a few industrialized countries or regions. It is unclear, therefore, how significant the net nonproliferation benefits of the concept could be.

[80] The core of a 100 MW battery with 20-year life would require 20 tons of heavy metal containing 4 tons of U-235. At 0.2 tails, this would demand 900 tons SWU separative work.

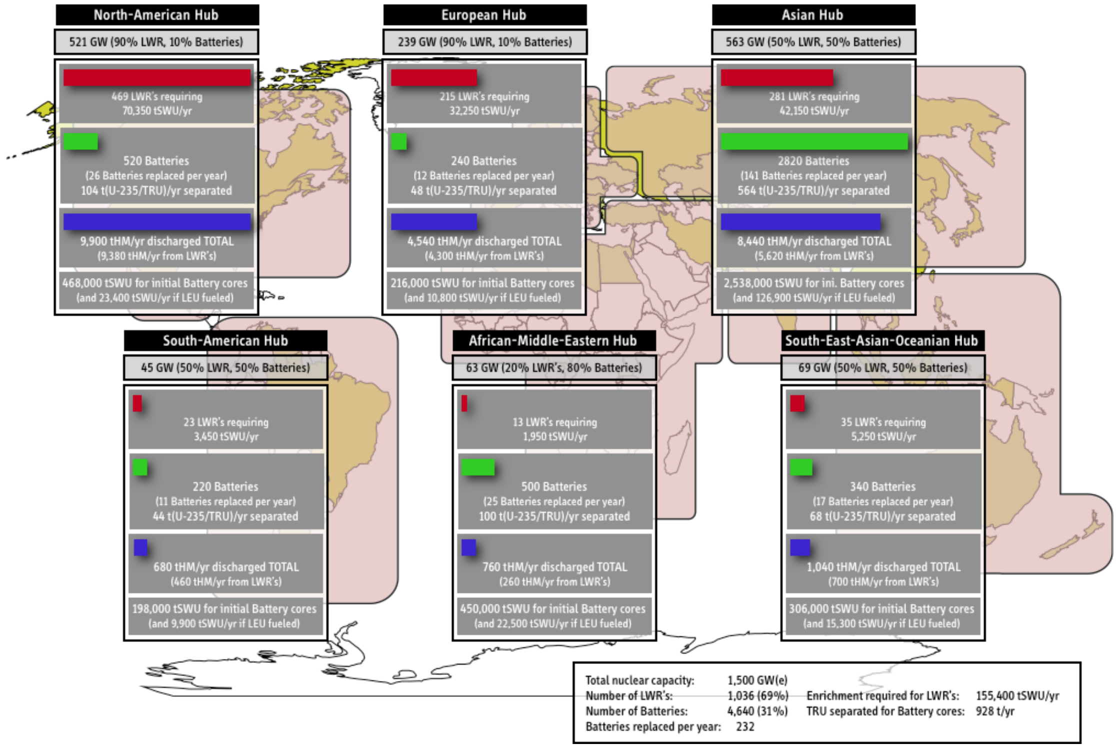

Figure A.4. The Hub-Spoke, Nuclear Battery Fuel Cycle.

It is possible to assume alternatively that breeders will be used to fuel the batteries during their build-up. In this case, the fractions of nuclear capacity in breeders and in batteries will depend upon the rate of growth of the nuclear system and the breeding ratio of the fast reactors. In a study done at Argonne, David Wade, using some plausible assumptions showed that the division during the buildup of the batteries could be roughly 50-50.[81] We do not explore this alternative more in this draft.

Nonproliferation Aspects

The battery reactor concept has proliferation-resistance credentials. These may be summarized as follows:[82] first, appropriation by a sub-national group of the reactor, though it is transportable, would be a daunting challenge. The 180 MW battery is roughly 20 meters long, with a 3-meter diameter and, including the transport cask, weighs during transport approximately 400 tons. We assume that a 100 MW version would have similar dimensions. The fuel, which could be either 20-percent enriched uranium or a uranium-plutonium fuel having 18 percent plutonium, is embedded in a mass of lead-bismuth (solid during transport, liquid during operation) throughout the core life. It would further

