9 The Uncertain Future of Nuclear Energy

Frank von Hippel, Editor

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International Panel on Fissile Materials

The Uncertain Future of Nuclear Energy

With contributions by Matthew Bunn, Anatoli Diakov, Ming Ding, Tadahiro Katsuta, Charles McCombie, M.V. Ramana, Tatsujiro Suzuki, Susan Voss, Suyuan Yu

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Table of Contents

Figures

Tables

About the IPFM

The International Panel on Fissile Materials (IPFM) was founded in January 2006. It is an independent group of arms-control and nonproliferation experts from seventeen countries, including both nuclear weapon and non-nuclear weapon states.

The mission of the IPFM is to analyze the technical basis for practical and achievable policy initiatives to secure, consolidate and reduce stockpiles of highly enriched uranium and plutonium. These fissile materials are the key ingredients in nuclear weapons, and their control is critical to nuclear disarmament, halting the proliferation of nuclear weapons and ensuring that terrorists do not acquire nuclear weapons.

Both military and civilian stocks of fissile materials have to be addressed. The nuclear weapon states still have enough fissile materials in their weapon and naval fuel stockpiles for tens of thousands of nuclear weapons. On the civilian side, enough plutonium has been separated to make a similarly large number of weapons. Highly enriched uranium is used in civilian reactor fuel in tens of locations. The total amount used for this purpose is sufficient to make hundreds of Hiroshima-type bombs, a design potentially within the capabilities of terrorist groups.

The Panel is co-chaired by Professor R. Rajaraman of Jawaharlal Nehru University in New Delhi and Professor Frank von Hippel of Princeton University. Its members include nuclear experts from Brazil, China, France, Germany, India, Ireland, Japan, South Korea, Mexico, the Netherlands, Norway, Pakistan, Russia, South Africa, Sweden, the United Kingdom and the United States. Professor José Goldemberg of Brazil stepped down as co-chair of IPFM on July 1, 2007. He continues as a member of IPFM.

IPFM research and reports are shared with international organizations, national governments and nongovernmental groups. It has full panel meetings twice a year in capitals around the world in addition to specialist workshops. These meetings and workshops are often in conjunction with international conferences at which IPFM panels and experts are invited to make presentations.

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Explanatory Note

This report is a shortened version of a second draft of the chapter on nuclear energy that is to appear in the 2010 report of the Global Energy Assessment (GEA). It is being published as an IPFM report with the permission of the GEA because it provides useful background for IPFM studies relating to nuclear power. It does not include a substantial section on fusion energy authored by Professor Robert Goldston of Princeton University, which will appear in the GEA report. It has not yet been subject to final review and revision for inclusion in the Global Energy Assessment. The views expressed here should therefore not be attributed to the GEA.

Some topics that will be covered in other GEA chapters are not covered here—or covered only briefly. These include the health impacts of routine releases of radioactivity from the nuclear fuel cycle.

Some of the country studies that appear here in abbreviated form were authored as follows:

- China, Professor Suyuan Yu and Dr. Ming Ding, Tsinghua University.
- India, Dr. M.V. Ramana of Princeton University.
- Japan, Professor Tadahiro Katsuta, Meiji University; and Professor Tatsujiro Suzuki, Tokyo University.*
- Russia, Professor Anatoli Diakov, Moscow Institute of Physics and Technology; and Susan Voss, independent consultant.

Lead authors on other sections are:

- Institutional requirements, Professor Matthew Bunn, Harvard University.
- Public acceptance, Dr. M.V. Ramana.

Dr. Charles McCombie, Executive Director of the Geneva-based Association for Regional and International Underground Storage, advised on the section on radioactive waste as well as commenting very helpfully on the entire report.

* Now a member of Japan's Atomic Energy Commission

Summary

In the 1970s, nuclear energy was expected to quickly become the dominant generator of electrical power. Its fuel costs are remarkably low because a million times more energy is released per unit weight by fission than by combustion. But its capital costs have proven to be high. Safety requires redundant cooling and control systems, massive leak-tight containment structures, very conservative seismic design and extremely stringent quality control.

The routine health risks and greenhouse-gas emissions from fission power are small relative to those associated with coal, but there are catastrophic risks: nuclear-weapon proliferation and the possibility of over-heated fuel releasing massive quantities of fission products to the human environment. The public is sensitive to these risks. The 1979 Three Mile Island and 1986 Chernobyl accidents, along with high capital costs, ended the rapid growth of global nuclear-power capacity (Figures 1 and 2).

Today, there are hopes for a "nuclear renaissance" but nuclear energy in Western Europe and North America, which together account for 63 percent of current global capacity, is being dogged again by high capital costs and it is not yet clear that new construction will offset the retirement of old capacity. Cost escalation is more contained in East Asia, where the International Atomic Energy Agency (IAEA) expects 42 to 75 percent of global nuclear capacity expansion by 2030 to occur—mostly in China. China's top nuclear safety regulator has raised concerns, however, about "construction quality and operational safety" [*New York Times*, 16 Dec. 2009] and, even for its high-nuclear-growth projection, the IAEA does not expect nuclear power to significantly increase its current share of about 15 percent of global electric-power generation.

The most important danger from fission is that its technology or materials may be used to make nuclear weapons. Of the thirty-one nations that have nuclear power today, seven are nuclear-weapon states[1]and almost all the others have their non-weapon status stabilized by either being part of the European Union and NATO or another close alliance to the United States. Such stabilizing arrangements do not exist for the majority of the countries that have expressed an interest in acquiring their first nuclear power plants (See Introduction, Table 2). Of these, some are suspected of having mixed motives for their interest in fission technology.

1 In historical order: the United States, Russia, the United Kingdom, France, China, India and Pakistan. Israel and North Korea have nuclear weapons but do not have nuclear power plants.

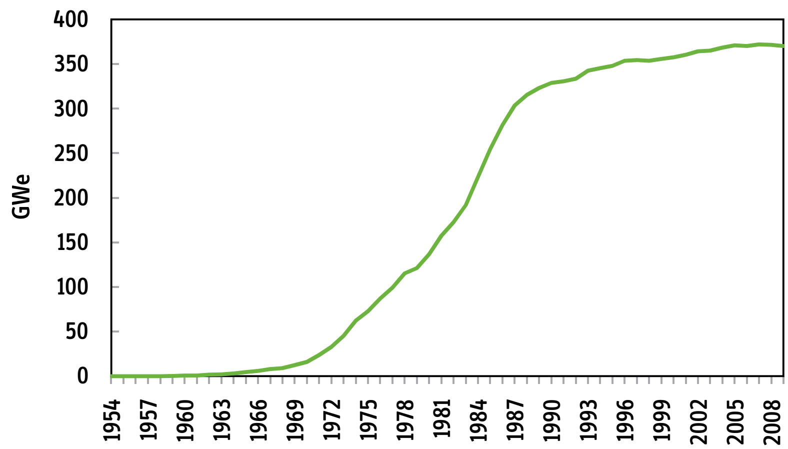

Figure 1. **Growth of global nuclear-power capacity (GWe)** [IAEA-PRIS, 9 January 2010].

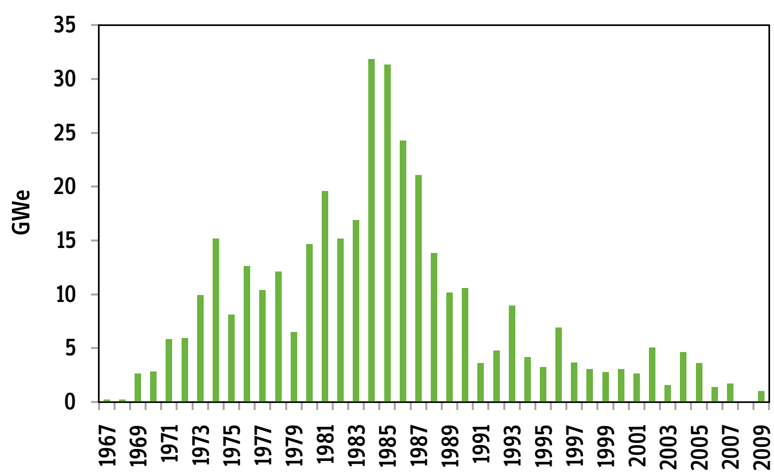

Figure 2. **Nuclear capacity installed by year (GWe)** [IAEA-PRIS, 9 January 2010].

The dominant nuclear power reactor type today, the light-water reactor (LWR), is relatively proliferation resistant when operated on a "once-through" fuel cycle. It is fueled with low-enriched uranium (LEU), which cannot be used to make nuclear weapons without further enrichment. Its spent fuel contains about one percent plutonium but it is mixed with highly radioactive fission products that make it inaccessible except by "reprocessing" with remotely controlled apparatus behind thick radiation shielding. There is no good economic or waste-management reason today to separate out this plutonium.

Much of the leadership of the global nuclear-energy establishment, however, continues to promote the uranium-conservation and waste-reduction benefits of recovering plutonium from the spent fuel and recycling it. This provided cover for India's nuclear-weapon program, which used plutonium separated under the international "Atoms for Peace" program to make its first nuclear explosion in 1974 and also for the weapons dimensions of at least seven other national nuclear programs.[2] Plutonium recycle is not expected to become economic for the foreseeable future, however, and reprocessing and plutonium recycle in LWR fuel, as practiced today in France, does not reduce the problem of radioactive waste [Schneider and Marignac, 2008].

The other route to nuclear weapons is enrichment of uranium to a level above 20 percent uranium-235 (typically, to more than 90 percent). Historically, acquiring this capability required a massive investment in a gaseous-diffusion plant, with thousands of stages of compression of an ever smaller stream of corrosive uranium-hexafluoride gas through porous barriers. Today, however, the dominant enrichment technology is the gas centrifuge, which, as Brazil, India, Iran and Pakistan have demonstrated, can be deployed in affordable plants that can begin operating on a scale smaller even than required to fuel a single gigawatt-scale LWR. Unfortunately, such plants can easily be used or reconfigured to produce weapon-grade uranium and a plant sized to fuel a single 1-gigawatt electric (GWe) LWR could produce enough material for 25 nuclear weapons a year. Today, much of the attention of the nonproliferation community is being devoted to preventing the spread of small national centrifuge enrichment plants.

The final issue that contributes to the uncertainty of the future of nuclear energy is persistent public opposition. As memories of the Three Mile Island and Chernobyl accidents fade and concerns about the consequences of global warming increase, the trend has been toward public opinion that is more favorable. Continuing public concern about radioactive waste and "not-in-my-backyard" opposition to the siting of central spent-fuel storage sites have, however, helped keep reprocessing plants alive as alternative destinations for spent fuel, despite their poor economics and proliferation dangers.

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2 Argentina, Brazil, France, South Korea, Pakistan, Sweden and Taiwan. Fortunately, all but France and Pakistan abandoned their nuclear-weapon programs.

In the 1970s, nuclear-power boosters expected that by now nuclear power would produce perhaps 80 to 90 percent of all electrical energy globally [US AEC, 1974]. Today, the official high-growth projection of the Organization for Economic Co-operation and Developments (OECD) Nuclear Energy Agency (NEA) estimates that nuclear power plants will generate about 20 percent of all electrical energy in 2050 [NEA, 2008a]. Thus, nuclear power could make a significant contribution to the global electricity supply. Or it could be phased out—especially if there is another accidental or a terrorist-caused Chernobyl-scale release of radioactivity. If the spread of nuclear energy cannot be decoupled from the spread of nuclear weapons, it should be phased out.

1 Introduction

Fission energy is released when the nucleus of a very heavy "fissile" atom such as uranium-235 or plutonium-239 splits in two. Fission is induced by the absorption of a neutron and releases typically 2 or 3 neutrons. If there is a sufficient concentration and mass of fissile material, i.e., a "critical mass", a fission chain reaction can occur.

Current-generation fission reactors are mostly "slow-neutron" reactors. The fast neutrons emitted by fission are slowed by multiple collisions with the nuclei of a "moderating" material before they cause additional fissions (Figure 3). Because the range out to which fissile nuclei can capture neutrons increases greatly at low neutron velocities, this makes it possible to sustain a chain reaction in a mixture in which the fissile atoms are quite dilute. Indeed, the first reactors were fueled by natural uranium in which uranium-235 constituted only one out of 140 uranium atoms but captured about half of the slow neutrons. The remaining atoms in natural uranium are virtually all non-fissile uranium-238, which captures most of the slow neutrons not absorbed by U-235 and is thereby converted into chain-reacting plutonium-239.

The emissions of greenhouse gases per kilowatt-hour (kWh) from fission power on a life-cycle basis are less than 10 percent those than from fossil-fueled power plants.[3] Five hundred to 700 GWe of nuclear capacity, i.e., 1.3–1.8 times current global capacity, could forestall the annual release of 10^9 tons of carbon to the atmosphere if used to replace coal-fired power plants that do not sequester their carbon dioxide emissions.[4] This would be about one eighth the global annual release of carbon into the atmosphere from fossil fuels and cement production

3 Emissions from coal-fired power plants are about 1000 grams CO_2 per kWh. Emission estimates for nuclear power plants range from 1.4 to 200 g CO_2/kWh [Sovacool, 2008a]. At the low end, the analyses are not comprehensive. At the high end, they tend to be associated with very low ore grades. Typically, the uranium being mined today has concentrations of 0.1 percent uranium and higher [van Leeuwen, 2008, Figure D-3]. The lowest ore grade reported as being mined is in a gold mine where uranium is recovered as a byproduct. The ore is reportedly 0.013 percent uranium with a recovery rate of 50 percent [van Leeuwen, 2008, Figure D-5].

4 Assuming that 25.8 kilograms of carbon are released to the atmosphere per 10^9 joules of energy released from bituminous coal [World Energy Assessment, 2000, Box D.1], an efficiency range for new coal power plants of 35 to 50 percent and an average nuclear-power plant capacity factor of 90 percent (478.5–683.6 GWe).

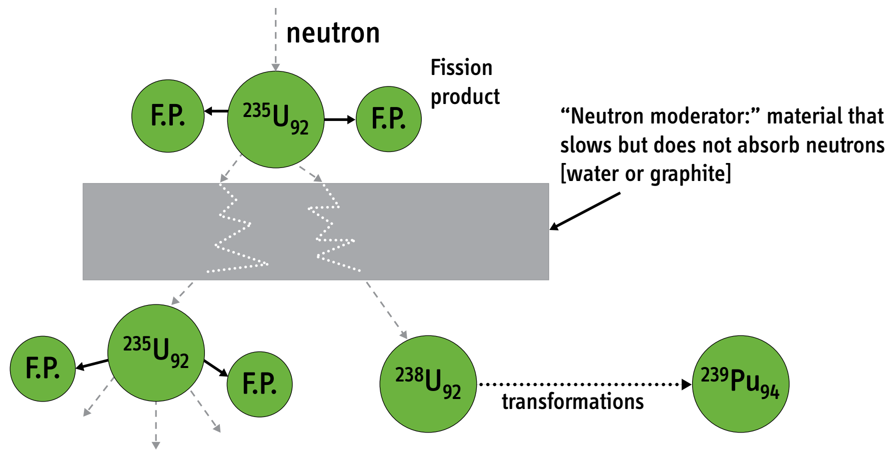

Figure 3. **A fission chain reaction in a slow-neutron reactor.** Each fission splits a nucleus of a fissile atom (shown here as uranium-235) into two unequal medium-weight nuclei (fission products, F.P.) and also produces typically two neutrons that can go on and cause further fissions. In almost all of today's power reactors, these neutrons are slowed by collisions with the nuclei in "moderating" material (typically with hydrogen nuclei in water) which increases the probability that they will cause fissions. In a reactor operating in steady state, one fission causes on average one fission. The extra neutrons are mostly absorbed by uranium-238, converting it into uranium-239, which decays by electron (and antineutrino) emission into neptunium-239 (which has 93 protons) and then into plutonium-239 (94 protons). Plutonium-239 is itself a fissile isotope and contributes increasingly to the chain reaction in the reactor core as the U-235 is depleted and the plutonium concentration builds up.

in 2005 [IPCC-PSB, 2007, p. 139] and 5 to 12 percent of the releases projected for 2030 in the full range of IPCC scenarios [IPCC-SRES, 2000, Figure 5-2]. In practice, nuclear power would displace a mix of other types of electric power plants and the savings would be less [Socolow and Glaser, 2009].

The other routine occupational and environmental impacts of nuclear power plants per kWh are relatively low in comparison to fossil power. But the potential for catastrophic releases of radioactivity makes the reputation of the global nuclear industry vulnerable to unsafe practices in any country. It therefore is critical to maintain high safety and security standards in design, construction and operation everywhere.

Although relatively little nuclear capacity has been added in recent years (Figure 2), nuclear power plants increased their average capacity factors steadily to 80 percent and therefore maintained their share of generated electricity at about 17 percent from 1988 till 2001 before dropping to about 14 percent in 2007 [IAEA, 2009c, Tables 3 and 4].[5] For nuclear energy to maintain its share of the global electrical-power market, there will have to be a dramatic increase of nuclear capacity construction—especially as most existing nuclear capacity will have to be replaced during the period 2010–2050.[6]

Given the uncertain capital costs of nuclear power plants today, the risks associated with uncertain demand-growth projections, and the possibility of catastrophic accidents, private capital is not likely to fund nuclear power plant construction without government guarantees. Such support is available, however, in the form of direct government funding, loan guarantees, or guaranteed payback of investments through government-regulated markets for electric power.

In China, nuclear power plant construction by state-owned companies is centrally approved in the five-year plans of China's National Development and Reform Commission and investors receive tax incentives and low-interest loans. In France, two huge government-owned companies: AREVA, which sells reactors and fuel-cycle services, and Électricité de France (EDF), the national utility, are partnering to finance and build reactors in other countries. In Russia, Rosatom, the government-owned company that builds and operates reactors and supplies fuel-cycle services, is using government funding and its own income to invest in a major expansion of both domestic capacity and sales overseas. In Japan, the government is providing loan guarantees for foreign reactor sales. In India, the national government is financing nuclear-power-reactor construction. In the United States, the Congress passed a major package of incentives and loan guarantees in 2005 to restart reactor orders after a hiatus of three decades and some state regulators are allowing utilities to charge their customers for the costs of construction before their reactors start generating power.

