Managing the Civilian Nuclear Fuel Cycle

Chapter 7 from the forthcoming

Global Fissile Material Report 2007

Second report of the International Panel on Fissile Materials

www.fissilematerials.org
Managing the Civilian Nuclear Fuel Cycle

Over the past twenty years, there has been little construction of new nuclear-power plants, with the exception of in Asia, where there has been some limited building. There is now, however, an active debate about the possibility of a dramatic nuclear “renaissance,” driven in part by concerns over climate change. This chapter examines the potential implications of an expansion in nuclear power for fissile-material controls. The main concerns relate to the proliferation of national enrichment and reprocessing capabilities, which give states the capability to produce fissile materials for weapons. Overall, we emphasize that:

- Nuclear power worldwide would have to expand five-fold or more to make a significant contribution to greenhouse-gas reductions. Such an expansion is far from certain, however, and even industry optimists do not see it being achieved before 2050.

- Even if nuclear power expands substantially, there is no economic rationale for reprocessing, for the recycling of plutonium in light water reactors (LWRs), or for the adoption of closed fuel cycles of any type. Furthermore, there are compelling security reasons to avoid reprocessing and recycling.

- Concern that some countries could use gas-centrifuge uranium-enrichment plants to make material for nuclear weapons has led to calls for dividing the world permanently into fuel-supplier states—basically, the NPT weapon states plus Europe and Japan—and fuel-recipient states. Such a division is in all likelihood unworkable. Using multinational ownership to protect against proliferation may be politically more feasible and is already happening to some degree.

Nuclear Power Today

At the end of July 2007, 438 nuclear-power plants, with a generating capacity of 371 gigawatts-electric (GWe) were in operation in 31 countries (see Table 7.1). These units provide about 16 percent of electrical energy worldwide. Eight countries accounted for 80 percent of global nuclear capacity: the United States, France, Japan, Germany, Russia, South Korea, Ukraine, and Canada.
Table 7.1. Operating reactors and nuclear capacities by country, 2007.

<table>
<thead>
<tr>
<th>Country</th>
<th>No. of Units</th>
<th>Total GW(e)</th>
<th>Country</th>
<th>No. of Units</th>
<th>Total GW(e)</th>
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<tbody>
<tr>
<td>Argentina</td>
<td>2</td>
<td>0.9</td>
<td>Mexico</td>
<td>2</td>
<td>1.4</td>
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<tr>
<td>Armenia</td>
<td>1</td>
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<td>Netherlands</td>
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<td>Belgium</td>
<td>7</td>
<td>5.8</td>
<td>Pakistan</td>
<td>2</td>
<td>0.4</td>
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<tr>
<td>Brazil</td>
<td>2</td>
<td>1.8</td>
<td>Romania</td>
<td>1</td>
<td>0.7</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>2</td>
<td>1.9</td>
<td>Russian Federation</td>
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<td>Canada</td>
<td>18</td>
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<td>Czech Republic</td>
<td>6</td>
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<td>South Africa</td>
<td>2</td>
<td>1.8</td>
</tr>
<tr>
<td>Finland</td>
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<td>2.7</td>
<td>Spain</td>
<td>8</td>
<td>7.5</td>
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<tr>
<td>France</td>
<td>59</td>
<td>63.3</td>
<td>Sweden</td>
<td>10</td>
<td>9.0</td>
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<td>20.3</td>
<td>Switzerland</td>
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<td>3.2</td>
</tr>
<tr>
<td>Hungary</td>
<td>4</td>
<td>1.8</td>
<td>Taiwan, China</td>
<td>6</td>
<td>4.9</td>
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<tr>
<td>India</td>
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<td>Ukraine</td>
<td>15</td>
<td>13.1</td>
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<tr>
<td>Japan</td>
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<td>Korea, Republic of</td>
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<td>United States</td>
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<td>100.3</td>
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<tr>
<td>Lithuania, Republic of</td>
<td>1</td>
<td>1.2</td>
<td>Total</td>
<td>438</td>
<td>371.0</td>
</tr>
</tbody>
</table>

Nuclear Capacity Growth Projections

Short-term projections to 2030. Out to 2030, projections can to some extent be based on actual plans. Such projections vary somewhat, but tend to fall into the range of 400–600 GWe installed nuclear capacity in 2030. Table 7.2 shows two scenarios offered by the OECD’s International Energy Agency (IEA), which projects worldwide capacity at 416 or 519 GWe in 2030, depending on policies. Light-water reactors account for about 88 percent of the world’s nuclear capacity, and an even greater fraction of current plant construction.