[81] D.C. Wade, "The STAR Concept …," *op. cit.*

[82] James J. Sienicki and David C. Wade, "Nonproliferation Features of the Small, Secure, Transportable Autonomous Reactor (SSTAR) for Worldwide Sustainable Nuclear Energy Supply," *op. cit.*; Dave Wade, "Overview of Advanced Nuclear Development Activities on Small Reactors of Long Refueling Interval Supported by Centralized Fuel Cycle Infrastructure," *op. cit.*

be possible to include fission products in the fuel or “seed” the reactor with gamma-emitting cesium-137 before shipment, thus surrounding even the fresh fuel in a radiation shield. The reactor does not give a country a useful source of neutrons: it is not possible to insert fertile material for irradiation. As noted, the core life of the reactor would be 20 years and during this period there would be no refueling. If operated on the hub-spoke concept, the client country would need no fuel fabrication facility and no fuel management capability. Because the reactor operates “almost autonomously,” the client country would need few operators of the nuclear system. Overall, the hub-spoke concept could diminish the rationale and opportunities for a country to develop research facilities and trained cadres of scientists and technicians that could later be diverted to weapons activities.

Presumably, the client country would be able to break into the sealed reactor – but it should be possible to ensure that such an attempt to obtain nuclear fuel could be detected. Moreover, the acquisition of the fuel after a break-in would probably take some time (days to weeks).

Opposed to these advantages, there are some matters of concern. One, the spent fuel of the reactor (using a nominal 100 MW capacity) will contain roughly 4000 kilograms of plutonium and TRU. Also, if the fuel is removed from the reactor before its full lifetime, the plutonium could be weapon grade or close to that. The uranium fuel, if obtained by a would-be proliferant, would not be weapons usable, but would require less separative work for production of weapons grade uranium than ordinary light water uranium fuel.

These problems notwithstanding, a nuclear system based on international energy parks, if it could be developed, does present an arguably proliferation-resistant strategy for nuclear power in the long run. At the least, it could allow an expansion of nuclear power to many countries that might not have the means or inclination to mount their own domestic nuclear industry. But, as we have stressed above, this should not mean that in a future nuclear world, the battery would be the *only* nuclear technology permitted to certain countries.

But are international energy parks realistic alternatives on political and economic grounds? International energy parks run against the strong wish of many countries to become energy independent. Also, they will require that client countries either accept discriminatory restrictions on their nuclear activities not accepted by the countries hosting the nuclear parks, or that all countries, including the industrialized countries, accept a high degree of international control over their nuclear energy programs. Beyond these considerations, countries will also be wary of concentrating too much of their energy future in a few places, with their attendant risks of common-mode failures, disruption of transmission lines or shipping, etc.

Appendix B – An Overview Assessment of Regional and International Arrangement for the Nuclear Fuel Cycle (L. Scheinman)

Since the beginning of the nuclear age various ideas have been put forward on how to provide an institutional framework for peaceful nuclear activities, most notably power generation, which would minimize the risk that acquired nuclear knowledge, technology and assets would be misused to make nuclear weapons. The 1946 Acheson-Lilienthal report on international control of atomic energy concluded that as the ability to produce special nuclear material was a critical step toward weapons, "a system of inspection super-imposed on an otherwise uncontrolled exploitation of atomic energy by national governments would not be an adequate safeguard" and could not therefore assure effective separation of civil and military uses of nuclear technology. The solution recommended, and subsequently incorporated in the US-sponsored Baruch Plan at the United Nations, was to establish an international agency with managerial control or ownership of all atomic energy activities potentially dangerous to world security and authority to control, inspect, and license all other atomic energy activities. Under any circumstances this was a far-reaching proposal for an international order based on the principle of sovereign states. Whatever chance there might have been that it might be accepted was foreclosed by the Cold War tensions that dominated postwar relations.