All this government support will certainly result in the construction of some power reactors. Whether the new construction will be significant on a global scale remains to be seen. Assuming a cost of $4,000 per kilowatt (KW) of generating capacity, not including interest during construction [MIT, 2009], the cost for even replacing the aging fleet of power reactors would be about $1.5 trillion. The IAEA believes that, with high growth rates for electric-power consumption and favorable public policies, both electric power demand and nuclear power production could double by 2030 and that nuclear power could increase its current 14 percent share of the global market for electric power to 16 percent by 2030. The IAEA's low-growth scenario has global nuclear power capacity increasing by about 40 percent by 2030 but its market share dropping to 13 percent [IAEA, 2009c].

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5 The capacity factor is the ratio of the output of a power plant over a time period divided by its output had it operated at full capacity the entire time.

6 Assuming 40 to 60-year operating lifetimes (see Figure 2).

Much of the continuing government support for nuclear power stems from large government nuclear research and development (R&D) establishments in the nuclear-weapon states. The first power reactors in the Soviet Union, United Kingdom and France were derivatives of their natural-uranium-fueled, graphite-moderated, plutonium-production reactors.[7] Canada developed a natural-uranium fueled heavy-water-moderated reactor and exported it to other countries interested in independence from foreign suppliers of enrichment services—most notably India. Today's most successful power reactor, the LEU-fueled LWR, stems from the compact water-cooled reactors developed for submarine propulsion.

Thus, most of the initial R&D relevant to nuclear power technology was paid for by government military nuclear budgets. Later, separate civilian nuclear-energy R&D programs developed but they continued to have privileged access to national treasuries relative to other energy R&D programs—receiving over the past three decades more than 50 percent of government expenditures on energy research, development and demonstration projects (RD&D) (Figure 4). This bias toward nuclear energy propagated into the national R&D establishments of some non-weapon states, most notably that of Japan.

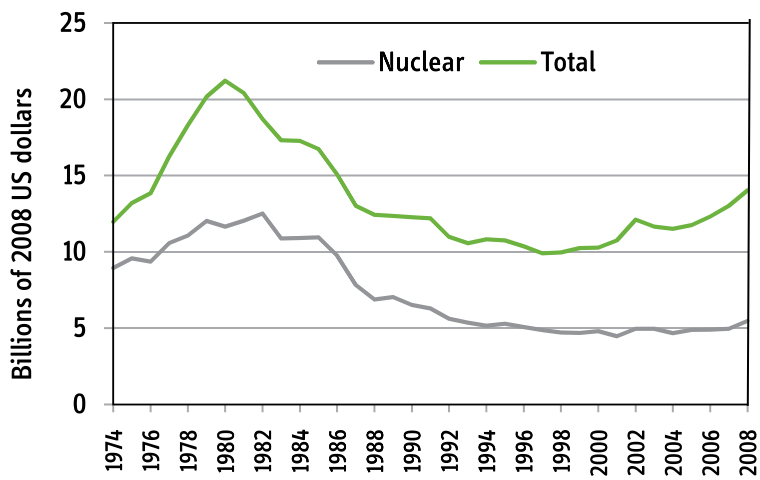

Figure 4. **Government energy RD&D expenditures in the OECD countries, 1974-2006.** Nuclear includes both fission and fusion [International Energy Agency, 2008, Figure 4.2].

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7 Graphite and heavy water are used in reactors fueled with natural uranium to "moderate" (slow) the typically two or three neutrons emitted by fissions to speeds where a large fraction of them will be absorbed by the uranium-235 and continue the chain reaction. The probability that the graphite or heavy water will itself absorb the neutrons is relatively low. The probability of neutron absorption is higher in the ordinary water used in light-water cooled reactors. This is why light-water reactors require enriched uranium fuel which results in a reduced fraction of the neutrons being absorbed by the U-238.

Perhaps the most important question with regard to fission power is whether it will be possible for it to grow and spread without spreading nuclear weapons. Various efforts have been undertaken over the past decades to contain the spread of national spent-fuel reprocessing and uranium enrichment plants that remain the keys to producing nuclear-weapon materials. There is resistance from have-not countries, however, to foregoing the option of acquiring national enrichment plants. And, even though reprocessing and plutonium recycle are uneconomic and have few environmental benefits when used with current nuclear-power reactors, the opposition of local communities to expanding at-reactor spent-fuel storage facilities or hosting central interim storage facilities has sustained reprocessing in Japan as an alternative destination for spent fuel and has helped foster a revival of interest in reprocessing in the United States and South Korea.

Global and regional nuclear capacity

Thirty countries plus Taiwan have nuclear power plants: 19 in Europe (including Russia and the Ukraine), five in Asia (plus Taiwan), five in the Americas and one in Africa (South Africa) (see Figure 5).

At the end of 2009, global nuclear-generating capacity was 370 GWe: 46 percent in Europe (including Eastern Europe and Russia), 30 percent in North America and 21 percent in the Far East. The rest of the world: Africa, Latin America, the Middle East and South Asia, accounted for only three percent (Table 1)—but contributed a large fraction of the controversy over its proliferation implications.

Region	Generating Capacity [GWe]		Nuclear percentage of electric energy generated
	Total	Nuclear	
North America	1282	113.3	19.0
Latin America	297	4.0	2.4
Western Europe	780	122.5	26.7
Eastern Europe (including Russia)	494	47.5	18.3
Africa	118	1.8	2.1
Middle East and South Asia	364	4.2	1.0
Far East	1157	78.3	10.1
World Total	4662	371.6	14.0

Table 1. **Global distribution of nuclear power capacity in 2008** [IAEA, 2009c].

Figure 5. **Power-reactor capacity by country, end of 2009** [IAEA-PRIS, 9 January 2010].

Projections for Expansion

The IAEA makes annual projections of global nuclear growth. Between 1985 and 1995, even the low projections were higher than what was built by 2000 and 2005 [IAEA, 2007a, Figures 29 and 30]. There were few new orders for new nuclear power plants and many orders were either cancelled or delayed because of decreased electric-power consumption growth rates and construction and licensing delays. As a result, projections of growth declined through 2000 and the low projections in 2000 even showed future declines in global nuclear capacity if retirements of old plants exceeded new builds.

New orders resumed in 2005, however, and most power reactor licenses in the United States are being extended to allow operation for up to 60 years. The projections, therefore, began increasing again. The 2009 projection was for a net increase in global nuclear generating capacity of 139–435 GWe by 2030 [IAEA, 2009c]. The high end of the range corresponds to more than a doubling of the

2007 global nuclear capacity and assumes an average net addition of new capacity of 26 GWe/year between 2020 and 2030. This corresponds to a growth rate that was only achieved in the past during the late 1980s (Figure 2).[8]

Much of the projected increase would be in the Far East (105–181 GWe) and Eastern Europe (including Russia) (35–73 GWe), reflecting especially the ambitious plans of China and Russia (see case studies below). North America is also projected for a significant increase (14–55) GWe. In the low projection, nuclear capacity in Western Europe declines by 41 GWe while, in the high projection, it increases by 35 GWe. The rest of the world (Latin America, Africa, the Middle East, South Asia, Southeast Asia and the Pacific) altogether are projected to add 27–91 GWe.

The IAEA's low and high projections for nuclear power are associated respectively with 2.2 and 3.2 percent average annual growth rates in global electric-power production between 2008 and 2030 [IAEA, 2009c]. For comparison, between 1996 and 2006, global electricity consumption increased at an average annual rate of 3.3 percent [US EIA, 2008c]. Given the likelihood of a steep increase in electricity prices associated with a shift away from fossil fueled generating capacity, global electricity consumption growth rates could decline. On the other hand, if a significant fraction of automobile transport shifts to electric cars or plug-in hybrids, that might offset the price effect.[9]

Reflecting the revived interest in nuclear power, as of 2010, 61 countries had requested advice from the IAEA about acquiring their first nuclear power plants [IAEA, 2010d]. A 2008 NEA report lists 26 countries, five of which have "planned or approved projects"[10] and 21 of which have "proposed or intended" projects. Excluding Iran, whose first nuclear power plant is virtually complete, and adding Israel, which is the only country that is not on the IAEA list [NEA, 2008a, Table

[8] According to the press release accompanying the 2009 IAEA projection, "The low projection…assumes that…there are few changes in the laws and regulations affecting nuclear power…The high projection assumes...that recent rates of economic growth and electricity demand, especially in the Far East, continue. It also assumes that national policies to reduce greenhouse gas emissions are strengthened, which makes electricity generation from low-carbon technologies, like nuclear power and renewables, more attractive."

[9] The current global population of automobiles is about 700 million [*Transportation Energy Databook*, 2009, Table 3.1]. If they travel 15,000 km each on average, that would be about 10^{13} automobile-km per year. Assuming that 0.2 kWh would be required per km [Electric Auto Association Europe, 2008] about $2x10^{12}$ kWh would be required per year, equivalent to the output of about 250 GWe of generating capacity operating at an average capacity of 90 percent.

[10] "Planned or approved projects:" Belarus, Indonesia, Turkey and Vietnam. "Proposed or intended projects:" Bahrain, Bangladesh, Egypt, Georgia, Ghana, Iran, Israel, Kazakhstan, Kuwait, Libya, Malaysia, Namibia, Nigeria, Oman, Philippines, Qatar, Saudi Arabia, Thailand, Uganda, United Arab Emirates and Yemen.

2.1], the 61 countries are listed in Table 2.[11] In 2009, one of them, the United Arab Emirates (U.A.E.) contracted with South Korea to build four 1.4-GWe LWRs [Reuters, 27 Dec. 2009].

In many cases, the widespread interest in nuclear power reflects a broadly-shared perception of the need to shift away from fossil fuels because of concerns about climate change. There is a concern, however, that some countries are also interested in moving toward a nuclear-weapon option. Currently, this concern focuses especially on Middle Eastern countries that are alarmed about the nuclear-weapon potential of Iran's uranium-enrichment program. In the U.A.E.-U.S. Agreement for Peaceful Nuclear Cooperation however, the United Arab Emirates agreed to forgo the acquisition of uranium enrichment or spent-fuel reprocessing technologies [UAE-US, 2009].

Table 2 lists the 2007 Gross Domestic Product (GDP) for each of the 61 countries and the generating capacity in GWe that would have been required, at a 60 percent capacity factor, to generate the electric energy that they generated in 2005, 2006 or 2007. In terms of GDP, the countries range from Mongolia (2007 GDP, $4 billion) to Turkey (GDP, $657 billion). Some are so poor that it is difficult to understand how they could pay back the $4 billion cost of a standard 1-GWe nuclear power plant. The World Bank and Asian Development Bank do not give loans to purchase nuclear power reactors [Schneider *et al.*, 2009, p. 55]. Until recently, South Africa (2007 GDP, $278 billion) had plans to add 20 GWe of nuclear capacity by 2025. In December 2008, however, the South African government announced cancellation of its request for tenders for the first 4 GWe of capacity because "it is not affordable at this present juncture" [WNN, 5 Dec. 2008]. It seems unlikely that a country with an annual GDP of less than $50 billion could afford a $4 billion nuclear power plant.

Also, the capacity of many countries' grids may not be large enough to accommodate a standard 1-GWe nuclear power plant. The IAEA recommends that a single nuclear-power reactor not constitute more than 5 to 10 percent of the generating capacity on a grid [IAEA, 2007b, p. 39].

The "x's" in Table 2 indicates that only 24 of the 61 countries interested in acquiring a first nuclear power plant pass both a $50 billion annual GDP and a 5-GWe grid capacity screening requirement. Even though the threshold size for a grid required to support a nuclear-power reactor has been reduced to 5 GWe to allow for the possibility of a doubling in the grid capacity before the first nuclear power plant comes on line, the grid requirement appears to be the most stringent. It is mitigated, however, in regions where there is a strong supranational grid. For example, there is an existing grid that connects Malaysia, Singapore and Thailand

[11] More detailed information on how serious the interest is in many of these countries can be found in the Centre for International Governance Innovation's (CIGI) Survey of Emerging Nuclear Energy States [CIGI, 2010].

Country	GDP (billions of 2008$)	Estimated Grid Capacity (2006, -7 or -8) (GWh/5000 hrs = GWe)	GDP >$50 x 10^9/y and Estimated Grid Capacity > 5 GWe
Albania	12	0.5	
Algeria	174	6	x
Bahrain	16	2	
Bangladesh	79	5	
Belarus	60	6	x
Benin	7	0.02	
Bolivia	17	1	
Cameroon	23	1	
Chile	169	12	x
Columbia	244	10	x
Cote d'Ivoire	23	1	
Croatia	69	2	
Dominican Rep.	46	2	
Egypt	163	24	x
El Salvador	22	1	
Estonia	23	2	
Ethiopia	26	0.7	
Georgia	13	2	
Ghana	16	1	
Greece	357	12	x
Haiti	7	0.1	
Indonesia	514	27	x
Israel	199	10	x
Italy	2303	55	x
Jamaica	15	1	
Jordan	20	2	
Kazakhstan	132	14	x
Kenya	35	1	
Kuwait	112	9	x
Latvia	34	1	
Libya	100	5	x

Country	GDP (billions of 2008$)	Estimated Grid Capacity (2006, -7 or -8) (GWh/5000 hrs = GWe)	GDP >$50 x 10^9/y and Estimated Grid Capacity > 5 GWe
Madagascar	9	0.2	
Malawi	4	0.1	
Malaysia	195	21	x
Mongolia	5	1	
Morocco	86	4	
Myanmar (Burma)	??	1	
Namibia	9	0.3	
Niger	5	4	
Nigeria	212	4	
Oman	36	3	
Peru	127	5	x
Philippines	167	11	x
Poland	527	29	x
Qatar	53	3	
Saudi Arabia	468	30	x
Senegal	13	0.4	
Singapore	182	8	x
Sri Lanka	41	2	
Sudan	58	1	
Syria	55	7	x
Tanzania	20	0.2	
Thailand	261	27	x
Tunisia	40	3	
Turkey	794	36	x
UAE	163	14	x
Uganda	14	0.4	
Uruguay	32	2	
Venezuela	314	23	x
Vietnam	91	13	x
Yemen	27	1	

Table 2. **Countries that have recently expressed an interest in acquiring a first nuclear power plant** [IAEA-2010d], their GDPs [World Bank, 2009] and rough equivalent generating capacities in 2006, 2007 or 2008 [CIA, 2010 for kWh generated] and those that pass a screening test for GDPs greater than $50 billion/year and electricity consumption roughly equivalent to the output of 5 GWe.

and a proposed West Africa grid would include Ghana and Nigeria. The grid constraint also could be mitigated by use of nuclear power plants with smaller generating capacity.

Beyond 2030. The OECD's NEA has made high, low and phase-out projections of global nuclear capacity beyond 2030 (Figure 6, phase out scenarios not shown). They are rather arbitrary but the high projection reflects a judgment as to the maximum credible rate at which nuclear power could be expanded worldwide. In the high scenario, it is assumed that, after the industry tools up over the next two decades, it will be able to bring on line an average of more than 40 GWe/year of nuclear capacity during 2030–2050, about twice the rate of buildup between 1972 and 1987. Even so, the NEA high scenario has nuclear power generating only 22 percent of global electric energy in 2050—up from 14 percent in 2007 [NEA, 2008a, p. 105].[12]

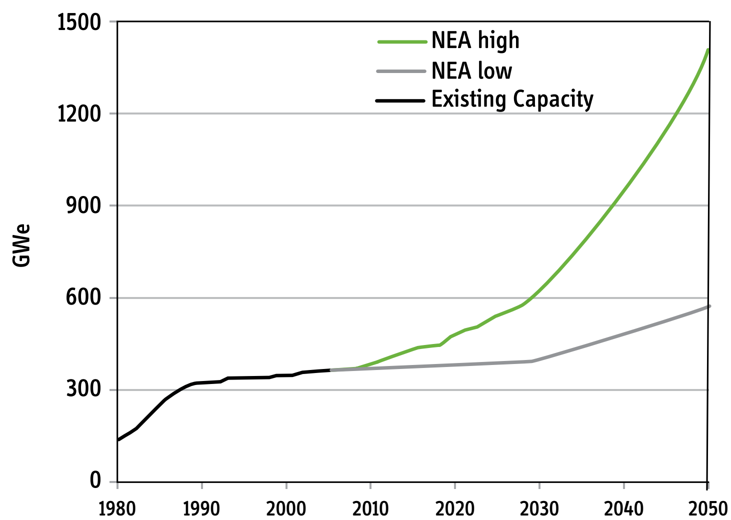

Figure 6. **Two Nuclear Energy Agency growth scenarios for nuclear power to 2050; "High" and "low".** Phase-out scenarios were also considered [NEA, 2008a, Figure 3.11].

12 At the country level, China and India have more ambitious plans than assumed in the NEA study, which assumes approximately 120 GWe in China and 90 GWe in India in 2050 (see Country studies).

Fuel cycles

Nuclear fuel is derived today from natural uranium. For the dominant reactor type, LWRs,[13] the chain-reacting uranium-235 in the uranium is enriched from its natural level of 0.7 percent to between four and five percent. Uranium in this enrichment range is called low-enriched uranium or LEU.[14] The remainder of the uranium is almost entirely non-chain-reacting uranium-238.

The fuel resides in the reactor core for a few years until most of its uranium-235 has been fissioned. About two percent of the uranium-238 is converted by neutron absorption into plutonium. About half of this plutonium too is fissioned, so that, at the time of discharge, plutonium constitutes about one percent of the heavy elements (uranium plus reactor-produced transuranic elements) in the fuel (Figure 7).

The fission products in "spent" fuel are highly radioactive and generate so much heat that the fuel must be water cooled in deep pools for several years. After this period, the fuel can be placed in air-cooled, radiation-shielded dry casks for either transport or storage [Alvarez *et al.*, 2003].

Uranium Enrichment

There are two technologies in commercial use for enriching uranium: diffusion and centrifugation of uranium hexafluoride (UF_6) gas. A third, based on selective ionization of UF_6 molecules containing uranium-235 with finely tuned lasers, may soon be commercialized.

Gaseous diffusion. Gaseous diffusion was the first uranium-enrichment technology used on a large scale in the United States, Russia, United Kingdom, France and China. It was originally developed by these countries to produce HEU for weapons. Because of all the compression work involved, gas-diffusion enrichment is very energy intensive and, because of the thousands of stages, economies of scale resulted in enormous plants. A 10-million separative work unit (SWU) gaseous diffusion plant that can supply enrichment services for 65 GWe of LWR capacity requires about 3 GWe of electrical power to operate at full capacity [Zhang and von Hippel, 2000, ref. 8]. Because of its energy inefficiency, gaseous diffusion is used today only in two plants in the United States and France, and these plants are scheduled to be shut down.