The lower projection is for the International Energy Agency’s reference scenario, which assumes that current government policies remain broadly unchanged. The higher projection represents what the agency judges could be achieved if government policies promoted nuclear power as part of the solution to climate change. The International Atomic Energy Agency (IAEA), envisioning greater potential for expansion, projects a global nuclear capacity ranging from 414 to 679 GWe in 2030. The U.S. Energy Information Administration estimates 438 GWe, near the lower end of the IEA and IAEA ranges. The uranium-fuel trading company NUKEM projects a capacity of 535 GWe in 2030.

Projections to 2050 and Beyond. For those advocating or expecting a serious nuclear renaissance, the period after 2030 is of greatest interest. The 2003 MIT interdisciplinary study on the future of nuclear power presented one high scenario, in which nuclear power capacity reaches 1500 GWe in 2050 (see Figure 7.1).
<table>
<thead>
<tr>
<th>Region</th>
<th>Nuclear Capacity [GW]</th>
<th>Share of nuclear in electricity generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>OECD</td>
<td>308</td>
<td>296</td>
</tr>
<tr>
<td>OECD North America</td>
<td>112</td>
<td>128</td>
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<tr>
<td>OECD Europe</td>
<td>131</td>
<td>74</td>
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<tr>
<td>OECD Pacific</td>
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<tr>
<td>Transition economies</td>
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<td>54</td>
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<tr>
<td>Developing countries</td>
<td>19</td>
<td>66</td>
</tr>
<tr>
<td>China</td>
<td>6</td>
<td>31</td>
</tr>
<tr>
<td>India</td>
<td>3</td>
<td>19</td>
</tr>
<tr>
<td>Other Asia</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Latin America</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Middle East and Africa</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>World</td>
<td>368</td>
<td>416</td>
</tr>
</tbody>
</table>

Table 7.2. International Energy Agency (IEA) nuclear capacity projections for 2030.

The MIT study estimated the distribution of this nuclear capacity by dividing the countries of the world into different groups based on their level of economic development. For the developed countries and Russia, the study then assumed that nuclear power would provide on average 51 percent of total electric power in 2050. In the large or advanced developing countries that already have nuclear power (including Argentina, Brazil, China, India, Mexico and South Africa) it was assumed to provide 30 percent of total electric energy in 2050.

Among the most populous, less-advanced developing countries, India was assumed to have 175 and Indonesia 39 equivalent GWe of nuclear power capacity in 2050. None of the least developed countries were assumed to have any nuclear power in 2050. How-
ever, several developing countries that have no or negligible nuclear power today—including Algeria, Armenia, Azerbaijan, Belarus, Georgia, Indonesia, Iran, North Korea, Malaysia, Pakistan, the Philippines, Poland, Thailand, Turkey, Turkmenistan, Uzbekistan, Venezuela, and Vietnam—were assumed to acquire nuclear-power plants by 2050. In fact, some of these countries are already expressing an interest in nuclear power.\textsuperscript{315}

**Constraints on Nuclear Growth**
Throughout most of the nuclear era, projections of future nuclear growth have been consistently too optimistic. Figure 7.2 shows the history of IAEA nuclear-power projections for OECD countries.

![Figure 7.2. IAEA forecasts made in 1973, 1977, 1982, and 2001 for nuclear capacity growth in OECD countries.\textsuperscript{316}](image)

Projections for nuclear-power growth outside of the OECD have been overoptimistic as well. For example, in 1985, the Chinese government projected a nuclear capacity of 20 GWe by the year 2000.\textsuperscript{317} At the end of 2005, China had only 6.4 GWe in operation. Similarly, in 1962, the Indian Atomic Energy Commission projected a capacity of 20–25 GWe in 1987.\textsuperscript{318} As of May 2007, India’s nuclear capacity was only 4.1 GWe.

Many of the factors that constrained nuclear power in the past—high capital costs, slower-than-projected growth in demand for electricity, scarcity of capital in developing countries, and problems with public acceptability—are likely to continue to dampen its growth. We find it unlikely that nuclear capacity will reach even the 1000 GWe of MIT’s low-growth scenario by 2050.

**High capital costs.** Figure 7.3 compares the International Energy Agency’s estimates of the cost of nuclear power with the costs of power generated by gas, coal, and wind. The cost estimates for gas and coal do not include the extra cost of capturing and sequestering carbon dioxide, which may become part of a future climate-change mitigation strategy. For the integrated gasification combined cycle (IGCC) system, carbon-capture costs are estimated to add about 1.5 cents per kWh.\textsuperscript{319}
The “overnight” capital costs assumed for nuclear power in Figure 7.3 (i.e., costs excluding interest charged during construction) were $2000/kWe (in 2006 dollars) for the low case and $2500/kWe for the high case. Nuclear power would be in the same cost range as coal and wind for the $2000/kWe case. The MIT study found, somewhat less optimistically, that nuclear power would be roughly competitive with coal if nuclear power’s overnight costs could be kept to $2000/kWe and countries enacted a substantial tax on carbon dioxide emissions to the atmosphere.