Well before the Baruch Plan was finally abandoned, the United States, in the Atomic Energy Act of 1946, established a policy of secrecy and denial, prohibiting any peaceful nuclear cooperation until Congress was satisfied that effective international safeguards were in place. The limitations of this approach, demonstrated by the entry of the Soviet Union and the United Kingdom into the "nuclear club," concern about security implications of a nuclear arms race, and the emergence of national nuclear programs in an increasing number of countries, led to a shift to a policy of nuclear cooperation and assistance spelled out in President Eisenhower's Atoms for Peace speech at the United Nations in December 1953. This second effort to establish an institutional framework for nuclear energy was based on the concept of regulated transfers/safeguards – initially applied bilaterally by suppliers, but ultimately by an international organization, the International Atomic Energy Agency that was envisioned in the Atoms for Peace plan as an international focal point for promoting civil nuclear cooperation as well as for verifying peaceful use through a system of safeguards. Although judged by the Acheson-Lilienthal report to be inadequate to the task of preventing nuclear proliferation, an international safeguards system was deemed to be the most that the traffic would bear with respect to the degree of infringement of national sovereignty most states likely would accept for the transfer of nuclear equipment, material and technology. Little has changed in this regard over the past fifty years – sovereign sensitivities and aversion to discrimination are still key factors when states consider the acceptability of limitations on their activities and restraints that are selective rather than universal.

Conclusion of the Treaty on the Nonproliferation of Nuclear Weapons (NPT) in 1968 brought with it the requirement that all non-nuclear weapon states party to the treaty conclude a comprehensive safeguards agreement with the IAEA, making that institution and its safeguards system a centerpiece of the nonproliferation regime. In those states, safeguards apply on all peaceful nuclear activities and materials for the purpose of verifying that material has not been diverted to nuclear weapons or other nuclear-explosive devices. Safeguarded states were obligated to declare <u>all</u> nuclear material and the Agency had the right to ensure that this was the case. In practice however the focus was on material accountancy and verification of the <u>correctness</u> of state declarations rather than on whether the declaration was complete.

In the aftermath of the 1991 Gulf War and the discovery in Iraq of extensive undeclared activities associated with a clandestine nuclear weapons program, which underscored significant safeguards deficiencies, the IAEA took steps to strengthen the safeguards system initially by implementing measures for which it already had statutory authority (e.g. environmental sampling, no-notice inspections), and subsequently by seeking additional authority in the form of an Additional Protocol to comprehensive safeguards agreements that was approved by the Board of Governors in 1997. The objective is to be able to draw a credible conclusion that "<u>all nuclear material in the state had been declared and placed under safeguards</u> and that it remained in peaceful nuclear activity or was otherwise adequately accounted for." The core elements of the Additional Protocol are increased access to information through an expanded state declaration among other things of all fuel cycle related research and development activities whether or not nuclear material was present; the location of nuclear fuel cycle related research and development not involving nuclear material, as well as fuel cycle development plans for the ensuing ten year period; the location and operational status of uranium mines and concentration facilities; and complementary physical access to ensure credible assurance of the correctness and completeness of information provided and of the absence of undeclared nuclear material and activities.

Strengthened safeguards are a work in progress involving current and future challenges. Even today, years after they joined the NPT, more than 30 states with limited or virtually no significant nuclear activity have yet to sign a comprehensive safeguards agreement despite the fact that they are obligated to do so within 18 months of adhering to the Treaty, and despite the availability to them of a small quantities protocol (SQP) that holds in abeyance most operational provisions in standard safeguards agreements. A second limitation arises from the fact that unlike comprehensive safeguards agreements that are required by the NPT, the Additional Protocol is voluntary, not obligatory. At present, ten years after the IAEA Board of Governors approved it, more than 70 states, including a number with significant nuclear activities, have yet to sign and implement a Protocol agreement. Given the importance of universality to the normative impact of agreements, and the current political, security and energy environment in which we live, (discussed below) the salience of these two deficiencies are all the more relevant and challenging.

Safeguards can be further strengthened based on existing legal obligations (e.g. implementing IAEA Statute Article XII.A.6 providing for inspector access "at all times to all places and data and to any person who…deals with materials, equipment, or facilities which are required…to be safeguarded…"), by striving to achieve agreement on new obligations (e.g. making the Additional Protocol a condition for nuclear cooperation), and by voluntary measures. Nevertheless, it bears emphasis that even a strengthened system is not a panacea for preventing the misuse of nuclear technology provided and declared for civil use only. While safeguards are essential to the acceptability of widespread use of nuclear energy for civil purposes, and can be very effective if fully supported by the international community, they are not necessarily alone a sufficient means to prevent proliferation. The basic fact remains, as pointed out by a former chairman of the Israeli Atomic Energy Commission, David Bergmann, "…by developing atomic energy for peaceful uses, you reach the nuclear weapon option. There are not two atomic energies." In other words, whether a state would cross that line or not is a matter of motivation, incentive, and political decision – all considerations that largely derive from factors beyond technical capacity, although dependent on it. It is that consideration that provides added justification for exploring institutional/structural options for the nuclear fuel cycle in addition to international safeguards.