Gas centrifuge. Beginning in the 1960s in the Soviet Union and in the 1970s in Western Europe, a much more energy-efficient enrichment technology, the gas centrifuge, was deployed. UF_6 gas is spun at high speed in a vertical cylinder.

[13] The core of an LWR is cooled by ordinary "light" water. The hydrogen nuclei in the water also moderate (slow) the neutrons in its chain reaction.

[14] The IAEA defines uranium enriched to less than 20 percent in uranium-235 as LEU [IAEA, 2001]. Uranium enriched to 20 percent or higher is called highly-enriched uranium (HEU) and is considered weapon useable.

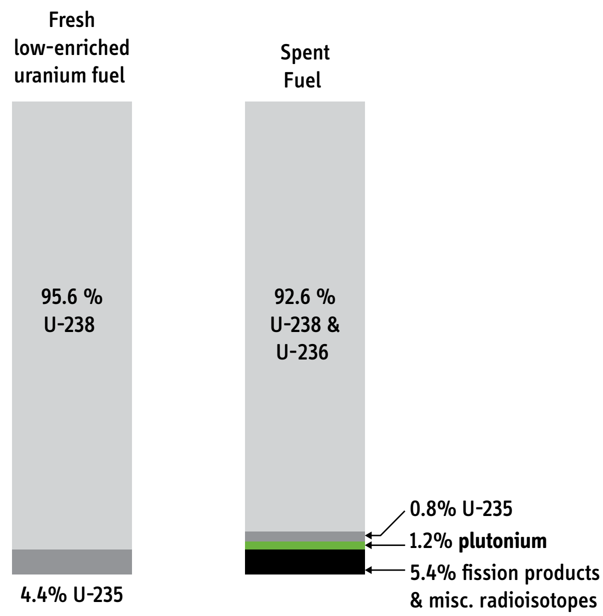

Figure 7. **Example of composition of fresh and spent light-water reactor fuel.** Fresh fuel used in standard light-water reactors is "low-enriched" in uranium-235 when it is put into the reactor core. Three to five years later, less than one percent of the U-235 remains in the "spent" reactor fuel. Most has been fissioned and somewhat less than one percent has been converted to U-236 by neutron absorption without fission. About 3.5 percent of the non-chain-reacting U-238 has been converted to plutonium and heavier "transuranic" isotopes but more half of the plutonium has been fissioned. (Based on NEA, 1989, Table 9, assuming 53 megawatt-days/kgU energy release).

Because the molecules containing uranium-238 atoms are slightly heavier, they concentrate near the wall. The fraction of the gas nearer the cylinder's axis is thereby slightly enriched in uranium-235 and can be skimmed off.

In a gas centrifuge system, the separation factor of a single stage is 1.3 to 1.7 [Glaser, 2008, Table 2].[15] For a separation factor of 1.5, only 15 stages are required to produce low-enriched and 40 to produce weapon-grade uranium. As a result, it is affordable to build small plants, and more countries have been able to acquire them—in some cases for weapons purposes (Table 3).

15 The definition of the separation factor is $[e_p(1 - e_t)]/[(1 - e_p)e_t]$, where e_p and e_t are respectively the fractional amounts of uranium-235 (enrichment) of the product and depleted "tails" from a single stage of enrichment. For low enrichment, it can be approximated as e_p/e_t.

Country	Plant (year for projected growth →) [Reference]	Capacity (10^6 SWU/year)		
		Operating	Under construction	Planned
Brazil	**Resende** (2015)	0.12 → 0.2		
China	**Shaanxi** [IBR, 2008]	1.0 → 1.5		
	Lanzhou II	0.5		
France	**George Besse II** [Areva, 2008]		7.5	
Germany	**Gronau** [Urenco, 2007]	1.8 → 4.5		
India	**Rattehalli** (military)	0.004-0.01		
Iran	**Natanz**	0.005 → 0.125		
Japan	**Rokkasho** (2017) [JNFL, 2007]	→ 1.5		
Netherlands	**Almelo** [Urenco, 2007]	3.6		
Pakistan	**Kahuta** (military)	0.015-0.02		
	Chak Jhumra, Faisalbad			0.15
Russia [IBR, 2004]	**Novouralsk**, Sverdlovsk region (2011)	→ 13.9		
	Zeleznogorsk, Krasnoyarsk region (2011)	→ 8.3		
	Angarsk, Irkutsk region (2015) [WNN, 25 June 2007]	2.5 → 10		
	Seversk, Tomsk region (2011)	→ 4.1		
United Kingdom	**Capenhurst** [Urenco, 2007]	4.2		
United States	**Urenco**, NM [Urenco, 12 December 08]		5.9	
	AREVA, Idaho		3	
	USEC, Portsmouth, Ohio		3.5	
	GLE, NC (laser) [GE-Hitachi, 2008]			3.5-6
	Total	**→ 52.5**	**19.9**	**3.65-6.15**

Table 3. **Centrifuge and laser-enrichment plants, operating, under construction and planned** (including planned expansion). All plants, other than GLE in the US, are centrifuge plants. Where references are not given, see IPFM, 2008, Table 4.2.

Laser enrichment. Laser enrichment technology has been a candidate to compete with centrifuge enrichment since the 1980s but was unsuccessful due to unresolved technical difficulties. The difficulties have apparently been overcome, and, in 2008, a joint subsidiary of GE and Hitachi, later joined by the Canadian uranium producer, Cameco, was formed to commercialize in the United States a laser-enrichment technique developed by the Silex Company of Australia [GE-Hitachi, 2008].

If all of the planned capacity shown in Table 3 is built, global enrichment capacity around 2017 will be 70-80 million SWU per year, enough to support at least 500 GWe of LWR capacity.

Spent-fuel reprocessing

In France, India, Japan and the United Kingdom, most spent fuel is shipped to a "reprocessing plant" where it is dissolved, using equipment operated remotely behind thick radiation shielding, and the uranium and plutonium are separated from the fission products (Table 4). In France, the recovered plutonium is mixed back with uranium (about seven to eight percent plutonium mixed with 92 to 93 percent depleted uranium) to make "mixed oxide" (MOX) fuel for LWRs (Figure 8). Since the plutonium from about seven tons of spent LEU fuel is required to make about one ton of MOX fuel [NEA, 1989], plutonium recycle can reduce LEU fuel requirements by approximately 15 percent. This is currently being done in France. Japan plans to do the same but its program has been delayed for a decade by mistakes and public opposition [CNIC, Nov./Dec. 2008]. Russia and China reprocess only a small fraction of their spent fuel. Some of the uranium recovered by reprocessing is also recycled [IAEA, 2007g]. If it were all recycled, it could reduce natural uranium demand by almost an additional ten percent.

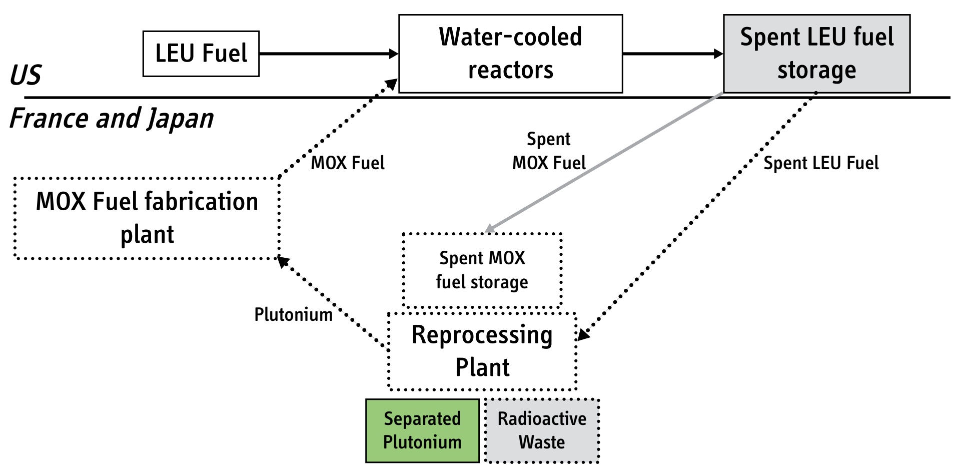

Figure 8. **Current spent fuel disposition strategies.** Above the horizontal line, the "once-through" fuel cycle as currently practiced in the United States and many other countries. LEU fuel is irradiated in a light-water reactor and then stored. The reprocessing and recycle system that is in operation in France and is planned in Japan is shown below the line. It currently involves the separation of the plutonium and its recycle once in "mixed-oxide" (MOX) fuel. The spent MOX fuel is then stored. Because of the high cost of reprocessing, the cost of producing MOX fuel is much higher than the cost of LEU fuel and most countries have decided that it is not worthwhile.

A study done for the French Prime Minister in 2000 estimated that reprocessing and plutonium recycle increases the cost of nuclear power by about 0.2 US cents/kWh [Charpin *et al.*, 2000, assuming 5 ₣/dollar (1999)]. A study for the Japanese Atomic Energy Commission in 2004 found the cost increase due to reprocessing in Japan to be about three times as large, 0.6 ¥/kWh [CNIC, 2004b].

Country	Reprocessing Plant [Reference]	Level of activity[a] (tons spent fuel per year)
China	**Yumenzhen** (LWR) [Nuclear Fuel, 7 April 2008]	50 → 100 (design)
France	**La Hague**, UP1 + UP2 (LWR) [Areva-EDF, 2008]	1050 (domestic use)[b]
India	**Tarapur and Kalpakkam** (natural-U-fueled HWRs)[c]	100 + 100 [Mian et al., 2006]
Japan	**Rokkasho** (LWR)	Not operating, 800 (design)
Russia	**Ozersk, RT-1** (LWRs, BN-600, isotope production, naval and research reactor fuel)	130[d]
U.K.	**B-205** (Magnox)[e] and **THORP** (LWR), Sellafield	B-205 to be shut down, Thorp future uncertain.

Table 4. **Civilian spent-fuel reprocessing plants.**

[a] For data on design throughput, see IAEA, 2008b, Annex I.

[b] The reprocessing of foreign fuel once constituted about 50 percent of the reprocessing activity at La Hague but Germany and Japan, the largest foreign customers, as well as Switzerland and Belgium decided not to renew their reprocessing contracts. Currently, therefore, almost all of the reprocessing of spent fuel at La Hague is of domestic fuel [Schneider and Marignac, 2008].

[c] HWR stands for heavy-water moderated reactor. In heavy water, ordinary hydrogen is replaced by heavy hydrogen (deuterium) in which the atomic nucleus contains a neutron as well as a proton.

[d] Anatoli Diakov, personal communication, 13 October 2009.

[e] Magnox reactors are natural-uranium-fueled, graphite-moderated, gas-cooled reactors. Their phase-out will be completed in 2010.

Current reactor technology

The dominant power reactor technology today is the LWR (89 percent of global operating nuclear-power capacity [IAEA-PRIS, 9 Jan. 2009].[16] The fuel is in the form of cylindrical uranium-oxide pellets about one centimeter in diameter stacked inside long thin sealed zirconium-alloy tubes. This fuel is immersed in pressurized water that both slows (moderates) the neutrons in the chain reaction as they travel from rod to rod (Figure 3) and removes the fission heat from the fuel.

16 Six percent of global nuclear-power generating capacity is heavy-water moderated reactors; five percent is graphite-moderated reactors (both water and gas cooled), and two molten-sodium-cooled fast-neutron breeder reactors constitute 0.2 percent.

There are two basic types of LWRs, pressurized (PWRs) and boiling-water (BWRs). In a PWR, the superheated water is not allowed to boil but rather transfers its heat to secondary water that boils in a "steam generator." The steam then drives a turbo-generator (Figure 9). In a BWR, the water is allowed to boil in the reactor and the high-pressure steam goes directly to the turbine.

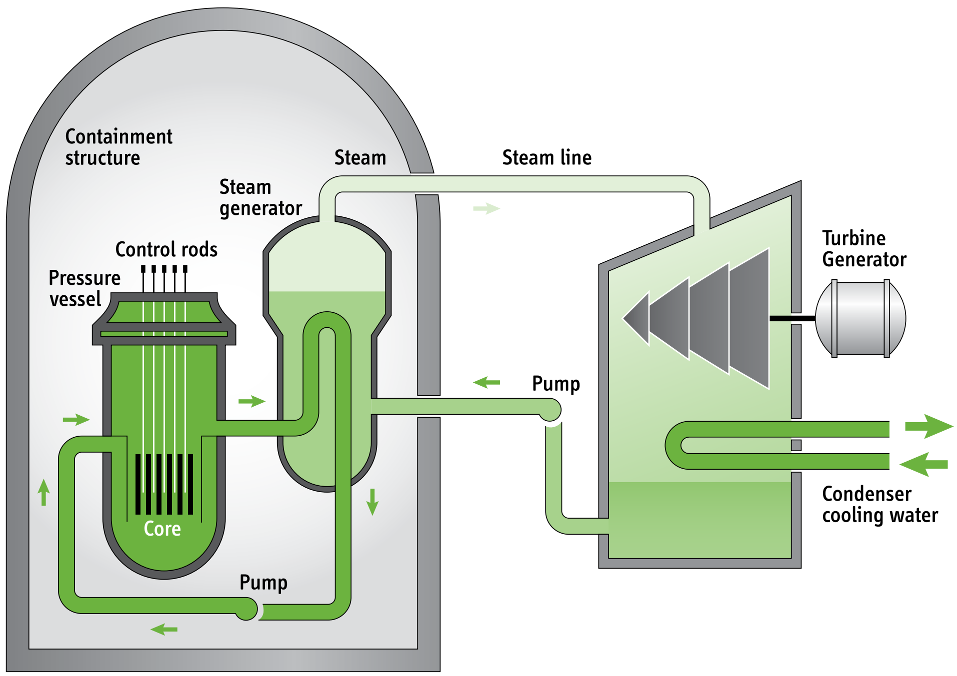

Figure 9. **Pressurized light-water reactor** [adapted from U.S. Nuclear Regulatory Commission, 2010b].

2 Costs

The cost of nuclear power is determined primarily by the capital cost of the plant. For LWRs being ordered today, this capital cost is currently both uncertain and in flux. Based on recent orders, median capital costs worldwide are running around $4000 per kilowatt electric (kWe) and projected total generating costs are in the range of $0.10/kWh. Capital costs, however, currently vary by about a factor of two above and below the median.

Figure 10 shows the result of a 2008 compilation of “overnight” costs (which in most cases are estimated) of construction per kWe of nuclear generating capacity for plants in North America, Europe and Asia. “Overnight” cost excludes interest during construction. Over a 4 to 10-year construction period, a 10-percent annual cost of capital would increase the capital cost by 28–75 percent.

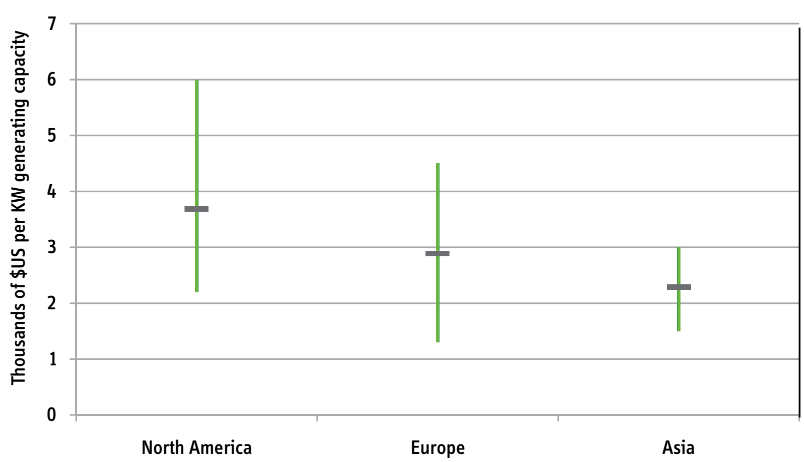

Figure 10. **Ranges of 2007-2008 “overnight” construction costs** (excluding interest during construction) for plants in North America, Europe (including Russia) and Asia [redrawn from IAEA, 2009a].

The large range of costs is attributable to a number of factors, including:

- The inclusion or exclusion of different costs, such as site costs and transmission connections;
- Biases in estimates, depending upon the institutional interests of the estimator (e.g., a vendor estimating low in order to obtain a contract to build a reactor or a utility estimating high because it wishes to obtain a larger loan guarantee);
- Whether the estimate is for the first or second reactor at a particular site, (follow-on reactors at the same site should be less costly to build); and
- Assumptions about escalation of material costs relative to general inflation.

Estimates of costs in North America are just that. No new construction has been launched since 1978. Many projects have been announced but cancellations, postponements and cost increases are announced monthly. The high end of the cost estimates in Europe are based primarily on the only two units that are under construction by Areva in Finland and France (discussed further below). The low end reflects costs quoted for Russian-built units. Fifteen nuclear power reactors are listed by the IAEA as under construction in Russia and by Rosatom in Eastern Europe. Ten of these units have, however, been nominally under construction since the 1980s. [Schneider *et al.*, 2009]. About half of the 52 power reactors listed by the IAEA as under construction today are in East Asia (25 units in China, South Korea, Japan and Taiwan). Today, nuclear-power-plant construction costs are the lowest in these countries.

The fact that estimated capital costs of nuclear power plants are higher in North America and Western Europe, where the nuclear power plant industry is being restarted with new designs, suggests that costs should come down as more plants are built. This is not certain, however. Figure 11 shows that, during the late 1970s and 1980s, the period when France and the United States brought on line most of their current nuclear power plants, the capital costs of both French and U.S. LWRs (measured in constant Francs and dollars respectively) actually increased with time. In France, the increase was roughly at the same rate as construction costs in general. In the United States, however, the cost increases were much greater than for other construction projects [Hultman *et al.*, 2007; Grubler, 2009]. Reasons for the lack of cost savings from industrial learning include that:

- Much of the cost of the construction of nuclear power plants is on-site and locally-hired workers don't benefit as much from experience at other sites;
- Quality standards are necessarily very high in the nuclear industry and mistakes often require tearing out and redoing the defective work;
- Regulatory requirements change as understanding of potential design problems improves; and
- Delays in completion result in extra interest charges.