The capital charge for the plant is the most important cost element for nuclear power and is affected by the economic conditions of each country. For developing countries, in which investors require high real interest rates and returns on capital, every additional $500 per kWe capacity in the “overnight” capital costs adds about 1.5 cents per kWh to the cost of electricity. Other costs are less, but can still be significant. Since 9/11, concerns about terrorist attacks have driven up insurance and security costs. The interest charged during construction also adds significantly to costs—especially if there are delays.

A recent estimate for the cost of building the first nuclear unit at a new U.S. site was $2400–3500 per kilowatt (in 2006 dollars). The uncertainties are large because no new plants have been built in the United States in recent decades, and only a few elsewhere. In Asia, the overnight costs for recent plants (in 2002 dollars) ranged from $1800/kWe to $2800/kWe. In Europe, the Olkiluoto-3 reactor now under construction in Finland has an estimated overnight cost of $2500–3000/kWe. Construction of this reactor is already behind schedule by a year and a half.

The U.S. Energy Policy Act of 2005 sought to reduce investor risks for the first six new nuclear power plants built in the United States through two billion dollars of government guarantees and incentives. Nevertheless, Standard and Poor’s, which sets
corporate credit ratings, stated in January 2006 that, “from a credit perspective, [the] provisions may not be substantial enough to sustain credit quality and make [nuclear generation] a practical strategy.”

**Slower-than-projected growth in electricity demand.** The 2006 IAEA nuclear projection of 414–679 GWe in 2030 was based on an assumed growth rate of total global electricity consumption of between 2 and 3 percent per year. This is the range in which consumption grew during the 1990s. However, as analyzed by Goldemberg and Lucon, growth rates in both OECD and non-OECD countries declined between 1971 and 2003 owing to increased efficiency in electricity use and the saturation of electrification. If this second-order trend continues, the lower end of the IAEA’s range for electricity demand in 2030 is more likely to be realized and global electric consumption in 2050 would be roughly two thirds that assumed in the MIT scenarios.

**Lack of capital for nuclear-power investments in developing countries.** Unlike dams and other infrastructure, nuclear power plants are not underwritten by the World Bank or most other international lending organizations. Nuclear energy is also not included in the Kyoto protocol mechanisms, under which the industrialized (Annex 1) states can obtain credits against their own greenhouse-gas emissions for investments that reduce emissions in developing countries. The large investments required for nuclear power would therefore compete in developing-country budgets with investments for health, education, and poverty reduction.

**Public acceptability.** Simply to replace retiring nuclear capacity will require building a large number of new plants in the coming decades. Given continuing public skepticism about nuclear power, this may be challenging. An IAEA-sponsored opinion poll of 18 countries in 2005 found that about two-thirds of those expressing an opinion opposed shutting down nuclear power, but about the same fraction opposed building additional reactors. When asked specifically about the possible use of nuclear energy to combat climate change, only 38 percent expressed support for an expanded reliance on nuclear power.

**Nuclear Power and Climate Change**

Nuclear power’s environmental appeal is that it emits less carbon dioxide to the atmosphere than does coal or natural gas. When compared to an equivalent modern coal plant, 1 GWe of nuclear capacity operating at an average capacity factor of 90% reduces the amount of carbon released to the atmosphere by about 1.5 million metric tons annually.

Total global carbon emissions to the atmosphere in 2006 from fossil fuels were approximately 7 billion metric tons per year. Assuming business as usual, emissions are projected to approximately double in 50 years (a 1.6 percent average annual growth rate). The deployment of an additional 700 GWe nuclear capacity by 2050—in place of building 700 GWe of modern coal-electric plants—would lessen projected emissions by one billion tons of carbon per year. If the rate of carbon emissions is to be stabilized and then reduced, other technologies will have to be deployed as well. These technologies will both complement and compete with nuclear power.

Energy efficiency is likely to be the most important. In the International Energy Agency’s “Alternative Scenario”—in which governments adopt an array of policies to reduce greenhouse gas emissions—energy efficiency accounted for two-thirds of the potential emissions reduction by 2030. Other studies of opportunities to reduce greenhouse gas emissions have reached similar conclusions.
On the supply side, wind power and integrated gasification combined cycle (IGCC) plants burning coal with carbon capture and storage currently appear to be the most economically promising among the non-nuclear technologies that could reduce carbon emissions from electricity production.