Indeed, although safeguards were the predominant institutional means by which to avert proliferation while facilitating peaceful use of nuclear energy they were not the only one. India's 1974 "peaceful nuclear explosion" using assistance provided for exclusively peaceful purposes prompted renewed attention to institutional arrangements that would limit access to technologies that could lead to the acquisition of weapons-usable material, in particular plutonium. This took several forms, among them establishment of a Nuclear Suppliers Group (NSG), and initiatives including an IAEA-led study on Regional Fuel Cycle Centers (RFCC), a US initiated International Nuclear Fuel Cycle Evaluation (INFCE) and efforts to put in place an International Plutonium Storage arrangement (IPS). It is useful to bear in mind that with the exception of the NSG none of the other initiatives took root.

NSG Following a US initiative, the key nuclear suppliers in the mid-1970s agreed on a code of conduct for international nuclear transactions including a nonproliferation commitment by recipients, acceptance of international safeguards on designated transfers of materials, equipment and technology, retransfer restraints and provisions for physical security for transferred materials and equipment. Although the suppliers group could not reach agreement on foreclosing any further transfers of sensitive nuclear technologies, they did agree to exercise restraint in considering export of enrichment, reprocessing and heavy water production technology and equipment and to encourage multilateral/regional arrangements for any such activities. Restraint has in fact been the de facto practice of the members – cooperation in these technologies has been limited to states that already had the technology in hand. In 1992, a significantly enlarged suppliers group agreed that comprehensive safeguards would be required for any further transactions. These guide-lines govern the export policies and practices of 45 member states today. Resented by some as a supplier cartel, the NSG is on the whole seen as an important contribution to nonproliferation and as facilitating rather than impeding legitimate international civil nuclear cooperation.

RFCC Insofar as institutional arrangements for the fuel cycle itself were concerned, the search in the 1970s was for less revolutionary ideas than those incorporated in the Baruch

Plan. A 1975 IAEA initiative initially endorsed by the Secretary of State Kissinger before the UN General Assembly focused on the prospect of developing one or more regional nuclear fuel cycle centers (RFCC) primarily with reprocessing activity in mind. The study concluded that in economic, environmental and nonproliferation terms such an approach had a significant advantage over national alternatives although risks such as takeover by the host country and technology transfer could not be discounted. This concept fell by the wayside in the wake of a slowdown in the growth of nuclear energy, a drop in uranium prices (making plutonium recovery less attractive), and the emergence of US resistance to reprocessing and the use of plutonium in power reactors in the Carter Administration.

The US Congress also endorsed the notion of regional multinational centers for dealing with enrichment and reprocessing activity. An amendment to the Foreign Assistance Act of 1976 went so far as to provide for a cutoff of economic and military assistance to any country that imported or exported reprocessing or enrichment materials <u>unless it agreed to place all such items under multilateral auspices and managemen</u>t when available along with acceptance by the recipient of comprehensive IAEA safeguards. The 1978 Nuclear Nonproliferation Act included a provision urging pursuit of an international nuclear fuel authority (INFA) one element of which would be creation of an institution that would control a stockpile of fuel to be available to non-nuclear weapon states under comprehensive safeguards that did not establish national enrichment or reprocessing facilities, and placed any such existing facilities under international auspices.

INFCE was inspired by the Indian nuclear test coupled with expectations of rapid growth in nuclear power and a concern regarding dissemination of sensitive nuclear technologies, especially reprocessing. Technical measures, strengthened safeguards and institutional options to minimize proliferation risk including having facilities under multinational auspices or in the framework of regional fuel cycle centers along with assurance of nuclear supply for civil purposes, including the concept of an international nuclear fuel bank all fell within the purview of the two year exercise. Among its conclusions were that there were no technical silver bullets to prevent abuse of civil nuclear power, which though not an efficient route to nuclear weapons, could not be discounted. Institutional arrangements were deemed to have greater potential than purely technical approaches but the best prospect for avoiding proliferation lay in a combination of technical, safeguards, and other institutional measures.