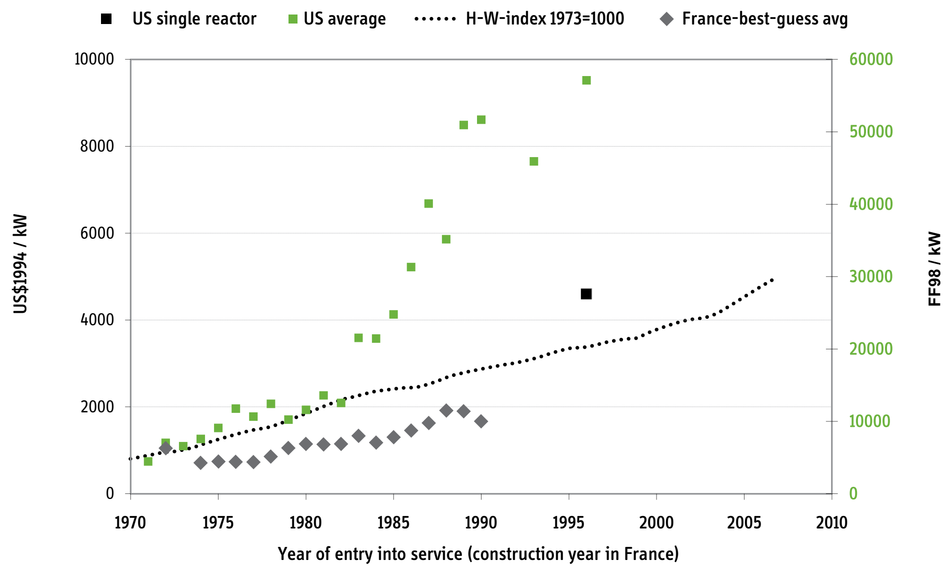

Figure 11. **French and U.S. nuclear reactor average construction costs by year** (including interest) compared with the Handy-Whitman U.S. construction cost index (1973=1000). [adapted from Grubler, 2009].

Other costs. Decommissioning costs are higher for nuclear reactors than for other infrastructure because of neutron-induced radioactivity of the primary pressure vessel and its internals. The World Nuclear Association cites without specifics costs of $200–550/kWe for water-cooled reactors [WNA, 2007] but the estimated costs for decommissioning the 0.4-GWe LWRs built by the Soviet Union range from $500-3500/kWe [IAEA, 2002]. Operating and maintenance costs are about 2 cents/kWh [Harding, 2007]. For a "once-through" fuel cycle, fuel costs are only about 0.7 cents/kWh.[17] Interim spent-fuel storage costs about 0.035 cents/kWh. Spent-fuel reprocessing costs in Japan are estimated at 0.63 ¥/kWh [0.6 cents/kWh, JAEC, 2004].[18]

Because of their high capital cost and relatively low operating cost, nuclear-power plants are ordinarily operated in a "base-load" fashion, i.e., at full power whenever they are not down for refueling, inspection, maintenance and/or repair.[19]

17 Assuming a cost of $150/kg of natural uranium, $150 per SWU, $11/kg to convert natural uranium to UF_6 or back and $300/kg of uranium for fabrication [von Hippel, 2008b].

18 Assuming a cost of $150/kg of spent fuel [Alvarez *et al.*, 2003].

19 Nuclear power reactors constitute such a large fraction of France's generating capacity that they operate in load-following mode.

Government subsidies

Nuclear power exists because of government subsidies. These include: government-funded RD&D, limitations on liability for catastrophic accidents, low-cost and guaranteed loans, and guarantees of private investments.

Research, development and demonstration. National investments in fission-energy RD&D have been huge in the nuclear-weapon states and Japan. In addition to investments in the development of enrichment and reactors for the production of nuclear weapons materials and the development of LWRs for naval propulsion,[20] an estimated $166 billion (2007$) was spent on civilian fission-energy R&D by Japan, the United States, France, the United Kingdom and Germany between 1974 and 2007 [IEA, R&D Statistics, 2009]. This is about $700 per kWe of nuclear capacity in these countries at the end of 2008 [IAEA, 2009c].

Loan and export guarantees. Some governments—notably, France, Japan and the United States—are supporting their nuclear-power industries with loan and export guarantees. These subsidies are crucial because the repayment of the capital cost of nuclear power plants largely determines the cost of the power and loan guarantees allow the purchasers of reactors to obtain the lowest possible interest rates. Loan guarantees also make it possible to finance a larger fraction of the cost of a plant with debt. This is an advantage because, even on low-risk projects, investors require about twice the rate of return on their capital as banks charge as interest on loans [US NAS, 1996, pp. 427-428]. Guarantees are even more important for nuclear power plants, which are considered a risky investment. In 2003, the U.S. Congressional Budget Office estimated, based on historical data, that the risk of default on guaranteed loans for nuclear power plants "to be very high—well above 50 percent" [US CBO, 2003]. The U.S. Energy Policy Act of 2005 (EPACT) provides government loan guarantees up to 80 percent of the project cost. Congress authorized up to $18.5 billion for this purpose in the Consolidated Appropriations Act of 2008 and, in its budget proposal for Fiscal Year 2011, the Obama Administration recommended an increase of the limit to $54.5 billion [US DOE, 2010b, Vol. 2, p. 259]. One U.S. utility estimates that a loan guarantee would reduce generation costs of electricity from its proposed nuclear power plant by 40 percent [Schneider *et al.*, 2009, p. 79].

Limitations on liability for catastrophic accidents. In most countries, nuclear power plants are government owned and the governments would decide after the fact how much restitution to make for the consequences of any catastrophic accident. In the United States, the government began encouraging private investment in nuclear power in 1954 but found the private market unwilling to invest without its liability being limited. Liability limitation was granted in the Price-Anderson Act of 1957, which has been modified and extended four times, most recently in the 2005 EPACT. In the current version, plant owners are

[20] The United States spent about $130 billion on the production of plutonium and HEU between 1948 and 1966 and $51 billion on naval nuclear propulsion between 1948 and 1996 [Schwartz, 1998, pp. 65, 143].

required to obtain the maximum amount of liability insurance available from private insurers ($300 million in 2004). Beyond, that, if an accident occurs, each owner is required to contribute up to $96 million (to be adjusted for inflation) to a pool of about $10 billion per incident to help cover damages. Beyond that, the government would be responsible [Hore-Lacy, 2008]. Estimates of the cost savings to utilities from the liability limitation are very uncertain [Heyes and Liston-Heyes, 1998; Heyes, 2002].

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3 Country studies

Brief case studies are provided below on the current nuclear expansion programs of China, India, Japan, South Korea, the United States and Western Europe.

China[21]

China's engagement with nuclear power began in 1970. Technology has been drawn from France, Canada and Russia, with local development based largely on French designs. The latest technology has been acquired from the United States (the AP1000 reactor) and France (the EPR). As of the end of 2009, China had 9 GWe of operating nuclear capacity under two companies: China National Nuclear Corporation (CNNC) and China Guangdong Nuclear Power Holding Company (CGNPC). CNNC is state owned, has a major R&D capability and provides architect-engineer services to CGNPC. Because of the planned expansion, additional power companies are co-investing in nuclear power plants but are not building or operating the plants themselves.

Prior to 2000, China was in an exploratory mode with regard to nuclear technology. Over a period of about 15 years, it built an indigenous 0.3-GWe PWR, ordered two GWe-scale reactors each from Canada (heavy-water reactors), France and Russia (PWRs) and built two PWRs in a China-France joint venture. Recently, however, the Chinese Government has committed itself to a large-scale PWR construction program that emphasizes an indigenized version of the French PWR, the CPR1000. Domestic production of pressure vessels for the Westinghouse AP1000 reactor has begun and it is proposed to develop an indigenized 1.4 GWe version, the CAP1400 [Kubota, 2009].

In March 2008, the newly-formed State Energy Bureau set a target for 2020 of five percent of electricity from nuclear power, requiring at least 50 GWe to be in operation by then. In June of 2008, the China Electrical Council projected 60

21 The sources for this section include China National Development and Reform Commission, *State Mid-Long Term Development Plan for Nuclear Power Plants (2005-2020),* Oct. 2007; and *China Nuclear Power*, Vol. 1, Nos. 1-4, 2008. See also "Nuclear Power in China," WNA, 2010b and "China's Nuclear Industry at a Turning Point" [Kubota, 2009]. We also would like to thank Dr. Yun Zhou, then of the Center for International and Security Studies, School of Public Policy, University of Maryland and currently of Harvard University's Managing the Atom Project, for sharing with us a draft of her working paper, "China's Nuclear Energy Policy: Expansion and Security Implications."

GWe of nuclear capacity by 2020. The total capacity of the nuclear power units under construction as of the end of 2009 was 20 GWe [IAEA-PRIS, 10 Jan. 2010].

In May 2007, China's National Development and Reform Commission announced that its target for nuclear-generation capacity for 2030 was 120–160 GWe, corresponding to an average rate of construction of 5–7 GWe/yr Altogether, sites have been nominated for a potential total nuclear-generating capacity of about 155 GWe. Various tax incentives have been provided for the construction of nuclear-power plants.[22]

This projected growth of China's nuclear capacity cannot be dismissed. Extraordinary growth rates have been realized in other areas of China's infrastructure. Expansion of China's nuclear industry at this rate faces multiple challenges, however—most importantly, a lack of trained personnel. Given that there are insufficient nuclear engineers being trained by the universities, engineers with other backgrounds have been recruited and given one year of training to familiarize them with nuclear technology. Construction companies with experience building coal-fired power plants are similarly being trained to build nuclear-power plants, starting with the non-nuclear buildings and turbo-generators. The capabilities of China's nuclear regulatory agency, the National Nuclear Safety Administration, will also have to be strengthened. Finally, China's nuclear operators will have to develop a safety culture, including information sharing among plants with regard to safety-related incidents. Li Ganjie, the director of China's National Nuclear Safety Administration, has warned that, "if we are not fully aware of the sector's over-rapid expansions, it will threaten construction quality and operation safety of nuclear power plants" [*New York Times*, 16 Dec. 2009]. He has also indicated that China's nuclear industry is challenged on all fronts [Kubota, 2009]:

- Shortages of trained personnel;
- An inadequate foundation in R&D;
- Lack of manufacturing and installation capabilities;
- Inadequate management;
- Weak safety oversight; and
- Insufficient dialogue with the concerned public.

China's ambition to generate nuclear energy on a large scale has attracted the country's largest heavy-engineering enterprises to develop the capacity to manufacture nuclear-power-plant equipment. Most of the equipment used

[22] These tax incentives for the construction of nuclear power plants include: 1) A rebate of 75 percent on the value-added tax during the first five years of operation, decreasing to 70 percent in the following five years and 55 percent for the third five-year period; 2) A waiver of tariffs on the import of nuclear energy equipment and materials that cannot be produced domestically; 3) A rebate on land-use taxes on land associated with nuclear power plants; and 4) A 15 percent income tax rate with a reduced tax base and possible tax waiver (Dr. Yun Zhou, personal communication, 22 April 2009).

in nuclear power plants, including steam generators, main pumps and high-pressure piping, can be manufactured in China. The China First Heavy Industries Corporation has developed the capability to produce pressure vessels for GWe-class pressurized-water reactors as well.

Uranium Supply. China's known resource of uranium at a recovery cost of less than $130/kg is 70,000 metric tons of uranium but estimates of undiscovered resources in favorable areas exceed one million tons [NEA, 2008c, Table 2 and p. 155]. Domestic production of 840 tons per year supplies about half of China's current requirements. The remainder is reportedly imported from Kazakhstan, Russia and Namibia. In 2006, China signed a deal with Australia to buy up to 20,000 tons of uranium a year, enough for about 100 GWe of LWR capacity [BBC, 3 April 2006].

Fuel cycle–front end. China's original enrichment plants used gaseous-diffusion technology but have been replaced with gas-centrifuge plants imported from Russia under 1992, 1993 and 1996 agreements between the Tenex subsidiary of Rosatom and the China Nuclear Energy Industry Corporation. The agreements have resulted in the construction of 1.5 million SWU/yr of enrichment capacity in China at two sites based on Russian sixth-generation centrifuges with expansion by an additional 0.5 million SWU/yr underway. This is enough for about 17 GWe of LWR capacity. Reportedly, additional capacity expansion is planned [Kubota, 2009]. China also buys enrichment services abroad. A contract with Urenco supplies 30 percent of the enrichment for the two 0.944-GWe LWRs at Daya Bay and Russia's Tenex nuclear-exporting company has agreed to supply 6 million SWU in LEU to China between 2010 and 2021.

*Spent fuel and reprocessing***.** In 1987, China announced at an IAEA conference that it was pursuing a "closed" fuel cycle. Accordingly, CNNC has drafted a state regulation requiring the reprocessing of power-reactor spent fuel. Construction of a centralized spent-fuel storage facility for a pilot reprocessing plant at the Lanzhou Nuclear Fuel Complex near Yumenzhen in Gansu province began in 1994. The initial storage capacity is 550 tons, which could be doubled. The pilot PUREX reprocessing plant has a capacity of 50 ton/yr, which also could be doubled.

In November 2007, Areva and CNNC signed an agreement to assess the feasibility of building commercial-scale reprocessing and MOX fuel fabrication plants in China, at an estimated cost of €15 billion. In mid-2008 CNNC stated that an 800 ton/year reprocessing plant operated by Areva would start operations in 2025, probably in Gansu province in far western China. High-level reprocessing wastes would be vitrified, encapsulated and put into a geological repository 500 meters below the surface. Site selection for a repository is focused on six candidate locations and is to be completed by 2020. An underground research laboratory would then operate for 20 years and actual disposal would begin in 2050.

India

India's nuclear power program dates back to the late 1940s. Thanks to decades of sustained government support, the Department of Atomic Energy (DAE) has developed expertise and facilities that cover the entire nuclear fuel cycle, from uranium mining to the reprocessing of spent nuclear fuel [Sundaram *et al.*, 1998].

Most of India's current power-reactor capacity is based on 0.22-GWe Heavy Water Reactors (HWRs), modified versions the CANDU reactors India imported from Canada before its 1974 nuclear test resulted in a cutoff of its nuclear imports. Two Russian 1-GWe LWRs are under construction at Kundankulam at the southern tip of India, with plans for two to four more such reactors at the same site over the next decade. A 0.5-GWe Prototype Fast Breeder Reactor, to be fueled with MOX (plutonium-uranium) fuel, is under construction at Kalpakkam on the southeast coast.

The DAE's program is still based on the three-stage strategy first announced in 1954 by the founder of India's nuclear program, Homi Bhabha [Bhabha and Prasad, 1958]:

1. Heavy-water-moderated reactors fueled with natural uranium. The spent fuel is being reprocessed to recover the produced plutonium.
2. The separated plutonium is to be used to provide startup cores for fast-neutron plutonium-breeder reactors. These cores are to be surrounded by "blankets" of either natural or depleted uranium in which more plutonium will be produced to provide startup fuel for more breeder reactors.
3. After a large enough fleet of breeder reactors has been established, thorium is to be substituted for uranium in the fast-breeder reactor blankets to produce fissile uranium-233. The uranium-233 will be used to fuel the fast-neutron reactors, which would operate with a lower breeding ratio—but still above a self-sustaining level—using India's abundant thorium resources as their ultimate fuel.

DAE planners have a history of making optimistic projections for the growth of nuclear power in India. In 1962, Bhabha predicted that India would have 20–25 GWe of installed heavy-water and breeder-reactor capacity by 1987 [Hart, 1983, p. 61]. This was subsequently replaced by the goal of 43.5 GWe of nuclear capacity by 2000 [Sethna, 1972]. At the end of 2009, however, India's nuclear capacity amounted to just 4 GWe, about three percent of the country's total electric-power generation capacity [IAEA-PRIS, 11 Jan. 2010].

Prior to the 2008 lifting by the Nuclear Suppliers Group (NSG) of its ban on uranium and nuclear-technology trade with India, the DAE was projecting a nuclear-generating capacity of 20 GWe by the year 2020 and 275 GWe by the year 2052 [Grover and Chandra, 2006]. Since the NSG waiver, there have been even higher predictions [*Financial Express*, 14 Oct. 2008; India, Ministry of Power, 2008]. A more cautious nuclear growth projection for India has been offered by the U.S. Energy Information Administration (EIA). Its reference case forecast is for India's nuclear power capacity to grow to 20 GWe by 2030 [US EIA, 2008d].

Uranium constraint. India has known resources of about 60,000 metric tons of low-cost uranium [NEA, 2008c, p. 207], sufficient for a 40-year-lifetime supply for only about 10 GWe of HWR capacity. India's relatively small resource base of uranium has been the primary justification for the DAE's plans to build only 15 GWe of heavy and light-water cooled reactor capacity and to focus on breeder reactors designed to have a very high breeding ratio for plutonium.[23] This justification has not changed despite the lifting of the NSG ban on exporting natural and enriched uranium to India.

The plutonium supply constraint. But the rate at which India can build up its breeder capacity is limited by the rate at which it can produce excess plutonium for initial cores. The DAE assumes a starting capacity of 6 GWe of high-breeding-ratio, metal-fueled breeder reactors in 2022. This would require about 22 tons of fissile plutonium for startup fuel. Because of the limited rate of plutonium production by India's heavy-water reactors, the DAE's stock of fissile plutonium is unlikely to exceed this amount by 2022.[24] Of this inventory, the DAE plans, however, to use at least 15 tons for startup fuel and the first two fuel reloads for the four oxide-fuel-based breeder reactors with a low breeding ratio that are to be an intermediate step toward the more advanced metal-fueled breeder reactors. The remaining plutonium therefore will be sufficient only to start about 1 GWe of metal-fueled breeder reactor capacity by 2022.

The growth rates that DAE projects after 2022 also are unachievable. Even with a fuel residence time inside the reactor of two years and an optimistic out-of-reactor time of only two years to cool the spent fuel, reprocess it and fabricate the extracted plutonium into new fuel, it would take four years for a given batch of plutonium loaded into a breeder reactor to become available for recycle with some extra bred plutonium that could be used as startup fuel for new breeder reactors.

23 The breeding ratio is increased by eliminating material that could slow down the neutrons. For this reason, all of India's fast breeder reactors after 2020 are proposed to be fueled with metal fuel rather than the higher-melting-point oxide fuel that has been used in demonstration reactors in other countries [Grover and Chandra, 2006].