Efficiency improvements in the power sector could also have a substantial impact. In its business-as-usual scenario, the IEA estimated that coal-based electricity production would roughly double by 2030, with an average efficiency reaching about 40%. Today, the worldwide average efficiency of coal-based plants is below 30%, but newer coal plants have efficiencies up to 46%. By 2030, efficiencies could reach 50% or higher. Using technologies to shift the average efficiency of the world's coal-based plants from 40% to 45% in 2030 would save roughly the same amount of carbon emissions as would replacing 266 GWe of 50%-efficient coal plants with nuclear power, assuming both operated at a 90% capacity factor.

At a national level, the average efficiency of China's 307 GWe of coal-fired plants was only 23 percent in 2004. The IEA predicts an efficiency of about 37% in 2030. If this could be raised to 42% for the 1040 GWe of coal-fired capacity that China is expected to have online by 2030, that would save 3.5 times as much carbon as would the 31 GWe of nuclear capacity that the IEA expects China to deploy by then.

**Minimizing Proliferation Dangers from the Growth of Nuclear Power**

The proliferation implications of an expansion in nuclear power depend primarily on what happens at the front and back ends of the nuclear fuel cycle. At the front end, where nuclear fuel is produced, the primary concern is the proliferation of national uranium enrichment plants. At the back end, the concern is the management of plutonium in the spent fuel.

*The spread of national uranium enrichment plants.* In 2006, global demand for uranium enrichment was 44 million SWU/yr. This enrichment demand was met almost entirely from enrichment plants in Russia, Western Europe, and the United States. For the MIT scenario of 1500 GWe in 2050, in which virtually all new reactors would be light-water reactors, the annual enrichment demand would climb to 225 million SWU.

A five-fold increase in uranium enrichment capacity need not result in a corresponding increase in the risk of proliferation. The large enrichment enterprises in Russia, the United States, and Western Europe could increase their output to supply enough LEU to satisfy global demand. It is likely, however, that some countries—for reasons of energy security, technological pride, or interest in a nuclear-weapon option—would want to construct their own national enrichment facilities. Brazil and Iran are current examples. Future enrichment plants, like those being built today, would probably be based on gas centrifuges.

In some cases, a national centrifuge-enrichment capability may be justified on economic grounds. In industrialized nations, a modern centrifuge plant could be economically competitive at around 1.5 million SWU/yr capacity—enough to service about 10 GWe of light-water-reactor capacity. In the MIT 1500-GWe scenario, approximately 20 countries are forecasted to have at least 10 GWe of nuclear capacity by 2050, including Indonesia, Iran, and Pakistan.

Economics are not likely to be a barrier, even in countries where a national capability would not be economically competitive, however, because the cost of nuclear power is relatively insensitive to the cost of enrichment. A doubling of enrichment costs raises
the cost of nuclear electricity by only a few percent. This could be acceptable to a country interested in acquiring a national capability to avoid fuel-supply disruptions, or for other non-economic reasons.

In 2004, President Bush called upon the Nuclear Suppliers Group (NSG) of countries to deny enrichment and reprocessing technologies “to any state that does not already possess full-scale, functioning enrichment and reprocessing plants” and to ensure that states which do not already have enrichment plants have reliable access to civilian reactor fuel. Other NSG member states, which had not sold either technology since India’s nuclear test of 1974, agreed to continue their moratorium on exports on a year-to-year basis—but did not embrace the proposal of a permanent ban.

Indeed, President Bush’s proposal may have triggered an unprecedented burst of interest in uranium enrichment capabilities. Concerned that the United States was trying to foreclose their future enrichment options, half a dozen non-weapon states announced an interest in building national enrichment plants in the near future.

Mohammed El-Baradei, Director General of the IAEA, put forward an alternative proposal: to put fuel-cycle facilities under multi-national control and give fuel-supply assurances to countries foregoing national enrichment plants.

These and other proposals were discussed in a study commissioned by the IAEA, and at an IAEA workshop in Vienna in September 2006. In both venues, representatives of many countries made clear that they viewed any plan that created, or appeared to create, a permanent two-tier system of fuel-producer and fuel-purchasing states as unacceptable. One prominent ambassador participating in the expert study apparently spoke for many when he said:

“Any system that is not perceived to be fair and aimed at universal rights is bound to fail and risks unraveling the whole structure of nonproliferation. … Limitations on technological development will need to be universal, not just for some and not for others.”

This suggests that, unless a generally accepted and non-discriminatory framework for the supply of fuel-cycle services through a small number of multinational enterprises can be developed, the spread of nuclear power is likely to stimulate more countries to acquire a national enrichment capability—and with it the option to produce weapon-grade uranium on short notice.