IPS The conceptual basis for International Plutonium Storage (IPS) is inscribed in Article XII.A.5 of the IAEA statute which specifies circumstances in which the Agency can require that excess special fissionable materials from peaceful use be deposited with the Agency in order to prevent stockpiling of such materials and to be returned for peaceful use under safeguards. Study was undertaken in 1976 and concluded in 1982. Several possible models were identified and discussed but agreement could not be reached on any of them. The key points of difference related to how to define excess material and what conditions should apply for their release.

Taking stock of the nuclear nonproliferation regime, IAEA Director General El Baradei, recently commented that "In regard to nuclear proliferation and arms control, the fundamental problem is clear: either we begin finding creative, outside-the-box solutions or the international nuclear safeguards regime will become obsolete."[83] This judgment reflects the significant changes that have taken place in the past decade and their implications for the adequacy of the current regime to meet the challenges posed by those changes. At least five developments can be identified that collectively characterize the current nuclear environment and confirm the need for resourceful and pragmatic initiatives to address the challenge of reconciling the development of nuclear energy for peaceful purposes with preventing states using their nuclear capacity to acquire nuclear weapons.

First, the once predominating Cold War and the discipline it imposed on state behavior has been displaced by regional political-security agendas. For some states, whose sense of security is more tenuous the prospect of being in a position to develop a nuclear deterrent, if necessary, may be greater. For others, aspirations to regional predominance and/or international standing may motivate a similar interest. In either event, regional and international stability stand to suffer if those incentives translate into concrete actions.

Second, over time sources of supply of sensitive nuclear technologies or their components, particularly dual-use items, have multiplied and expanded to more states, and beyond states to illicit, black market transfers as underscored by the revelations of the prolific activities of A.Q. Khan. Even among states, not all adhere to the nuclear supplier guidelines or exercise sufficient controls on the transfer of sensitive technologies or dual-use items by companies or industries under their jurisdiction.

Third, is the experience of states party to the NPT either conducting clandestine weapons relevant activities (Iraq, North Korea, Libya earlier) or more ominously using their NPT status to openly and legally accrue fuel cycle capabilities that could put them in a position to rapidly transition to nuclear weapon status should they decide at some point in time to invoke the NPT withdrawal clause. That facilities and activities be declared and under international safeguards is critically important, but that speaks only to capabilities and not to motivations and intention.

Fourth is the fact that national security and international stability is now threatened not only by the risk of state proliferation, but as well by the potential of organized trans-national terrorist organizations obtaining access to nuclear weapons or weapons-usable material. The experience of 9/11 looms large in this regard. The larger the number of potential sources of such materials the greater the risk to the social order.

Fifth is the prospect of a surge in nuclear power development and with it the potential for more states to eventually seek full fuel cycle capacity. Environmental concerns, in particular global warming, has rekindled interest in harnessing nuclear energy in ways

[83] L. Scheinman, "Rethinking Nuclear Safeguards," *Washingtonpost.com,* June 14, 2006

and at levels not heretofore considered likely. The speed and degree to which the prospect of a nuclear renaissance will take place is uncertain, but to the extent that it materializes it will bring with it increased demand for nuclear fuel and increased interest in states considering developing fuel cycle activities along with power reactors either in pursuit of reduced energy dependence and increased self-sufficiency, or to emulate and join advanced industrial states in having a full array of nuclear technologies either to support domestic consumption or to compete in international markets, or for more explicit political reasons, i.e., to be counted among the advanced societies of the world and to enjoy and capitalize on the political prestige that such status brings. And, as indicated in the first point above, there is the possible interest of states in acquiring the ability to produce nuclear weapons in the event that national security or international status dictates that course of action. Of particular concern here, unlike the 1970s, is the front end of the fuel cycle where safeguards is deemed to be more challenging than in the case of spent fuel reprocessing.

This brings us back to the issue of reconciling a prospective surge in nuclear expansion, potentially involving full fuel cycle development, with ensuring that the non-proliferation regime has the means by which to exercise effective control over proliferation-sensitive technologies, and to the "outside the box" thinking referred to by Director General El Baradei. As indicated earlier, international safeguards have been quite effective in deterring diversion of declared nuclear material but face a challenge in detecting undeclared nuclear activities, in particular enrichment facilities based on centrifuge technology. Even in the case of declared facilities that are under safeguards there is the latent risk of a state withdrawing from the NPT and retaining control over facilities capable of producing weapons-usable material – a prospect already experienced in the case of North Korea's withdrawal from the NPT with all of its facilities intact, outside safeguards, and under its national control.