24 The fissile or chain-reacting isotopes of plutonium are plutonium-239 and plutonium-241. The spent fuel of India's pressurized heavy water reactors contains about 2.6 kilograms of fissile plutonium per ton. The amount of plutonium that India can separate is limited by the capacity of its two reprocessing plants, which each can only reprocess 100 metric tons of spent-fuel per year. Little is known about the operations of these plants except that the older operated at a 25-percent capacity during its first ten years (1982–1992). The second began operations in 1998. Assuming that the reprocessing plants operated and will operate at an average of 80-percent capacity otherwise, they will have separated about 10 tons of fissile plutonium through 2018. That is the earliest that India could bring on line additional reprocessing capacity. Assuming that its reprocessing capacity steps up to 2000 tons per year thereafter, and operates at 80-percent capacity, it could separate out another 13 tons of fissile plutonium during 2019–2021 [Ramana and Suchitra, 2009].

A careful calculation finds that the plutonium growth rate is lower than in the DAE's estimate and the achievable metal-fueled breeder reactor capacity in 2052 would be less than 25 percent of the 260 GWe projected by the DAE [Ramana and Suchitra, 2009]. Unless India's nuclear establishment shifts its focus away from breeder reactors, nuclear power therefore is unlikely to contribute significantly to electricity generation in India for the next several decades.

*Cost of breeder electricity***.** Even if the capital costs of breeder reactors were the same as those of heavy water reactors, electricity from the breeders would be more expensive because of the high costs of reprocessing breeder spent fuel and fabricating plutonium fuel. The cost of electric-power generated from India's first commercial-scale breeder reactor would be at least 80 percent higher than from heavy water reactors—mostly because of the high fuel cycle costs associated with reprocessing and the fabrication of plutonium-containing fuel [Suchitra and Ramana, submitted for publication]. Breeders are competitive with heavy water reactors fueled with natural uranium and operating on a once-through fuel cycle only for uranium prices well above $1000/kg—vs. a typical average price of around $50/kg during recent decades.

Japan

Japan has the world's third largest nuclear generating capacity. It is one of the few non-weapon states with an enrichment program, and the only one that reprocesses spent fuel.

Nuclear Generation Capacity and Projections. As of the end of 2009, Japan had fifty-three operational commercial LWRs with a generating capacity of 47 GWe. Two LWRs (2.7 GWe) were under construction[25] and ten (13.6 GWe) were planned to be commissioned by 2020. Some of Japan's older reactors are being decommissioned while others are proposed to have their licenses extended.[26] According to the current plans of the electric utilities, a total of 66 LWRs (65.1 GWe) will be operating in 2020. Although Japan's projections for nuclear power growth have been overly optimistic in the past, the goal of 61.5 GWe by 2030 may be achievable. A new government plan under discussion would reduce Japan's CO_2 emissions by 50 percent by 2050. According to one estimate, in order to reach that goal, Japan would have to have 90 GWe of nuclear power by 2050 [CRIEPI, 2008].

Uranium Enrichment Capacity. Japan Nuclear Fuel Limited (JNFL), the nuclear-fuel-cycle subsidiary of Japan's nuclear utilities, started operating Japan's first commercial enrichment plant with a capacity of 150,000 SWU per year in 1992. Its capacity was increased every year by one cascade line with a capacity of

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[25] Two 1.37-GWe Advanced Boiling Water Reactors: Shimane-3 and Ohma, which are scheduled to go into operation in 2011 and 2012 respectively.

[26] On February 17, 2009, Japan Atomic Power published its plan to extend the operation of Tsuruga-1, a 0.357-GWe boiling water reactor, commissioned in 1966, for another 20 years.

150,000 SWU/yr until it reached a nominal capacity of 1.05 million SWU/yr as of January 2009. Five of the seven cascade lines have been shut down permanently by technical troubles, however. Cumulatively, only about one million SWUs have been produced.[27]

JNFL launched development of a more advanced type of replacement centrifuge in 2000. Prototypes began testing with UF_6 gas in 2007. JNFL plans to introduce the new centrifuges into commercial operation starting in 2010 and hopes to achieve an enrichment capacity of 1.5 million SWU/yr by around 2020 [JNFL, 2007].

Spent-fuel Management. The local governments hosting Japan's power reactors generally oppose the expansion of on-site storage and no local government is willing to host a central spent-fuel storage facility. Japan's policy therefore is to reprocess its spent fuel. In the late 1970s, Japan contracted to ship 5500 tons of spent fuel to France and the United Kingdom for reprocessing [Albright *et al.*, 1997, Tables 6.4 and 6.5]. Japan subsequently decided to build a domestic reprocessing plant at Rokkasho, the northern tip of the main island, with a design capacity of 800 tons a year of uranium throughput. Commercial operation of this plant was to begin in 2003 but, due to various technical problems, has been postponed repeatedly—most recently till late 2010 [see, e.g., CNIC, 2009b].

As a result of the many years of delays in the startup of the Rokkasho Reprocessing Plant, Japan has a developing shortage of spent-fuel storage capacity. As of September 2007, 12,140 tons of spent nuclear were stored at nuclear power plant sites in Japan [JAEC, 2008]. Utilities were installing new racks for denser storage in the pools and transferring spent fuel from one pool to another within the same site. A three-thousand-ton capacity spent-fuel storage pool at the Rokkasho reprocessing plant started accepting spent nuclear fuel in 2000 but was almost full (2,817 tons of spent fuel) as of the end of 2008 [JAEC, 2008]. The first away-from-reactor interim storage facility at Mutsu city in Aomori prefecture near the reprocessing plant is to start operating at partial capacity in 2010. Ultimately, it is to have 5,000 tons of spent-fuel storage capacity. Japan will need about five interim storage facilities of this scale by 2050, even if the reprocessing plant operates as planned [Katsuta and Suzuki, 2006; Japan-METI, 2008].

Reprocessing at Japan's Tokai pilot reprocessing plant is being phased out. The reprocessing of spent fuel that Japan sent to France and the United Kingdom has been completed. As a result of its foreign reprocessing program and domestic pilot program, as of the end of 2008, Japan had about 47 tons of separated plutonium,

[27] 1,599 tons of uranium have been enriched. Assuming 4.4 percent enrichment with 0.3 percent of uranium-235 in depleted uranium, this would correspond to 1.2 million SWU.

mostly in France and the United Kingdom [IAEA-INFCIRCs549, Japan, 2009].[28] Japan's second commercial reprocessing plant, originally scheduled to begin operating in 2010, is now not scheduled to become operational before 2040.

MOX fuel program. As a result of various scandals and public opposition, Japan's plan to partially fuel 16 to 18 LWR power plants with MOX fuels made from Japanese plutonium in Europe by 2010 has been delayed [CNIC, Nov./Dec. 2008]. The loading of the first MOX fuel into a Japanese LWR (Genkai 3) finally occurred in October 2009 [WNN, 5 Nov. 2009].

JNFL plans to produce MOX fuel for Japan's LWRs from plutonium separated in Japan. A commercial MOX fuel fabrication plant is to be built next to the Rokkasho Reprocessing Plant with a maximum capacity matched to that of the reprocessing plant, about ten tons of plutonium mixed with 120 tons of uranium to make 130 tons of MOX fuel per year. Construction was to have started in October 2007 but the plant is still in the pre-construction licensing phase. According to JNFL, it is to start its commercial operation in 2015 [JNFL, 2010].

Breeder Reactor R&D. Japan's first experimental breeder was the Joyo [140 megawatt thermal (MWt), no electricity generation] which has operated about 27 percent of the time since it achieved first criticality in 1977. Japan's prototype 280 megawatt-electric (MWe) fast breeder reactor, Monju suffered a sodium leak and fire in 1995 after its first three months of operation. After repairs and many delays, it finally restarted 15 years later on 8 May 2010. In 2006, the Nuclear Energy Subcommittee of the Ministry of Economy, Trade and Industry's Advisory Committee published a long-term program under which a follow-on demonstration breeder reactor would be built by 2025. Commercialization of breeder reactors, the original justification for Japan's reprocessing program, has slipped by 80 years from 1970 to 2050 [Japan-METI, 2006; Suzuki, 2010].

High-level radioactive waste disposal. In May 2000, a "Law Concerning the Final Disposal of Specific Radioactive Waste" was passed that outlines the legal responsibility, cost sharing and site-selection processes. A voluntary site selection process started in December 2002. Thus far, only one application (Toyo Town) was received and officially accepted, but was subsequently withdrawn due to local public opposition.

Budget. Japan accounts for almost half of the total nuclear-energy R&D carried out in all the OECD countries. For 2007, it was ¥261 billion ($2.2 billion) about 65 percent of Japan's budget for energy R&D [IEA, R&D Statistics].

28 Since 2007, Japan's government has been reporting to the IAEA only the quantity of "fissile" isotopes (plutonium-239 and plutonium-241) held abroad. Based on a comparison of the declarations of 2005 and 2006 with 2007, these numbers must be multiplied by approximately 1.5 to recover the number for tonnage of total plutonium.

South Korea[29]

The Republic of Korea (ROK) has the world's fifth largest nuclear-generating capacity; 20 units with a capacity of 17.7 GWe, with eight units (9.6 GWe) under construction as of the end of 2009 and four more (5.6 GWe) planned for completion by 2021. Except for four heavy-water reactors, all of these reactors are pressurized light-water reactors (PWRs). All are located at four sites. The new reactors are all of Korean design with all the major components, including pressure vessels, produced in Korea. South Korea has been actively trying to export its reactors and, at the end of 2009, obtained a $20 billion contract from the United Arab Emirates for four 1.4-GWe reactors to be completed by 2020 and another $20 billion contract to jointly operate them for 60 years [Reuters, 27 Dec. 2009].

South Korea has the world's largest nuclear-power program without a national enrichment or reprocessing facility. This reflects the desires of its close ally, the United States, and also the 1992 Joint Declaration with North Korea on the Denuclearization of the Korean Peninsula, under which the two countries agreed not to acquire enrichment or reprocessing facilities. North Korea violated this agreement and there is resentment within South Korea's nuclear establishment that the United States acquiesced to Japan acquiring these technologies and not South Korea. After North Korea's May 2009 nuclear test, there were calls from South Korea's opposition party for "nuclear sovereignty," i.e., that South Korea should have the same rights as Japan.

As in Japan, the spent-fuel pools at South Korea's older reactors are filling up and local governments are resisting the construction of more on-site storage. As a solution to the problem, South Korea's Korea Atomic Energy Research Institute (KAERI) promotes a form of reprocessing, "pyroprocessing,"[30] and the use of liquid-sodium-cooled fast-neutron reactors to fission the recovered plutonium and minor transuranic elements. This vision is supported by one of the ROK's R&D ministries, the Ministry of Education, Science and Technology but not the Ministry of Knowledge and Economy, which is closer to South Korea's national nuclear utility and is worried about the cost. The G.W. Bush Administration was also interested in pyroprocessing and supported joint R&D between the U.S. Department of Energy's (DOE) nuclear laboratories and KAERI.

South Korea, like most other countries with nuclear-power programs, is having difficulty siting radioactive-waste repositories. It succeeded in siting an underground low and intermediate-level radioactive waste repository at one of its reactor sites in exchange for $300 million for the local government plus $600 per waste drum for up to 800,000 waste drums and a commitment by the government-owned utility, Korea Hydro and Nuclear Power, to move its headquarters and staff from Seoul to a small city adjoining the site [Park Seong-won *et al.*, 2010]. This

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29 This section is mostly based on von Hippel, 2010.

30 In pyroprocessing, spent fuel is dissolved in molten salt and the transuranics are separated electrochemically.

is still small, however, in comparison to Japan's trillion-yen ($10 billion) subsidy to Aomori prefecture for accepting the Rokkasho Reprocessing Plant [Takubo, 2008] and the ¥11 trillion ($100 billion) estimated cost of building, operating and decommissioning the Rokkasho reprocessing plant [CNIC, 2004a].

Russia

Russia has the world's fourth largest nuclear generating capacity, 21.8 GWe, provided by fifteen PWRs, eleven graphite-moderated, water-cooled RBMK-1000 (Chernobyl-type) reactors and the BN-600 sodium-cooled fast breeder prototype reactor.[31] The expansion of this capacity and foreign sales of Russian-designed reactors and fuel-cycle services have become a key economic goal of the Russian government. In April 2007, President Vladimir Putin consolidated Russia's civilian nuclear activities into one giant state-owned company, Atomenergoprom under Rosatom, which operates Russia's military nuclear programs as well [*Moscow Times*, 2 May 2007].[32]

Five 1-GWe PWRs and a 0.8-GWe demonstration breeder reactor are currently under construction [IAEA-PRIS, accessed 16 Jan. 2010].[33] According to the Russian Government's 2008 long-term plan [Russian Federal Target Program, 2008], starting in 2009, construction was to be initiated each year on two new 1.2-GWe PWRs. By the end of 2015, eleven new nuclear power units were to be put into operation and construction was to be initiated on an additional ten (see Figure 12). In late 2009, the schedule slipped and only eight of the PWRs are to be completed by the end of 2015 [WNA, 2010a].[34] Beyond 2015, Rosatom is supposed to find its own funding.[35]

Outside Russia, Rosatom has under construction two VVER-1000 PWRs at the Belene nuclear power plant (NPP) in Bulgaria, two at the Koodankulam NPP in India and one at the Bushehr NPP in Iran [Rosatom, 26 Sept. 2008]. Russia has agreements with India to construct eight more VVER-1200s in India (four at Koodankulam and four in West Bengal) and with China to construct two more at the Tianwan nuclear power plant in China, where two VVER-1000s are already operating [WNA, 2010a].

31 The numerical suffixes indicate the approximate gross electric power-generating capacity in MWe. The net capacity is typically about 10-percent lower [see IAEA-PRIS].

32 Rosatom's English-language website may be found at http://www.rosatom.ru/en/.

33 One graphite-moderated reactor, Kursk-5, has also been listed as under construction since 1985. Barge-mounted reactors are discussed separately here.

34 The reactors under construction at the end of 2009 plus Rostov-3 (also known as Volgodansk-3) and two VVER-1200 light-water reactors, Leningrad-2 and -3.

35 After 2015, Rosatom plans to build two VVER-1200s per year, costing an estimated $4.6 billion. According to Figure 12, in 2015, Atomenergoprom would have a capacity of 33 GWe. Assuming that these reactors operate at an 80 percent capacity factor, they would generate 0.23 trillion kWh per year. Atomenergoprom, therefore, would have to be raising 2 cents for capital investment per kWh generated.

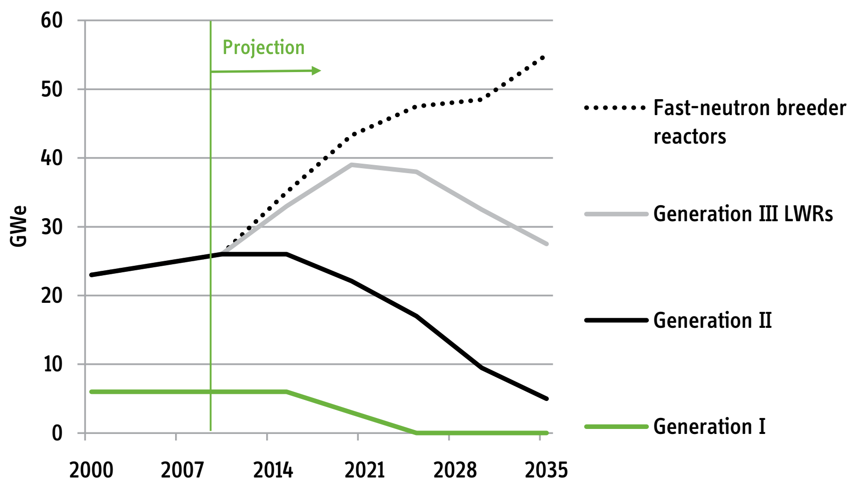

Figure 12. **Plans for Russian nuclear power expansion as of 2007** [adapted from Saraev, 2007].

Uranium supply. Russia's confirmed uranium reserves could support about 100 GWe of LWR capacity for 45 years.[36] All uranium mining activity has been consolidated within Rosatom under Atomredmetzoloto OJSC (ARMZ). ARMZ plans a major expansion of its uranium mining, including joint ventures in Kazakhstan. If these plans are realized, in 2025, ARMZ will be mining enough uranium to support about 100 GWe of LWR capacity. ARMZ is also planning joint ventures with companies in Canada, Armenia, Mongolia and the Republic of South Africa [Atomenergoprom, 2008a].

Reprocessing. Russia has a small reprocessing plant (Mayak) near Chelyabinsk in the Urals at which it reprocesses the spent fuel of the last three of its first-generation VVER-400 reactors, along with its fast-reactor naval and research-reactor spent fuel. Russia has declared to the IAEA that, as of the end of 2008, about 45 tons of civilian separated plutonium were stored at its reprocessing

[36] Operating at a 90-percent capacity factor, a 1-GWe VVER would require 140–200 tons of natural uranium per year, assuming 0.1 to 0.3 percent uranium-235 in the depleted uranium. In 45 years, 100 GWe of VVER capacity would, therefore, require 630,000–900,000 tons of natural uranium. Russia is reported to have 545,600 metric tons of uranium in "Reasonably Assured Resources" plus "Inferred" extensions of explored deposits recoverable at up to $130/kgU, plus 276,000 tons in "prognosticated" resources (estimated resources in partially explored geologies) and 714,000 tons in "speculative" resources (undiscovered resources based on statistical inferences from geological types) [NEA, 2008c]. The price of uranium in 2009 was about $100/kgU.

plants [IAEA-INFCIRCs/549, Russia, 2009].[37] Rosatom is funding R&D related to the possibility of building a pilot reprocessing plant on the site of the never-completed RT-2 reprocessing plant at the Krasnoyarsk Mining and Chemical Combine in Zhelznogorsk [Russia Federal Target Program, 2006].[38]

Breeder reactors. As shown in Figure 12, Russia's nuclear establishment, like India's, is planning on the near-term, large-scale commercialization of plutonium breeder reactors. One 0.8-GWe BN-800 sodium-cooled reactor, on which construction began 1985, is now scheduled to be put into operation in 2014 [AtomInfo, 2009]. China is seriously considering ordering two units [WNA, 2010b]. A 1.8-GWe BN-1800 is being designed to be deployed in the 2020s. In January 2010, the Russian Government approved a ten-year 110 billion ruble ($3.6 billion) federal target program for the development of fast-neutron reactors and their fuel cycle [Rosatom, 22 Jan. 2010].