There is already a significant multinational presence in the global uranium enrichment market. The two largest suppliers of enrichment are Urenco and Tenex. Urenco is already multinational, co-owned by the Netherlands, the United Kingdom, and Germany. The French Government owned conglomerate Areva now co-owns with Urenco the Enrichment Technology Company (ETC), which has been producing centrifuges for Urenco and now will do so for enrichment plants to be built in the United States and France.

Tenex markets Russia’s national enrichment services. In 2006, President Putin proposed the creation of an international uranium-enrichment center in Russia to provide nuclear enrichment services on a non-discriminatory basis and under the supervision of the IAEA. More specifically, he offered to other countries the opportunity to become co-owners of a uranium enrichment plant at Angarsk. Chapter 8 describes this initiative in more detail.
**The problem of plutonium in spent fuel.** At the back end of the fuel cycle, worldwide, about 10,000 metric tons of spent fuel containing approximately 75 tons of plutonium are discharged from reactors each year. To manage this material, two spent-fuel strategies are being used:

- Reprocessing of the spent fuel, with the separated plutonium either recycled in mixed-oxide fuel (MOX) for LWRs, or stored indefinitely for possible future use in fast breeder or burner reactors.

- Interim storage of the spent fuel with the object of either direct disposal in a geological repository, or of making a later decision between reprocessing or direct disposal.

France and Japan both plan to reprocess most of their spent fuel. France recycles its plutonium once and then stores the resulting spent MOX fuel to be reprocessed when fast-neutron reactors are commercialized. Japan plans to do the same. The United Kingdom has been reprocessing most of its spent fuel and storing the plutonium but plans to stop reprocessing around 2012 and not to reprocess the spent fuel from any future reactors. Russia reprocesses a small percentage of its spent fuel and is storing the separated plutonium for future use in plutonium-breeder reactors.

A dozen countries that previously sent spent fuel to France, the United Kingdom, or Russia for reprocessing, have now switched or are switching to interim storage. The United States adopted an interim-storage strategy in the late 1970s but is once again debating reprocessing owing to delays in the opening of its spent-fuel repository.

In recent years, an average of approximately 2000 metric tons of spent fuel have been reprocessed annually. The total plutonium separated is about 20 metric tons per year. Approximately one-half of the separated plutonium has been recycled in MOX fuel in Europe. This resulted in a savings of about 1300 tons of natural uranium per year—about 2 percent of world uranium demand. Most of the remaining separated plutonium is being added to the stockpiles at reprocessing plants in the United Kingdom, Russia, and Japan.

The alternative to reprocessing is dry-cask storage. The U.S. Nuclear Regulatory Commission has concluded that such storage would be safe and secure for at least 100 years and has licensed casks for 60 years. Virtually every operating reactor in the United States either already has dry-cask storage, or has such storage under construction or planned. The same is true in an increasing number of other countries with nuclear-power programs.

In comparing the costs of the two management options, two flows of material should be kept in mind:

- In the non-reprocessing alternative, all of the spent uranium fuel is put into dry-cask storage within about 20 years of discharge from the reactors; and

- With reprocessing and MOX recycling, the separated high-level waste (HLW) and the spent MOX fuel are stored indefinitely at the reprocessing plant.

The MIT study estimated that the costs of storing and disposing of unreprocessed spent fuel to be about the same as storing and disposing of high-level wastes and MOX spent fuel. This seems reasonable since the high-level wastes contain all the fission products and all the transuranics other than plutonium, and the spent MOX fuel still contains...
tains about 70 percent as much plutonium as fresh MOX fuel. The French Government similarly estimated the “end of cycle” costs for the two fuel cycles as virtually the same.

If the storage and disposal costs are assumed to be roughly equal, the economic comparison between the two alternatives is dominated by the reprocessing and MOX fuel fabrication costs less the saving of the cost of the LEU fuel that is replaced by the MOX fuel. In this comparison, the reprocessing costs far exceed the uranium and enrichment savings made possible by the use of MOX fuel. If, for example, uranium costs $130/kg, reprocessing costs $1000/kg, and MOX fabrication costs $1500/kg, then electricity generated with MOX fuel will cost roughly 2 cents per kilowatt-hour more than electricity generated with LEU fuel.

In the longer run, advocates of reprocessing believe that a growing nuclear economy, rising uranium prices and limited waste repository space should persuade countries to move to closed fuel cycles based on a mix of light-water and fast-neutron reactors. In the 1970s, this transition was projected for the 1990s. Today, however, even the advocates project it to be about 50 years away. Nevertheless, some countries persist in their reprocessing and fast-reactor programs despite the economic penalties associated with them. This is partly because of institutional inertia and local resistance to storing spent fuel at nuclear reactor sites.