A spate of initiatives has been put forward to address the array of concerns outlined above – at least nine according to one report.[84] These include, among others, proposals by the United States (GNEP), Russia (GNPI), the UK (enrichment bonds), a Six Country proposal on reliable access to nuclear fuel (RANF), and an IAEA multilateral alternatives to national nuclear fuel cycles proposal. Virtually all seek to limit the further spread of enrichment and reprocessing technology and include provisions for assurance of nuclear fuel supply for civil power reactors. Among the most prominent are the United States proposal for a Global Nuclear Energy Partnership and IAEA Director-General El Baradei's promotion of the idea of placing enrichment and reprocessing facilities under some form of multinational control.

In a speech at the National Defense University in February 2004 President Bush proposed that Nuclear Supplier Group members agree not to transfer sensitive nuclear technology to any country that did not already have a fully operational enrichment or reprocessing capability and to ensure those who forgo national enrichment and reprocessing a reliable supply of nuclear fuel for civil purposes. GNEP, a much broader

[84] Chaim Braun, "Technical Review of Fuel Assurance Proposals," IAEA Special Event, September 2006.

enterprise, with more emphasis on opportunity than on constraint and denial strives to do the same thing: it entails expansion of domestic and international use of nuclear energy, pursuit of proliferation-resistant recycling of spent fuel, development of advanced reactors, and the establishment of reliable global fuel services by a consortium of suppliers for states that forgo national development of sensitive fuel cycle activities. It goes further in calling for supplier responsibility for dealing with spent fuel—a cradle to grave concept of supply assurance. Without explicitly challenging the right of NPT parties to pursue fuel cycle development for peaceful purposes in conformity with the purposes of the NPT, GNEP effectively seeks to finesse the incentive to do so by offering a better alternative that would be more cost effective and reliable than indigenous development for states undertaking to forego domestic enrichment and reprocessing in exchange for reliable supply of nuclear fuel. States accepting that offer would qualify for nuclear fuel assurance.

Director-General El Baradei has taken a more ecumenical and inclusive approach to the problem. He starts from the premise that under the NPT sensitive nuclear technology development and use for civil purposes is not proscribed, and having that capability is not inconsistent with the NPT. Nevertheless, in pursuing the capacity to do so for peaceful purposes a state also acquires the ability to produce sensitive nuclear material for military use – an echo of the Bergmann dictum noted earlier. To this end he has endorsed pursuing strategies that, while dependent upon international safeguards, reach beyond them, the objective being to achieve better control over sensitive nuclear fuel cycle activity, and to do so by institutional means through some form of multinational control that would not only be effective, but also equitable.

In pursuit of that objective El Baradei appointed an international committee of experts to examine ways and means to manage the fuel cycle with particular attention to how to bring about multilateral oversight for sensitive activities including assurance of nuclear supply, and options for dealing with spent fuel storage. The outcome of that study was the identification of a layered approach beginning with strengthening of existing commercial market mechanisms through long term contracts and transparent supplier arrangements with government backing; developing international supply guarantees with IAEA participation, with particular attention to involving the IAEA as a guarantor or manager of a nuclear fuel bank; promoting voluntary conversion of existing facilities to multilateral enterprises; establishing through voluntary agreements new regional or multinational facilities involving joint ownership potentially including co-management; and in the longer run, assuming significant expansion of nuclear energy, development of a nuclear fuel cycle with stronger multilateral arrangements, possibly by region, but also involving the IAEA.

A fundamental difference between the two approaches sketched above is that between pursuing a restrictive or a cooperative strategy, the former entailing non-nuclear weapon state acceptance of denial of technology related to sensitive nuclear fuel cycle activity, the latter focusing on institutional alternatives to strictly national operation of such activities as enrichment or reprocessing, both reinforced by a reliable assurance of supply mechanism. A restrictive approach raises a basic issue regarding the provisions in

Article IV of the NPT concerning the "inalienable right of non-nuclear weapon state parties to develop nuclear energy for peaceful purposes," and the obligation of the all state parties to facilitate and cooperate in "the fullest possible exchange of equipment, materials, and scientific and technological information for the peaceful uses of nuclear energy."