MOX fuel for Russia's first plutonium breeder reactors could be fabricated using Russia's separated civilian plutonium. In addition, Russia has committed to dispose of 34 tons of excess weapon-grade plutonium in parallel to U.S. use of an equal amount of excess weapon-grade plutonium in MOX LWR fuel. Russia plans to dispose of its excess weapon-grade plutonium in breeder-reactor fuel. Until Russia builds a MOX-fuel-fabrication pilot plant, however, the BN-800 will be fueled with HEU enriched to slightly above 20 percent—as the BN-600 has been since 1980 [Nigatulin and Kozyrev, 6 May 2008].

United States

The United States has the world's largest nuclear-generating capacity, 104 power reactors with a net generating capacity of 100.6 GWe as of the end of 2009 [IAEA-PRIS]. Construction on all of these reactors began before 1978, more than three decades ago [US, EIA, 2008e]. As of the end of 2009, however, U.S. utilities had applied for 18 combined construction and operating licenses for 28 reactors with a total capacity of 37 GWe [US NRC, 2010a]. At the end of 2009, only 12 of these applications were active,[39] however, and only five had signed engineering,

[37] It is possible that this includes some of the separated plutonium stored at the Seversk and Zhelznogorsk reprocessing plants. These plants produced weapon-grade plutonium for Russia's weapons program but, according to the 1997 Russian-U.S. "Agreement…Concerning Cooperation Regarding Plutonium Production Reactors," any plutonium separated at these plants after January 1, 1997 would not be used for weapons purposes [Russia-U.S. Agreement, 1997, Annex III, Subsidiary Arrangement B, Article II].

[38] According to Task 30 of the 2006 Federal Target Program, sources other than the federal budget (presumably Rosatom) are to supply 1.617 billion Rubles ($65M at $24.6/ruble) through 2015 for R&D in support of a pilot reprocessing plant at the Krasnoyarsk Mining and Chemical Combine.

[39] The applications for Callaway, Unit 2, Grand Gulf Unit 3, River Bend Unit 3, and Victoria County Station Units 1 and 2 are shown as suspended and that for Nine Mile Point Unit 3 has been inactive since 2008 and the review of the application for Turkey Points Units 6 and 7 has not yet begun (see application review schedule for each project at US NRC, 2010a).

procurement and construction contracts with reactor vendors (for nine reactors) [WNA, 2010c]. As of the end of 2009, the IAEA still listed only one reactor under construction in the United States; the Tennessee Valley Authority's Watts Bar II, a reactor on which construction began in 1973 but was suspended in 1988 when it was about 80-percent complete because of a reduction in the growth rate of U.S. electric power demand [Reuters, 1 Aug. 2007].

Renewed U.S. interest in nuclear power reflects in part concerns about the future cost of natural gas, following a temporary quadrupling in well-head prices between 1998 to 2008 [US EIA, 2010] and a move away from coal-fired power plants because of anticipation of policies aimed at reducing greenhouse gas emissions. It also reflects government incentives. In the Energy Policy Act of 2005 (EPACT), the U.S. Government created major incentives to investors to commit quickly to build new nuclear power plants. This includes government loan guarantees equal to up to 80 percent of project cost. Congress authorized up to $18.5 billion for this purpose in the Consolidated Appropriations Act of 2008. In June 2008, the DOE solicited requests for the loan guarantees. The response was applications for $122 billion in guarantees to cover 65 percent of the cost of 21 reactors with a total generating capacity of 28.8 GWe [US DOE, 2008a]. In its budget proposal for Fiscal Year 2011, the Obama Administration proposed to increase the funding available for nuclear loan guarantees to $54.5 billion [US DOE, 2010b, Vol. 2, p. 259]. Four companies were on the short list for the first tranche of loan guarantees. They are also four of the five companies that have signed engineering, procurement and construction contracts for new nuclear power plants [Bloomberg, 17 Dec. 2009]. (The fifth was responding to state-level incentives, see below). In January 2010, one of the utilities received a loan guarantee for $8.3 billion that reportedly would cover up to 70 percent of the project cost for two 1.1-GWe reactors, which would correspond to a cost of at least $5.4 billion/GWe. Additional loan guarantees might be supplied by the Japanese government because the reactors will be built by Westinghouse, which is now a subsidiary of Toshiba [*New York Times*, 17 February 2010].

EPACT also allows for up to $2 billion to compensate companies building the first six nuclear power reactors for regulatory delays in the startup process. Finally, EPACT provides for a production tax credit of 1.8 cents per kWh, up to a total of $6 billion, for power produced by 6 GWe of advanced nuclear power capacity during its first 8 years of operation.[40]

[40] The U.S. Congressional Budget Office puts the limit at $7.5 billion [US CBO, 2008].

State-level policy is also important in the United States. Thirty-six out of the 50 states regulate the investments of utilities in the generation and transmission of electric power.[41] Under these regulations, if a state regulatory authority authorizes investment in the construction of a power plant, the investor is allowed to charge customers for the cost of building and operating that power plant plus a guaranteed rate of return.

In Florida, the Public Service Commission has gone further and permits investors to start charging the customers even before a nuclear power plant is under construction. If, for some reason, the plant is never completed, the owners of the reactors still will be entitled to recoup "prudent" costs from their customers.[42] The only utility that has signed engineering, procurement and construction contracts for new nuclear power plants without the expectation of a loan guarantee is Progress Energy, a Florida utility that is the beneficiary of such a ruling. Georgia has a similar policy [WNN, 18 March 2009]. Plans for a plant in Missouri were shelved after the utility was unable to obtain repeal of a state law banning charges for Construction Work in Progress [*Fuel Cycle Week*, 24 April 2009].

The U.S. EIA projected at the end of 2009 that only 8.4 GWe of new nuclear electric generating capacity will actually come on line in the United States by 2035 [US EIA, 2009a]. After 2030, U.S. nuclear power plants will achieve 60 years of operation at an average rate of about 5 GWe per year and U.S. power reactors will have to be licensed to operate for more than 60 years—a possibility that is already being discussed—or the rate of reactor construction will have to increase greatly if U.S. nuclear capacity is not to decline [US EIA, 2008b].

Western Europe

At the end of 2009, nuclear capacity in Western Europe totaled 122 GWe with two 1.6-GWe units under construction in Finland and France by the French company Areva [IAEA-PRIS].

In seven out of the nine Western European countries with operating nuclear reactors, the youngest reactor was built in the 1980s (or earlier, in the case of the Netherlands). The United Kingdom completed one reactor in the 1990s. France completed an average of one power reactor per year during the 1990s but none

[41] Fourteen states have deregulated electric power production (Connecticut, Delaware, Illinois, Maryland, Maine, Massachusetts, Michigan, New Jersey, New Hampshire, New York, Ohio, Pennsylvania, Rhode Island, Texas). Eight have re-regulated (Arkansas, Arizona, California, Montana, Nevada, New Mexico, Oregon, Virginia). The remaining 28 states never deregulated [US EIA, 2008f].

[42] In late 2008, the Florida Public Services Commission authorized two utilities to charge their customers \$0.6 billion during 2009 for pre-construction expenses they expected to incur for four nuclear power reactors that they hoped to build [Florida Public Service Commission, 2007/8]. One of the utilities, Florida Public and Light, estimated that its completed cost for building two Westinghouse AP1000s would be \$5,780–8,071/kWe [*Nucleonics Week*, 21 Feb. 2008].

since.[43] Due to retirements, Western Europe's nuclear generating capacity has declined by about 4 GWe since 2000 [IAEA, 2007a and 2009c]. Unless the reactor licenses are extended or the rate of construction picks up, Western Europe's nuclear capacity will continue to decline.

France accounts for a little more than half of West Europe's nuclear capacity (63.2 GWe) and for one of the two new units under construction [IAEA, 2009c, Table 1]. The equivalent of about 76 percent of France's electricity is generated by nuclear power [IAEA, 2010a]. France is a major net exporter of electric power [Schneider *et al.*, 2009, p. 101]. France's national utility, Électricité de France, is also investing in nuclear power plants in China, the United Kingdom and the United States—and possibly in Italy and South Africa as well [WNN, 4 Dec. 2008a]. Both of the new 1.6-GWe EPR reactors being built by Areva are suffering, however, from serious delays and cost overruns. As of the end of 2008, the EPR under construction at Flamanville, France was expected to cost €4 billion ($5.1 billion) or $3,200/kWe [WNN, 4 Dec. 2008a]. In early 2009, Finland's Olkiluoto EPR was one and a half years behind schedule and expected to cost close to €5 billion ($6.6 billion) [*Nucleonics Week*, 5 March 2009]. Areva's client TVO was suing for compensation of €2.4 billion ($3.2 billion) for power replacement and other losses due to the delay. Areva for its part accused TVO of having slowed down the licensing procedure more than necessary, has filed an arbitration case with the International Chamber of Commerce and claims about €1 billion in compensation [*Nucleonics Week*, 19 March 2009]. A large part of the problem in both cases seems to be inadequately trained workers and inadequate quality control leading to rejection of completed work by safety inspectors [*New York Times*, 29 May 2009]. To some extent, these problems reflect a loss of expertise in the nuclear industry that might be overcome if the number of orders increases to the point where crews can move from one project to another at a nearby location in the same country. At the moment, this condition prevails only in China and South Korea.

Of the remaining eight West European countries with operating nuclear power plants, three have laws mandating a phase-out: Belgium (with 54 percent of electric power generated by nuclear plants in 2008), Germany (28 percent) and Sweden (42 percent) [IAEA, 2010a]. The current Swedish Government has announced, however, that it plans to overturn Sweden's phase-out law and replace its existing nuclear reactors as they are retired and Germany's Chancellor Angela Merkel is reportedly interested in at least extending the operating lives of Germany's nuclear power plants [*Guardian*, 5 Feb. 2009; Spiegel Online, 3 July 2007]. In both cases, however, the process of overturning the current policy, if carried through, would take years. The Netherlands is planning to build a new nuclear power reactor. Spain currently has no plans for new nuclear power plants. Despite its experience with Areva, Finland is considering buying a second new nuclear power reactor from another vendor [WNN, 5 February 2009]. Switzerland

43 The last reactor came on line in Belgium in 1985, Finland in 1980, France in 1999, Germany in 1989, the Netherlands in 1973, Spain in 1988, Sweden in 1985, Switzerland in 1984 and the United Kingdom in 1995 [IAEA-PRIS].

too has begun to plan to at least replace two of its aging nuclear plants that are due to shut down around 2020 [WNN, 4 Dec. 2008b].

The United Kingdom has the third largest nuclear capacity in Western Europe (10 GWe).[44] The last of its first-generation "Magnox" graphite-moderated, gas-cooled nuclear power plants are to be shut down in 2010 [UK NDA, 2008]. Its Advanced Gas Reactors (AGRs) have a design life of 35 years, which would have them all shut down by 2024.[45] In early 2008, the British Government, which has an ambitious plan to reduce U.K. carbon dioxide emissions, came out in support of the building of new nuclear power plants in the United Kingdom but declared that the government would not subsidize their construction [*Times*, 11 Jan. 2008]. In September 2008, France's government-owned utility, Électricité de France, bought the U.K. nuclear utility, British Energy, for $23 billion with the intention of building four new 1.6-GWe EPR LWRs on the AGR sites [*International Herald Tribune*, 24 Sept. 2008]. Other companies are also considering building new nuclear reactors in the United Kingdom [WNA, 2010d].

44 Germany is second with 20 GWe.

45 They may have to be shut down even earlier [*New Scientist,* 25 March 2004].

4 Advanced reactor technology

The major reactor vendors have developed and are licensing and selling advanced ("Generation III+") LWRs (see, e.g., US NRC, 2010a). With the renewed interest in nuclear power, however, there has also been renewed interest in exploring alternatives to the LWR. After a brief discussion of advanced LWRs, the discussion of the alternative reactors below is divided into two classes, fast-neutron and slow-neutron.[46] Finally small and transportable reactors are discussed, which may be of interest to countries or regions with small grids.

Generation III+ light-water reactors

After the 1979 accident at Three Mile Island, there were few reactor orders. The reactor vendors that survived used this period of slow business to develop and license evolutionary designs of LWRs intended to be both safer and less costly per unit output. The resulting so-called Generation III+ LWR designs and their instrumentation have been simplified and standardized and some have "passive" safety systems that operate automatically even if electrical power to the control system and pumps is lost. In the Westinghouse-Toshiba AP1000, for example, valves are designed to automatically open when the level of water in the reactor falls below a certain level and emergency cooling water is driven into the reactor initially with steam and nitrogen pressure. After the reactor vessel is depressurized, water flows in from elevated tanks without pumping and, after evaporating, is condensed at the top of the containment building and returns to the tanks to flow into the reactor again [Westinghouse, 2009]. These systems are calculated to reduce the probability of a core-meltdown accident considerably.

Despite their inherent reliability, the pressures generated by gravity-driven passive systems are modest in comparison with those produced by pumps. Their performance is therefore less certain in a situation where hot fuel can generate steam back-pressure. Also, by giving credit to the passive systems for reducing core melt-down probability, the U.S. Nuclear Regulatory Commission (NRC), whose

[46] In slow-neutron reactors, fission neutrons are "moderated" or slowed down by collisions with the nuclei of light elements. In contrast, neutrons lose relatively little energy to the recoil of the heavier nuclei of the liquid metals used to cool fast-neutron reactors. A primary advantage of slow-neutron reactors is that they can sustain a chain reaction in low-enriched—or even, in some cases, in natural uranium. A primary advantage of fast-neutron reactors is that, when fueled with plutonium, they can be designed to breed more plutonium than they consume.

regulations are usually treated as world standards, has reduced the reliability requirements on the active backup systems by not requiring them to be safety-grade and has allowed less robust containments. As a result, the net effect on overall safety of installing the passive systems is less certain [Lyman, 2008].

Fast-neutron reactors for breeding and burning

Although there is no reason to expect the dominance of LWRs to end in the foreseeable future, the major government nuclear-energy R&D establishments continue to develop potential successors. The OECD's Generation IV [Gen IV] International Forum coordinates research on six reactor types [Generation IV International Forum, 2008] and the IAEA-based International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) focuses on methodologies and generic technical challenges [IAEA, 2010b].

The most attention—but relatively little funding—is going to the liquid-sodium-cooled "fast-neutron" reactor, the reactor type in which the nuclear R&D establishments invested their greatest efforts in the 1960s and 1970s (Figure 13). Fast-neutron reactors fueled with plutonium can be designed to produce more plutonium from uranium-238 than they consume. This makes uranium-238, which constitutes 99.3 percent of natural uranium, the ultimate fuel of fast-neutron breeder reactors.

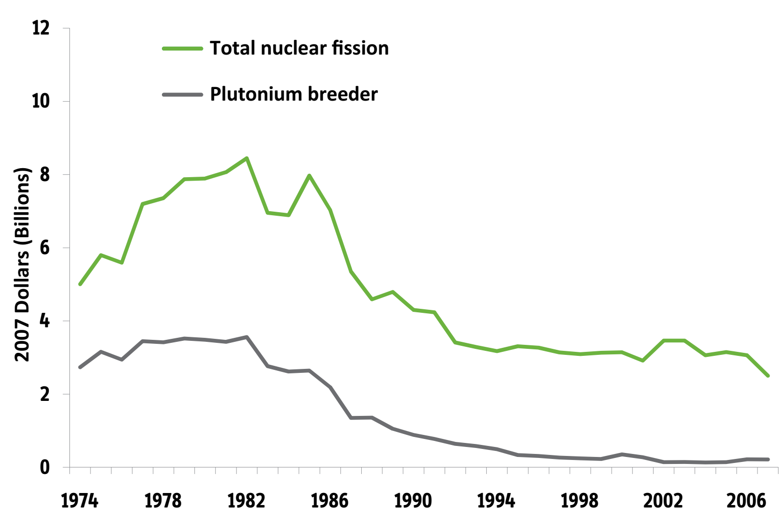

Figure 13. **Total fission and breeder research, development and demonstration funding in the OECD countries that had substantial breeder programs, 1974 to 2007** (Belgium, France, Germany, Italy, Japan, Netherlands, the United Kingdom and the United States). The breeder share is understated because France, which had the world's largest breeder program in the 1980s and 1990s, did not report most of its breeder RD&D activities as such [IEA, R&D Statistics, 2009].

Plutonium breeder reactors were pursued when it appeared that resources of high-grade uranium ore were very limited and global nuclear power capacity was expected to increase by 2010 to several thousand GWe [IPFM, 2010]. But nuclear capacity plateaued and high-grade uranium ore is much more abundant than previously believed. Enough low-cost uranium has been found to sustain 500 GWe of capacity for 100 years [NEA, 2008c][47] and much more probably remains to be discovered (see discussion below). The contribution of the cost of uranium to the cost of power at the cutoff grade in these estimates (uranium recoverable at a cost of $130 per kilogram or less) would only be about 0.3 cents per kWh.

Fast-neutron reactors cannot be cooled by water, because (as occurs in the collisions of billiard balls) neutrons are drastically slowed by a relatively small number of collisions with the light nuclei of the hydrogen atoms in the water. Liquid metal therefore is used because (as with the collision of a golf ball with a boulder) the heavy nuclei of the atoms take away little energy in a collision. As already noted, most development has focused on reactors cooled by molten sodium. Because sodium burns on contact with air or water, however, sodium-cooled reactors have proved to be much more costly and difficult to operate than water-cooled reactors and only a few experimental and "demonstration" reactors have been built with government support. Japan's 0.28-GWe Monju fast breeder demonstration reactor, which began operating in 1995, shut down a few months later as a result of a sodium fire and only restarted 15 years later in 2010. The largest demonstration liquid-sodium-cooled reactor built to date, France's 1.2-GWe Superphénix, spent so much time in repair that it had an average capacity factor of only seven percent over its operating life (1985 to 1996). Russia's BN-600 is the exception. Despite 15 sodium fires in 23 years, it has been kept on line with an average capacity factor of about 74 percent [Oshkanov, 2004].[48]

There are various ideas for reducing the cost of fast-neutron reactors. These include alternative coolants. Molten-lead is one candidate. Helium is also being considered but has the safety disadvantage that it has no heat capacity if there is a loss of pumping power.

Breeder reactors and uranium resources. Superphénix cost about three times as much as an LWR of the same capacity.[49] If the capital cost of a commercialized fast-neutron reactor were higher than that of an LWR by only $1000/kWe, it would require the cost of uranium to rise to about $1200/kg for the uranium savings

[47] Between 160 and 200 tons of natural uranium is required annually to fuel a 1-GWe LWR operating at a capacity factor of 90 percent, assuming 0.2 to 0.3 percent uranium-235 remaining in the depleted uranium from enrichment. With a global LWR capacity of 500 GWe, ten million tons of uranium would last 100–125 years.