The MIT study calculates the fissile-material flows for a 1500-GWe scenario with a mixture of LWRs and fast reactors. The plutonium and other transuranic elements fueling the fast reactors are obtained by reprocessing the spent fuel from all the reactors. In this scenario, about one thousand tons of plutonium are separated each year. This plutonium would not be self-protecting, even if it were mixed with the transuranics.

The once-through fuel cycle has the advantage that there is no nuclear-explosive material in the fresh fuel, and the plutonium in the spent fuel is left mixed with intensely radioactive fissile products. This provides a nearly intractable barrier to sub-national groups seeking to acquire fissile material from the civilian fuel cycle. Reprocessing, by contrast, puts huge quantities of separated weapon usable plutonium into the civilian fuel cycle.

Conclusion
If nuclear power grew approximately three-fold to about 1000 GWe in 2050, the increase in global greenhouse-gas emissions projected in business-as-usual scenarios could be reduced by about 10 to 20 percent.

Even a modest expansion of nuclear power would be accompanied by a substantial increase in the number of countries with nuclear reactors. Some of these countries would likely seek gas-centrifuge uranium-enrichment plants as well. Centrifuge-enrichment plants can be quickly converted to the production of highly enriched uranium for weapons. It is therefore critical to find multinational alternatives to the proliferation of national enrichment plants.

If a large-scale expansion of nuclear power were accompanied by a shift to reprocessing and plutonium recycle in light-water or fast reactors, it would involve annual flows of separated plutonium on the scale of a thousand metric tons per year—enough for 100,000 nuclear bombs. Fortunately, while there are strong security reasons to avoid plutonium recycling, there appears to be no economic rationale for such recycling for at least 50 years.
Endnotes

Chapter 7. Managing the Civilian Nuclear Fuel Cycle


309 The nuclear-power community often describes nuclear power reactors as belonging to a “generation.” Generation II reactors refer to those operating today. Generation III or III+ reactors are evolutionary designs of light-water reactors now under construction or in advanced development. Generation IV reactors, including, for example, the very high temperature gas reactor, the super-critical water reactor, the lead-cooled fast reactor, the sodium-cooled fast reactor, and the molten-salt reactor, are the subject of research efforts, but few are close to commercialization. In the case of sodium-cooled reactors, this is despite the expenditure of tens of billions of dollars in R&D since the 1960s. A gas-cooled pebble bed modular reactor is under development in China and South Africa, and could conceivably be deployed before 2030. See J. Ahearne, Advanced Nuclear Reactors: Their Use in Future Energy Supply, InterAcademy Council, 2005.


312 Nukem, Data Feature: 2005/2006 World Nuclear Electricity Generating Capacity, December 2006. The Nukem forecast includes a category of reactors optimistically labeled “anticipated.” With few exceptions, for most countries, all the reactors “planned” are assumed to come online after 2017 or later, and the reactors “anticipated,” not until 2022 or later. This category is based only on the expressed interest of possible future construction offered by some utilities. The projected Russian increase to 2030 is based on 33.1 GWe new planned capacity and 12.5 GWe anticipated. This is from a platform of 22 GWe now operating. There is great uncertainty about where the funds would come from to pay for all of this new construction (see Chapter 8).


314 Map drawn by IPFM based on MIT, The Future of Nuclear Power, 2003. The nuclear scenarios are described in detail in the MIT report’s Appendix to Chapter 2. The capacities given are “nuclear equivalent capacities” defined as the needed electricity consumption divided by 8760 hours per year. For a 90% capacity factor, actual capacities would be 11 percent greater. The MIT scenarios are based on a Masters thesis submitted to the Department of Nuclear Engineering and the Engineering Systems Division of MIT by C. M. Jones, June 2003.


316 Average of high and low projections in the IAEA/OECD series, Uranium: Resources, Production and Demand of the indicated years, courtesy of Tony McCormick, Urenco, August 2007.


321 *World Energy Outlook 2006*, op. cit., pp. 365–368. The low discount rate is based on a cost of debt of 8.0%, a required return to equity of 12.0%, a debt fraction of 50%, and a capital recovery period of 40 years; the corresponding figures for the high discount rate are debt cost of 10.0%, return to equity of 15.0%, debt fraction of 40%, and a 25 year capital recovery period. In both cases, a five-year construction period was assumed. Other parameters assumed for nuclear power were a capacity factor of 0.85, a unit cost of nuclear fuel of $0.50 per million BTUs, and a total annual operation and maintenance cost of $65/kWe. The unit cost of fuel translates into approximately 0.5 cents per kWh, and the operations and maintenance into about 1 cent per kWh.