This is a nuclear third-rail issue for many. During the course of the deliberations of the expert group the point was made on more than one occasion, and by many of the participants, that any attempt to redefine the conditions for peaceful use must take into account that any arrangement that is not seen to be fair and universal could put the nonproliferation regime at risk of unraveling, and that limits on the right to technological development cannot be selective, applying to one class of states and not to another, and to be acceptable will have to be applied universally, with no exceptions.

In the end, it gets down to equity, fairness, and non-discrimination and that gets us to the division of the world into classes of states – a few with, and most without nuclear weapons that is further complicated by de facto differences in the latter group between advanced industrial states and developing nations. If skepticism about the political acceptability of discrimination with regard to the fuel cycle is evident in the context of developing nuclear energy for peaceful purposes, it is further complicated by another issue, that of nuclear disarmament. As amply reflected in the discussions and debates in the NPT review conferences and in other venues as well the implementation of Article VI on nuclear disarmament is a major issue, particularly for many of the non-aligned states who also have found efforts to achieve a legally binding negative security assurance from the NPT weapon states impossible outside the framework of a nuclear weapon free zone. For many it is a diversion to contend that the solution to nonproliferation rests in limiting technological rights for states that are in compliance with their treaty undertakings while at the same time avoiding coming to grips head-on with nuclear disarmament and its relationship to a system of genuine collective security.

The NPT is widely regarded as a bargain in which non-nuclear weapon state parties would commit not to acquire nuclear weapons and weapon states would commit to negotiate in good faith toward nuclear disarmament. In this regard it is of interest to recall the 1996 Advisory Opinion of the International Court of Justice that the obligation to negotiate in good faith also means the obligation to conclude that negotiation. The prospect that non-nuclear weapon states will willingly forgo a right that is inherent in Article IV while nuclear weapon states continue to retain, and in some cases enhance their arsenals with weapons seen to be developed for use rather than deterrence, is remote. The only way in which progress in that regard can be achieved is through some kind of multi-lateralization of the fuel cycle as called for by DG El Baradei – an arrangement that somehow levels the playing field with respect to tightening controls over the nuclear fuel cycle, but does so in a way that is non-discriminatory, placing the same obligations and constraints on all parties while assuring all of equitable and timely access to required nuclear fuel for a civil nuclear program. All parties means all states including the nuclear weapon states. If the objective is to have states give up a right in a treaty, the result should not be further distinction between classes of states and discrimination, but rather the opposite. Conclusion of a fissile material cut-off treaty (FMCT) would be a significant step in the direction of reducing discrimination with respect to the fuel cycle, capturing not only the five states acknowledged as nuclear weapons states under the NPT, but India, Israel and Pakistan as well.

This brief review of past efforts to structure the nuclear fuel cycle in such a way as to facilitate widespread access to nuclear energy without incurring proliferation risks underscores the difficulties and challenges inherent in such an effort. Agreement on the NPT was achieved only after the question of equities and non-discrimination were addressed and resolved in the form of assurances regarding full access to the benefits of the peaceful use of nuclear energy (A. IV) and progress toward, and eventual achievement of, nuclear disarmament (A. VI). Those were the priority concerns of non-nuclear weapon states at the time the treaty was negotiated, and they remain so today. It was a member of the UN who chose not to sign the NPT, India, who asserted in the course of the negotiation of the treaty that one thing the non-nuclear states would not tolerate was atomic apartheid in the peaceful use of atomic energy. It is not, then, surprising that current efforts to rein in access to the means to produce special fissionable material, keeping that capacity in the hands of the few while curtailing access to the many, would present a significant political challenge. At the same time it is more than difficult to deny the risks associated with widespread access to the means to produce material that could be diverted from intended peaceful use to weapons of war. Innovative institutions built on the foundation of equity, fairness and mutual acceptance offers a more promising way forward than most readily available alternatives. We are not today any closer to the point where an Acheson-Lilienthal initiative for international ownership and control of the fuel cycle than we were 60 years ago. But with the proliferation of nuclear know-how, technology, material and equipment and a world rife with tensions and instabilities that go beyond the nation-state to include sub-state transnational terrorism, there is no option but to persevere in pursuing means by which to keep the nuclear risk under control.