[48] The BN-600 is actually fueled by HEU because its core would not be stable with plutonium fuel. It is therefore not a breeder reactor.

[49] The capital cost of the 1.2-GWe Superphénix was FF 34.4 billion (about $7 billion in 1996$) according the France's public accounting tribunal, the Cour des Comptes [*Nucleonics Week*, 17 Oct. 1996].

from a breeder reactor to offset its extra capital cost [Bunn *et al.*, 2005, Figure 3; MIT, 2003; IPFM, 2010]. This is about ten times the cost of uranium in early 2009.

Most uranium exploration has focused on deposits with recovery costs of less than $80/kg and findings are reported only for recovery costs less than $130/kg [NEA, 2008c]. These resources range from 0.03 to 20 percent uranium [van Leeuwen, 2008]. The concentration where the amount of electric energy extractable from the uranium in a ton of ore with a once-through fuel cycle would approximately equal the amount of energy extracted from a ton of coal is 0.005 to 0.02 percent.[50]

Despite consumption and inflation, known uranium resources even below recovery costs of $40/kg continue to increase from year to year [NEA, 2008c, Table 1]. Resources also are likely to go up rapidly at higher recovery costs [Deffeyes

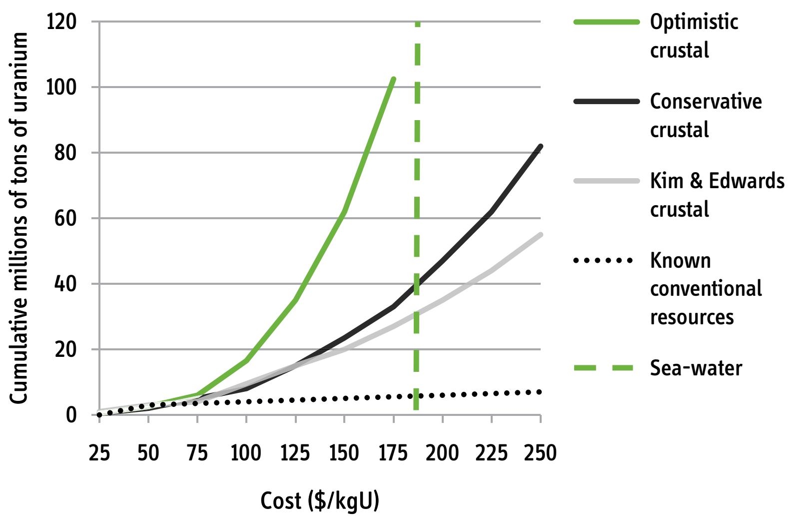

Figure 14. **Uranium resource availability.** Known Conventional Resources as reported in the NEA-IAEA Red Book compared with geological estimates of crustal abundance (Optimistic, Conservative and Kim & Edwards) and an estimated cost of $200/kg for recovery of uranium from seawater [adapted from Schneider and Sailor, 2008].

[50] At 0.005 percent uranium, a ton of ore would contain 50 grams of natural uranium. That would produce 6.25 grams of 4.4-percent enriched uranium (assuming 0.2 percent uranium-235 is left in the depleted uranium). For a burnup of 53 MWt-days per kilogram, the amount of fission energy released from the 6.25 grams of LEU would be 28×10^9 joules, about the amount of energy released from the combustion of a ton of coal. Van Leeuwen has the break-even level at 0.02 percent, in large part because he uses 50 percent gross thermal efficiency of the coal plant vs. 32 percent for an LWR and a uranium recovery factor of 50 percent.

and MacGregor, 1980]. Figure 14 compares the known conventional resources of uranium reported in [NEA, 2008c] with crustal abundance models and the estimated cost of recovering uranium from seawater [Schneider and Sailor, 2008]:

- The cost of recovery used to translate estimated crustal abundance to cost in the Conservative and Optimistic Crustal Models is assumed to be simply proportional to the amount of rock that must be mined and crushed and leached to recover a kilogram of uranium. Thus, for ore with half the concentration of uranium, it would cost twice as much to recover a kilogram of uranium.
- The Kim & Edwards cost curve assumes that the recovery cost per kilogram increases somewhat more rapidly with declining ore concentration. Thus, for example, the cost of recovering uranium from an ore grade with one tenth the concentration would be 19 times as high.
- The ocean contains about 4.5 billion tons of uranium but at a very low concentration of 3.3 parts per billion by weight. The estimate that uranium would be recoverable from seawater at a cost of $200/kg was developed by the U.S. Department of Energy Generation IV Fuel Cycle Cross Cut Group [see also Tamada *et al.*, 2006].

All the curves are constrained to agree on uranium resources at a uranium recovery cost of about $40/kg.

If the crustal-model approach is correct, 20-60 million tons of uranium should be recoverable at a cost of less than $130/kg. If global nuclear capacity increased linearly from 2020 to approximately 4,000 GWe, twenty-five million tons would be required to sustain a once-through LWR economy until the year 2100. An LWR capacity of 4,000 GWe would require about 6.4 million tons of uranium per decade.[51] Thus breeder reactors would be unlikely to be competitive until well beyond the end of the century—even if global nuclear capacity climbs into the thousands of GWe.

It would be much more useful to determine whether the crustal model is approximately correct and to refine the technology and cost estimates for recovering uranium from seawater than to embark on the promotion of a hugely expensive proliferative technology involving the separation and recycle of plutonium because of probably unfounded fears of uranium shortages.

Fast-neutron "burner" reactors and the spent-fuel problem. In 2006, the U.S. Department of Energy (DOE) proposed to design and build fast-neutron reactors as "burner" rather than breeder reactors [US DOE, 2006]. This was in response to public concern about the long-lived transuranic isotopes (plutonium, neptunium, americium and curium) in spent nuclear fuel and uncertainties about the performance of geological repositories over a time scale of tens to hundreds of thousands of years. Unlike LWRs, fast-neutron reactors can fission all the long-lived transuranic isotopes in spent LWR fuel relatively efficiently.

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51 Assuming 160 tons of natural uranium per GWe-year, i.e., a depleted uranium assay of 0.2 percent.

This was not a new proposal, however. Indeed, in 1992, the DOE asked the National Academy of Sciences (NAS) to thoroughly study proposals to reduce the longevity of the radioactive waste problem through separation and transmutation of long-lived radioisotopes. The resulting study [US NAS, 1996] was quite skeptical. It concluded that:

- "Although a significant fraction (90 to 99 percent) of many of the most troublesome isotopes could be transmuted [to shorter-lived or stable isotopes] this reduction of key isotopes is not complete enough to eliminate all the process streams containing HLW [high-level radioactive waste]…Transmutation thus, would have little effect on the need for the first repository…."
- "It would take about two centuries of operating time to reduce the inventory of the residual [transuranics] to about 1 percent of the inventory of the reference LWR once-through fuel cycle…."
- "Estimates of changes in dose [from nuclear power and radioactive waste] are small…Taken alone, none of the dose reductions seem large enough to warrant the expense and additional operational risk of transmutation…."
- "The excess cost of [a separation and transmutation] disposal system over the once-through disposal of the 62,000 [tons heavy metal in] LWR spent fuel [the approximate legislated limit on what could be stored in Yucca Mountain before a second U.S. repository came into operation] is uncertain but is likely to be no less than $50 billion and easily could be over $100 billion [$0.25–0.5+ cents/kWh, not including the extra cost of the fast-neutron reactors or other transmutation systems]."
- "The committee concluded that the once-through fuel cycle should not be abandoned…[T]his has the advantage of preserving the option to retrieve energy resources from the wastes for an extended period of time. This can be achieved by adopting a strategy that will not eliminate access to the nuclear fuel component for a reasonable period of time, say about 100 years, or by preserving easy access to the repository for a prescribed period of time, or by extending the operating period of the repository…A reason for supporting continued use of the once-through fuel cycle is that it is more economical under current conditions."
- "Widespread implementation of [separation and transmutation] systems could raise concerns of international proliferation risks…."

The last comment relates to the fact that, as currently envisioned, fast-neutron reactors only achieve the benefits of uranium savings and more complete fissioning of transuranics with a "closed" fuel cycle (one in which spent fuel is processed and the plutonium and other transuranic elements are recycled repeatedly in new fuel). Since the transuranic elements could be used to make nuclear weapons, this creates a proliferation risk. We discuss this issue below.

In 2007, the DOE requested a second NAS review of its nuclear-energy R&D program. The response was even more unequivocal: "domestic waste management, security and fuel supply needs are not adequate to justify early deployment of commercial-scale reprocessing and fast reactor facilities" [US NAS, 2007, p. S-8].

Thermal (slow)-neutron reactors

On its list of reactor types of interest, the Generation IV collaboration also has three types of thermal-neutron reactors: supercritical water-cooled reactors, very high temperature gas-cooled reactors and molten-salt reactors. The supercritical reactor would allow LWRs to take advantage of the increased efficiency of the conversion of heat into electricity at higher coolant temperatures. Some fossil-fuel plants already operate at supercritical temperatures.

Very high temperature gas-cooled reactor designs, with coolant temperatures up to 950 °C, are being examined in the United States—primarily as a way to produce hydrogen by heat-driven instead of electricity-driven chemical reactions. The "nuclear hydrogen" project was launched in the Energy Policy Act of 2005. The DOE and the U.S. Nuclear Regulatory Commission have defined a joint research program to provide the analytical tools to license such a reactor [US DOE, 2008d]. Otherwise, R&D in this area has been confined primarily to the development of the thermo-chemical processes [US DOE, 2008c]. Massachusetts Institute of Technology nuclear engineer, Charles Forsberg, has suggested that a more important use of high-temperature gas-cooled reactors that could produce heat with a temperature of 700 °C would be to replace fossil fuels to provide process heat for oil refineries and for extracting liquid fuels from oil shales and tar sands [*Oil and Gas Journal*, 11 August 2008].

Finally, the molten-salt reactor would have its fuel dissolved in molten salt. The heat would be extracted by pumping the salt through a heat exchanger and fission products would be removed and new fuel added by chemically processing a side stream. The problem with this design is the complexity of operating a reactor with an integrated small reprocessing plant [Generation IV International Forum, 2008].

Low-power and transportable reactors

The IAEA recommends that a single nuclear-power reactor not constitute more than 5 to 10 percent of the generating capacity on a grid [IAEA, 2007b]. As previously discussed (Table 2), gigawatt-scale reactors therefore require large grids. Smaller reactors might not have a major impact on global issues such as climate change and might be more costly per megawatt (MWe) of generating capacity than GWe-scale reactors but could provide an alternative for countries and regions with small grids and expensive power. A few relatively low-power LWR designs are available [WNA, 2008b].

The low-power (about 0.2 GWe) high-temperature graphite-moderated gas (helium) cooled reactor has been under development since the 1970s and continues to be the most plausible near-term relatively safe alternative to the LWR. It is being actively investigated in China, Japan, Russia, South Africa and the United States.

The interest of small developing countries and remote areas in nuclear power and the high cost of fossil-fueled power plants in such regions has inspired interest in even lower-capacity transportable reactors. One hope is that the economies of scale of factory production might offset the loss of economies of scale in the reactors themselves. Some small reactor designs emphasize long core life with the tradeoff being that the initial core would be more costly per unit output [IAEA, 2005a, Table 5; IAEA, 2007e; US NRC, 2009a].

One transportable nuclear power plant is under construction, a barge carrying twin 0.035-GWe reactors, based on a design used in some of Russia's nuclear-powered icebreakers. These reactors would be refueled after four years of operation. The first floating power plant is being finished in St. Petersburg with completion projected for 2011 [*Bellona*, 18 May 2009; IAEA, 2005a, Annex 6.5; Greencross, 2004]. In 2006, Rosatom was planning to complete seven floating nuclear power plants by 2015 [Rosatom press releases, 15 and 20 Dec. 2006]. It is believed that, because of Russia's interest in exporting these reactors, they will be fueled with LEU rather than the weapon-usable HEU used in Russia's submarines and nuclear-powered icebreakers [Sokov, 2006].

Safer reactor designs

Even though operational safety has been improved, the probability of terrorist attempts to cause a deliberate Chernobyl-type release appears greater today than it was in the 1980s. A terrorist group could conceivably penetrate a nuclear power reactor, cause a loss-of-coolant accident, prevent the emergency cooling system from functioning adequately and put a hole in the containment building so that volatile fission products released from the core meltdown would be released into the atmosphere. This is a major reason today why attention should be devoted to less vulnerable designs as well as to improved physical security.

In the case of the pebble-bed gas-cooled reactor, inherent safety has been attempted by putting the uranium into small particles, encapsulated in layers of pyrolytic carbon and silicon carbide to contain the fission gases. The chain reaction would shut down because of negative temperature feedback effects on the reactivity and the reactor would eventually reach thermal equilibrium by radiating away to the cooler wall of the containment the heat generated by the declining radioactivity of the fission products in the fuel. If the reactor power is low enough (less than 0.3 GWe), the peak temperature could be kept below the failure temperature of the particles [Labar, 2002]. Oxidation of the graphite moderator by penetrating air could provide an additional source of heat but one analysis finds that, even with a break in the largest coolant pipe, the rate of air inflow would be limited to a level where graphite oxidation would not drive the core temperature significantly higher [Ball *et al.*, 2006].

A recent report on the operational history of Germany's 46 MWt gas-cooled AVR (Arbeitsgemeinschaft Versuchsreaktor) pebble-bed reactor which operated between 1967–1988, however, has put its safety design adequacy into question.

It was revealed that the reactor had suffered serious leakage of fission products into the helium coolant. One reason attributed was "inadmissible high core temperatures…more than 200 °K higher than calculated." Another was that cesium-137 (30-year half-life), the most dangerous radioisotope released by the Chernobyl accident, diffuses through intact particle coatings. It therefore was concluded that the reactor would require a leak-proof containment like that required for modern LWRs. This would erase a major cost saving. Additional safety issues were noted for designs such as the AVR, in which water ingress into the graphite was possible. "Thus a safe and reliable AVR operation at high coolant temperatures [does] not conform with reality" [Moormann, 2008, Abstract].

With questions about the safety of what has been claimed by General Atomics for decades to be an "inherently-safe" reactor design [General Atomics, 2010] it would be useful to launch a new R&D program to consider, starting with a blank slate, the possibilities for a more inherently-safe, reliable and economic design.

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5 Once-through versus plutonium recycle

Today, five weapon states (China, France, India, Russia and the United Kingdom) plus Japan reprocess at least some of their spent fuel and the Netherlands has contracted with France to have the spent fuel from its single reactor reprocessed. Of the reprocessing states, France, India and Japan currently do or plan to reprocess most of their spent fuel. The United Kingdom is expected to end reprocessing after it has fulfilled its existing foreign contracts [*Nuclear Fuel*, 18 June 2007; 28 July 2008a]. Russia reprocesses only the spent fuel from its first-generation VVER-440 LWRs and its BN-600 demonstration fast-breeder reactor, with a combined capacity of 3 GWe [IAEA-PRIS]. And China has built but not yet operated a pilot reprocessing plant.

Of the remaining 24 countries with nuclear-energy programs, 12 have not reprocessed their spent fuel[52] and 12, which in the past shipped their spent fuel to France, Russia or the United Kingdom for reprocessing, have not renewed their contracts.[53] All 24 have decided on interim storage. As a result, measured in terms of fission energy released, worldwide, about one third of spent fuel is reprocessed today (Table 5).

The two primary reasons why almost all customer countries have stopped shipping their spent fuel abroad for reprocessing are:

1. Reprocessing and plutonium recycle are much more costly than spent-fuel storage; and
2. Countries providing reprocessing services are requiring their foreign customers to take back the high-level waste from reprocessing.

Thus, foreign reprocessing simply converts, at considerable cost, a politically difficult spent-fuel disposal problem into a politically difficult spent MOX fuel and high-level waste disposal problem. It is only politically attractive for an interim period because it buys two decades or so of respite.

52 Ignoring U.S. reprocessing prior to 1973.

53 In 2008, Italy contracted with France to have reprocessed 235 tons of irradiated fuel from reactors that were shut down after the 1986 Chernobyl accident.

Countries that reprocess (GWe)		Customer Countries that have quit or are planning to quit (GWe)		Countries that have not reprocessed (GWe)	
China (pilot plant)	8.6	Armenia (in Russia)	0.4	Argentina	0.9
France (80%)	63.3	Belgium (in France)	5.8	Brazil	1.8
India (≈50%)	3.8	Bulgaria (in Russia)	1.9	Canada	12.6
Japan (90% planned)	47.6	Czech Republic (in Russia)	3.6	Lithuania	1.3
Netherlands (in France)	0.5	Finland (in Russia)	3.0	Mexico	1.4
Russia (15%)	21.7	Germany (in France/U.K.)	20.5	Pakistan	0.4
U.K. (ending)	10.2	Hungary (in Russia)	1.8	Romania	1.3
		Slovak Republic (in Russia)	2.0	Slovenia	0.7
		Spain (in France/U.K.)	7.5	South Africa	1.8
		Sweden (in France/U.K.)	9.0	South Korea	17.5
		Switzerland (in France/U.K.)	3.2	Taiwan, China	4.9
		Ukraine (in Russia)	13.1	U.S. (since 1972)	100.6
Total	155.7	Total	71.8	Total	145.2

Table 5. **Country status for spent fuel reprocessing.** Most countries have decided on interim storage instead of reprocessing their spent fuel. The percentages shown for some countries in the first column reflect various limitations on the fraction of the spent fuel reprocessed.

Only Russia is routinely keeping its customers' separated plutonium. Among France's and the United Kingdom's reprocessing customers, Belgium, Germany and Switzerland have been recycling their separated plutonium in MOX (plutonium-uranium) fuel in the LWRs that produced it. France is doing the same and China and Japan plan to do so. India and Russia plan to use their separated plutonium for startup cores for plutonium breeder reactors. The Netherlands is paying France to dispose of its separated plutonium. France kept Spain's separated plutonium[54] and presumably will do the same for Italy and has included that offer in proposed reprocessing contracts to other countries such as South Korea [*Nuclear Fuel*, 13 July 2009].