325 J. Harding, *Costs and Prospects for New Nuclear Reactors*, presentation to the Northwest Power Council, February 2007. The new Asian reactors considered by Harding included the Japanese reactors Genkai-3 ($2818/kWe), Genkai-4 ($2286/kWe), Onagawa ($2409/kWe), KK6 ($2020/kWe), and KK7 ($1790/kWe), as well as the South Korean reactors Yonggwang 5 and 6 ($1800/kWe).


327 The Energy Policy Act extends catastrophic insurance coverage under the Price Anderson Act to include all new plants built and brought on-line by 2025. It also provides: up to $500 million for each of the first two nuclear plants, and $250 million each for the next four plants to cover cost overruns because of regulatory delays; government loan guarantees for up to 80 percent of the costs of advanced nuclear reactors; and a government production tax credit of 1.8 cents/kWh for the first eight years of operation of the first six nuclear plants, subject to a limit of $125 million per gigawatt-year. *Energy Policy Act of 2005*, www.ne.doe.gov/pdfFiles/epactFinal.pdf.


329 *Electricity and Nuclear Power Estimates for the Period up to 2030*, op. cit., Table 4, p. 21.


331 *Energy, Electricity and Nuclear Power Estimates for the Period to 2030*, op. cit.; the study shows a low and high projection of electricity generation in 2030 of 25,087 TWh and 38,200 TWh. Translating to consumption, i.e., assuming 20% transmission losses, it would be 21 thousand TWh low and 31.5 thousand TWh high.


333 Nuclear energy is not an option for projects implemented jointly (Article 6), or for the clean development mechanism (CDM, Article 12).

334 Globescan, “Global Public Opinion on Nuclear Issues and the IAEA,” prepared for the International Atomic Energy Agency, October 2005. The poll presented three choices: 1) Nuclear is safe, build more plants; 2) Use what’s there, don’t build more; and 3) Nuclear is dangerous, close down all plants. The fractions of support for these three options were 28%, 34%, and 25%. The countries polled were: Argentina, Australia, Cameroon, Canada, France, Germany, Great Britain, Hungary, India, Indonesia, Japan, Jordan, Mexico, Morocco, Russia, Saudi Arabia, South Korea, and the United States.
The weight of the carbon dioxide, in which the carbon is embedded, is 3.66 times greater. For details, see supporting online material for S. Pacala and R. Socolow, “Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies,” *Science*, Vol. 305, pp. 968–972, 13 August 2004. Assuming a lower heat-to-electricity conversion efficiency for coal of 50% and for gas of 60%—both numbers higher than yet realized—the authors show that a coal plant would emit about 186 g-C/kWh and a gas plant about half that. A 1-GWe plant at 90% capacity factor produces about 8 TWh of electricity per year. On this basis, a 1-GWe coal plant emitting 186 g-C/kWh would emit about 1.5 million metric tons of carbon per year, and a gas plant half as much.

“At the point of use, the largest contributor to avoided carbon dioxide emissions is improved end-use efficiency, accounting for nearly two-thirds of total savings,” in *World Energy Outlook 2006*, op. cit., p. 190; “The electricity saved in the residential and commercial sectors combined accounts for two-thirds of all the electricity savings in the Alternative Policy Scenario. By 2030, the savings in these two sectors avoid the need to build 412 GWe of new capacity”, p. 213.


In 2004, coal plants generated 795 GWe-years and emitted 7600 million metric tons of carbon dioxide, containing about 2100 million metric tons of carbon. Since a coal plant at 50% efficiency emits 186 grams of carbon per kWh, this implies an overall efficiency of about 30%, *World Energy Outlook 2006*, op. cit., p. 493. This calculation is only approximate because the carbon emissions given by the *World Energy Outlook 2006* include emissions from heat plants as well as electric power generation.


The coal electricity generated in 2030 is projected to be 14,703 TWh and the emissions from all coal power generation and heat plants to be 12,946 million metric tons of carbon dioxide containing 3540 million metric tons of carbon, *World Energy Outlook 2006*, op. cit., p. 493. This implies an overall efficiency of about 40%. Were the overall efficiency raised to 45%, the carbon savings would be approximately 400 million metric tons per year.

In 2004, coal plants in China operating at an average 65% capacity factor generated 1739 TWh of the national total 2237 TWh. In 2003, the average coal consumption per kWh was reported as 391 grams in China, compared to about 320 grams in advanced foreign countries, translating into an electricity efficiency of about 23% in China, compared to nearly 30% in industrialized countries, *World Energy Outlook 2006*, op. cit., p. 517. See also J. Wang, *Energy for Sustainable Development*, Vol. VII, No. 4, December 2003.

*World Energy Outlook 2006*, op. cit., p. 517. China coal electric generation in 2030 is projected to be 5980 TWh, and total carbon emitted by coal power generation and heat plants to be 1490 million metric tons. This implies an average efficiency of 37%. Raising the efficiency to 42% would save about 170 million metric tons per year, which could alternatively be effected by the deployment of 110 GWe of nuclear power operating at a 90-percent capacity factor instead of 50-percent efficient coal-fired plants. For the IEA's projection of China's nuclear capacity, see *World Energy Outlook 2006*, op. cit. p. 517.


P. Upson, CEO, Enrichment Technology Company (ETC), a joint venture of Urenco and Areva; remarks at IFPM meeting, the Hague, 1 March 2006.

For a fuel burn-up of 50MWd/kg, 4.3% enriched LEU would be required. For a depleted-uranium assay of 0.25% U-235, about 6.5 SWU would be required per kilogram of fuel. For a heat-to-electricity conversion efficiency of 0.33, a doubling of the SWU price from $120/SWU to $240/SWU would, therefore, contribute an additional 0.2 cents/kWh to the cost of electricity.

These countries include Argentina, Australia, Canada, Kazakhstan, South Africa, and the Ukraine.


IAEA Special Event on Assurances of Nuclear Supply and Non-Proliferation, Vienna, September 2006.

Off-the-record comment by a participant from a non-weapon state.


President Putin, statement on the peaceful use of nuclear energy, St. Petersburg, 25 January 2006.


Armenia, Belgium, Bulgaria, Czech Republic, Finland, Germany, Hungary, Slovak Republic, Spain, Sweden, Switzerland, and the Ukraine.


If one assumes 9 kg of natural uranium per kilogram of LEU and 7% plutonium in the MOX fuel, then 10 tons of plutonium recycled translates into 1300 tons of natural uranium saved.


Nuclear Energy Institute, *Fact Sheet: Status of Used Fuel Storage at U.S. Commercial Nuclear Plants*, September 2006. Fifty-seven reactors (including a few research reactors and shutdown reactors) were listed as having dry cask storage as of 31 December 2004, and 48 as having such storage under construction or planned.

In a fuel cycle in which all LEU spent fuel was reprocessed and the recovered plutonium recycled, about seven out of eight spent fuel assemblies would be reprocessed; with the eighth, a spent MOX assembly, stored indefinitely without reprocessing. No country has such a fuel cycle in place. France reprocesses most of its spent LEU fuel, however, and Japan plans to do so.

The MIT study assumed a cost of $400/kg for geological storage of LEU spent fuel; $300/kg of reprocessed spent fuel for geological storage of HLW; and $400/kg for MOX storage and disposal.


In the French Government’s comparison of reprocessing and plutonium recycle, it was estimated that the “end of cycle,” costs, i.e., the summed cost of long-term storage and disposal of reprocessing wastes and spent MOX fuel on the one hand, and spent LEU fuel on the other after 2049 were virtually the same, J. M. Charpin, B. Dessus and R. Pellat, *Economic Forecast Study of the Nuclear Power Option: Report to the Prime Minister, 2000*, p. 215, www.ipfmlibrary.org/cha00.pdf.

The reprocessing and MOX fabrication costs cited here are the base case assumptions of the MIT Study. However, the MIT study assumed a price for natural uranium of $30/kg, which now looks too low. At that price, the extra cost of MOX would be about 2.2 cents per kilowatt-hour. The estimated cost for reprocessing also may be too low. In a paper presented at the Nuclear Renaissance Workshop in Washington, M. Crozat of DOE estimated for a modern reprocessing plant of 2500 metric tons...
capacity per year an overnight cost of $12 billion, a marginal unit cost of $360/kg, an investor rate of return of 16%, an investment debt fraction of 40%, an interest rate of 10%, and a finance period of 30 years. With these figures, the separation cost would be about $1400/kg. Crozat noted that, with government loan guarantees, this could drop to just under $1000/kg, see: M. Crozat, “Evaluating the Economics for GNEP Deployment,” Nuclear Renaissance Workshop, Washington, D.C., 6 December 2006.

367 For example, the Global Nuclear Energy Partnership (GNEP), launched by the U.S. Department of Energy in May 2006, has as its explicit goal to move the United States to a closed fuel cycle in which plutonium and other transuranics contained in the reactor spent fuel would be separated and then recycled repeatedly into a fleet of fast reactors. See www.gnep.energy.gov.

368 For the 1500 GWe projection, the LWR and fast reactor capacities are 815 GWe and 685 GWe respectively. The Future of Nuclear Power, op. cit., Appendix to Chapter 4, p. 126.