The United Kingdom is not recycling its own separated plutonium and has as yet no disposition plans. By the time its domestic spent-fuel reprocessing contracts are fulfilled, the U.K. stockpile of separated plutonium will amount to about 100 tons—enough for more than ten thousand nuclear explosives. The U.K. Nuclear Decommissioning Authority is now examining disposal options [UK NDA, Jan. 30, 2009]. The storage of separated plutonium and reprocessing waste is significantly more expensive than storage of unreprocessed spent fuel. In addition, after several

54 The reprocessed fuel was from the Vandellós-1 reactor, a graphite-moderated, gas-cooled reactor that operated from 1972 to 1990 [WISE, 1999].

years in storage, americium-241, a decay product of plutonium-241 (14-year half-life), builds up in plutonium and has to be separated before fuel fabrication.[55]

Where plutonium is being recycled in LWR MOX, it is thus far only being recycled once. Irradiation results in a net reduction of the plutonium in the MOX fuel by about one third but also results in a shift of the isotopic mix in the plutonium toward the even isotopes (plutonium-238, plutonium-240 and plutonium-242) that are less easily fissioned in slow-neutron reactors [NEA, 1989, Table 12B]. With repeated recycle in "non-fertile" LWR fuel, i.e., without uranium-238 in which neutron capture produces more plutonium, it would be possible eventually to completely fission plutonium and the other transuranics except for reprocessing and fabrication losses. It would require shielded fuel fabrication, however, and long intervals (20 years) are recommended between cycles to allow radioactive decay to offset the steady buildup of neutron-emitting curium and californium isotopes. Significantly reducing the global inventory of transuranic elements would therefore take centuries [Shwageraus *et al.*, 2005].

In its Global Nuclear Energy Partnership (GNEP) initiative, the G.W. Bush Administration proposed that "fuel-cycle countries" would supply fresh fuel and take back and reprocess spent fuel from countries with reactors but no enrichment or reprocessing facilities. The "fuel-cycle countries" would recycle the separated transuranic elements domestically in fast-neutron reactors and dispose of the reprocessing waste in domestic geological repositories. Despite about $100 billion spent worldwide in efforts to commercialize fast-neutron reactors, however, no country has yet succeeded [IPFM, 2010]. Nor has any country yet been willing to volunteer to take other countries' radioactive waste. The U.S. Congress became skeptical about GNEP; the Obama Administration has cancelled the proposal to build a reprocessing plant and the U.S. reprocessing program has returned its focus to R&D.

Radioactive waste

Geological disposal is very widely accepted in the nuclear community as technically feasible and adequately safe [NEA, 2008b]. Absolute proof that there will be no significant releases over a hundred thousand years or more as a result of natural processes or human intrusion is impossible, however. In the United States, Congress mandated in the 1987 Nuclear Waste Policy Act that a site characterization program for a geological repository for spent power-reactor fuel be carried out only at Yucca Mountain, Nevada and, if justified by the results of that program, a repository should be built and licensed by 1998. More than $10 billion were spent on the project and an application for a license was submitted in 2008 [US DOE, 2008b]. In this sense, this repository may be the most advanced in the world. But it may never be completed because of fierce political and legal opposition from the state of Nevada, now supported by President Obama, who

55 Current MOX fuel fabrication plants cannot process LWR plutonium after the americium has built up for more than 3 to 5 years.

has proposed to cancel the repository project and has established a "Blue Ribbon Commission" to study alternatives [US DOE, 2010a].

Other countries have encountered similar opposition from potential host communities for geological repositories. This is resulting in the abandonment of centralized siting decisions in favor of a more consultative approach with possible host communities [Isaacs, 2006].

Finland and Sweden have adopted the consultative approach and, until its recent site selection, Sweden actually had two communities with nuclear power plants competing to host its repository [WNN, 3 June 2009]. In Finland, the construction of an underground test facility that is expected to be expanded to become a spent-fuel repository is underway, following acceptance by the local community and formal approvals granted by the regulator and the parliament [McCombie and Chapman, 2008].

In the design envisioned for the Finish and Swedish repositories, the spent fuel is to be encapsulated in a cask with a 5-cm thick copper outer layer and then embedded in bentonite clay, which swells when it is wet. Recently a technical challenge has emerged to the assumed durability of the cask [Hultquist *et al.*, 2009]. Whether this will derail progress toward the repositories remains to be seen.

The fact that communities that already have nuclear facilities appear to be more willing to host radioactive-waste repositories suggests that they may have a different assessment of both the risks and benefits than communities without nuclear facilities. This certainly makes sense on an objective basis, since as the Chernobyl accident showed, the potential scale of radioactive contamination of the surface from an operating nuclear facility dwarfs any potential surface contamination from a deep-underground facility. Also, if no off-site destination could be found for a nuclear-power plant's spent fuel, putting the spent fuel underground nearby would reduce the long-term risk to the local community.

Given the already large number of relatively small national nuclear-energy programs, there is interest in regional radioactive-waste repositories in Europe and East Asia, although few countries have expressed interest in hosting one. In the past, Russia has taken spent fuel back from Eastern Europe and the Ukraine and there is still interest in Russia's nuclear establishment in doing so. Disposing of foreign spent fuel is seen as potentially profitable and the plutonium in the spent fuel is seen as a future energy resource. Much of Russia's public opposes the importation of radioactive waste, however, and, for now, the leadership of Rosatom is not pushing the matter.

In Europe, the European Commission has encouraged projects aimed at developing shared repositories for its smaller member states [SAPIERR, 2010]. There should be economies of scale in the construction of repositories. A theoretical exploration, based on an identification of fixed and variable costs in the cost models developed by the Swedish, Finnish and Swiss repository projects, finds savings of 5 to 10 percent from building one repository instead of two, each with half the capacity. It estimates 60 percent savings if fourteen European countries with small nuclear-energy programs share a single repository but notes that 60 percent of those savings result from the countries sharing repository R&D costs [Chapman *et al.*, 2008].

Economies of scale may not be realized in the real world, however. The estimated cost of the large U.S. geological repository proposed for Yucca Mountain was as high as or higher per ton of spent fuel than the costs of smaller disposal projects being considered in Europe. In 2008, the estimated cost of the U.S. repository, not including transportation costs, was $76.8 billion for the equivalent of 122,100 tons of spent fuel,[56] or about $630/kg (2007$) [US DOE, 2008b]. For comparison, the estimated cost for disposal of 9500 tons of spent fuel in Sweden was about $700/kg,[57] $500/kg for 5600 tons in Switzerland,[58] and $400/kg for 5800 tons in Finland.[59]

Since implementing geological repositories is politically difficult and not technically urgent, and interim dry-cask storage is inexpensive and relatively safe, it is not surprising that interim storage at nuclear power plants has often become the path of least resistance. It has become the de facto spent-fuel management strategy in the United States, Germany and a number of other countries. It also avoids the risks of dispersal of radioactive waste while it is in liquid form at the reprocessing plant.[60]

It is not immune to controversy, however, because of concerns that interim may become indefinite storage. Indeed, with a few exceptions, local governments in Japan and South Korea have vetoed the construction of additional on-site interim storage. This is one of the reasons for the persistence of reprocessing in Japan [Katsuta and Suzuki, 2006] and the interest in reprocessing in South Korea [von Hippel, 2010].

56 This total would include 109,300 tons of spent civilian fuel. The remainder would be "defense nuclear wastes," including solidified high-level waste from U.S. production of plutonium for weapons and naval-propulsion reactor spent fuel.

57 46.5 billion Swedish Krona [SEK] (2003) assuming 7.1 SEK (2003) per 2007 US$ [SKB, 2003].

58 Assuming that 2065 packages of spent fuel and 720 packages of vitrified high-level waste are equivalent to 5570 tons of spent fuel and that 4.4 billion 2001 Swiss Francs equal 2.8 billion 2007 US$ [Chapman *et al.*, 2008, Appendix].

59 Assuming that 2899 spent-fuel containers hold 5800 tons of spent fuel and that €2.54 billion (2005€) equals $2.26 billion (2007$) [Chapman *et al.*, 2008, Appendix].

60 Both France and the United Kingdom have accumulated years of production of high-level liquid waste at their reprocessing plants because of technical problems with the vitrification process. This accumulated waste contains approximately one hundred times of the amount of cesium-137 (30 year half-life) that was released in the Chernobyl accident.

The cost of dry-cask interim spent-fuel storage is relatively low ($100–200)/kg or 0.02–0.05 cents/kWh) and keeps open all future options, including deep underground disposal and reprocessing/recycle. It is relatively safe because the fuel is typically about 20 years or more old and the heat generated by the radioactivity has declined to less than 2 KWt per ton [Alvarez *et al.*, 2003, Figure 5].[61] The ten tons in a typical hundred-ton cask therefore generate less heat than an ordinary automobile engine and only passive air cooling is required. The temperature of the fuel in the cask remains well below the fuel operating temperature in a reactor and its zirconium-alloy fuel rod cladding is expected to remain intact indefinitely. In Germany, Switzerland and Japan, the casks are stored inside thick-walled buildings. In the United States, they are stored outside (Figure 15). It is possible to puncture such casks with a missile tipped with a shaped charge but, based on an experiment with simulated fuel, it was concluded that, for a single puncture, only a few parts per million of the cesium-137 in the cask would be released. Even a hundred times larger fractional release would still be negligible on the scale of the Chernobyl accident where the equivalent of the amount of cesium-137 in approximately three casks of spent fuel was released [Alvarez *et al.*, 2003].

Figure 15. **Dry cask storage of older spent fuel at a U.S. nuclear power plant.** A 1000-MWe light-water reactor typically annually discharges spent fuel that originally contained about 20 tons of uranium. Each cask typically holds about ten tons and costs $100,000-200,000 per ton of contained spent fuel. Reprocessing a ton of spent fuel would cost $1-3 million [Connecticut Yankee, 2008].

[61] Spent fuel can be placed in dry cask storage as soon as three years after discharge, when the decay heat is about 6 KWt/ton.

6 Risks from large-scale releases of radioactivity to the atmosphere

The most serious release of radioactivity to the environment from a nuclear power plant accident occurred on the boundary between Belarus and Ukraine in late April and early May 1986. It was caused by a power spike that ruptured the cooling tubes, followed by a steam explosion as the water contacted the hot graphite in the core, and finally a graphite fire after the core was opened to the air.

The physical consequences of the Chernobyl accident included:[62]

- The deaths of 42 emergency workers from radiation illness within weeks [UN-OCHA, 2001].
- Exposure to high radiation fields of 600,000 civilian and military "liquidators" who were involved in the emergency decontamination of the reactor, the reactor site and the nearby roads and in the construction of the temporary "sarcophagus" over the reactor.
- Radioactive contamination of an area of about 3,000 km^2 by the 30-year half-life gamma emitter, cesium-137 to levels that resulted in its long-term evacuation (Figure 16).[63]
- A still growing epidemic of thyroid cancer among people in the region who received large thyroid doses from ingested and inhaled radioactive iodine (Figure 17).
- Other radiogenic cancers are suspected but undetectable in a much larger background of cancers due to other causes.[64] One recent theoretical estimate, based on dose estimates and dose-risk coefficients derived from Hiroshima and Nagasaki survivors, is typical: 4,000 extra cancer deaths among the 600,000 Chernobyl liquidators, 5,000 among the 6 million living in "contaminated areas" (above 37 kBq/m^2 of cesium-137) and about 7,000 in the 500 million population of the rest of Europe, which was subjected to lower doses. The total number of estimated cancer deaths

62 When not otherwise referenced, the source is UNSCEAR, 2000, Volume II, Annex J.

63 The area within a 30-km radius of the reactor was evacuated as well as some heavily contaminated villages outside this zone.

64 Almost 30 percent of deaths in developed countries are from cancer [American Cancer Society, 2007].

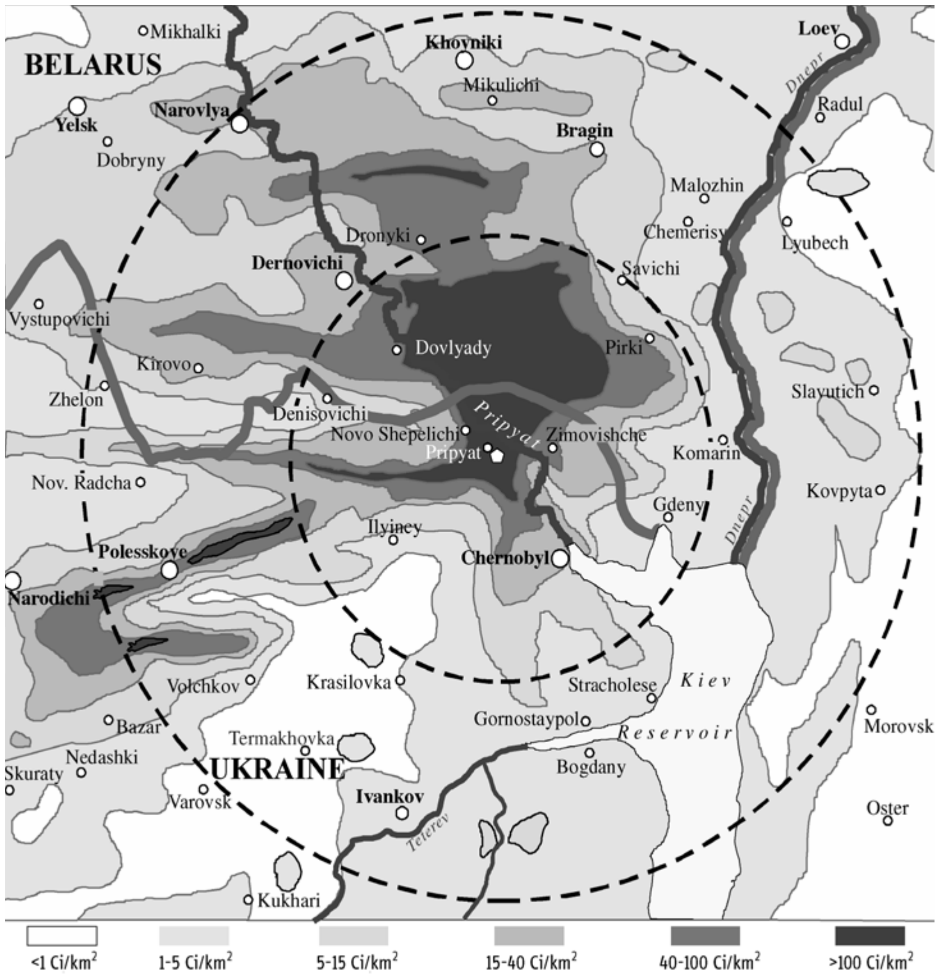

Figure 16. **Cesium-137 contamination levels around the Chernobyl nuclear power plant.** [UNSCEAR, 2000, Appendix J, Figure VII]. The circles are of radii 30 and 60 km around the reactors. Areas contaminated to greater than 40 Curies (Ci) Cesium-137 per square kilometer are still officially evacuated. Areas with contamination levels between 15 and 40 Ci/km^2 (about 10,000 km^2) were designated as areas of strict radiation control, requiring decontamination and control of intake of locally grown food. As a result, the annual accident-related effective dose in these latter areas has been kept below a level of about 5 mSv/year—about twice the global average natural background rate [UNSCEAR, 2000, Vol. 1, table 1 and Annex, para. 108]. A population subject to such a dose rate indefinitely would incur an extra cancer risk of about 3.5 percent, about half fatal [US NAS, 2006, pp. 4, 8].

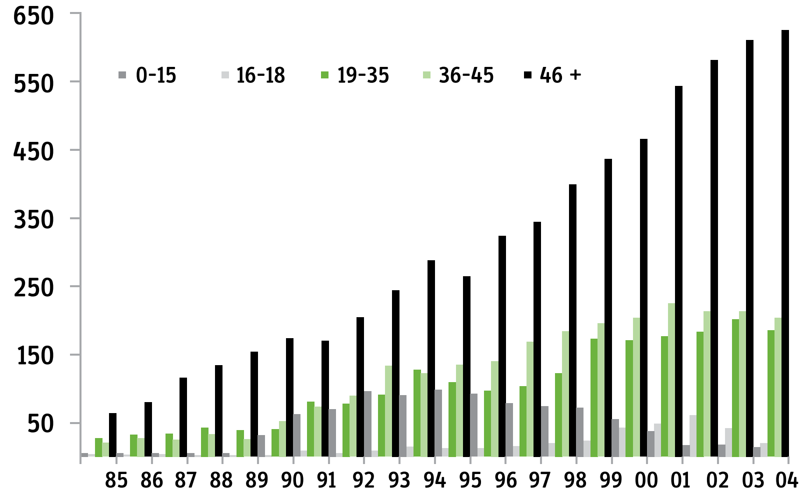

Figure 17. **Epidemic of thyroid cancer in Belarus following the 1986 Chernobyl accident.** Annual number of cases of thyroid cancer in Belarus grouped by age at the time of diagnosis. Note that the incidence of thyroid cancer in the youngest (0-15-year-old) group returned to low levels in 2002 when all the exposed population had graduated into older groups. The death rate in the younger groups with thyroid cancer has been low. This does not appear to be true, however, for the increasing number of cases among those 46 and over. (As of 2004, this group would have been over 27 at the time of the Chernobyl accident.) [Bespalchuk et al., 2007].

over the expected lifetime of the exposed population was 6,700–38,000 (95 percent confidence level) [Cardis *et al.*, 2006].[65]

Averaged over approximately 10,000 GWe-yrs of nuclear reactor capacity accumulated as of the end of 2008, these 16,000 deaths amount to less than two cancer deaths per GWe-yr—a rather modest level compared to the occupational and air-pollution deaths associated with coal-fired power plants. Perhaps the greatest harm from the Chernobyl release has been the social and psychological trauma to the approximately 200,000 persons who were permanently evacuated from their homes and the millions of people living in dread of the long-term consequences of their radiation exposures [UNSCAER, 2000, Appendix J. II.B&V.D].

Estimates of the economic cost of the Chernobyl accident range from $6.7 billion [Sovacool, 2008b] to $235 and $148 billion by the governments or Belarus and Ukraine respectively. In Belarus, Chernobyl expenses amounted to 20 percent of the national budget in 1992, falling to five percent in 2001. These expenses were

[65] An estimated figure of 4,000 cancer deaths from the IAEA's 2005 Chernobyl Forum is often quoted in rebuttal to higher estimates but the Chernobyl Forum estimate was limited only to the projected cancer deaths from doses in the most contaminated areas of Belarus, Russia and Ukraine [IAEA, 2005c, Table 5.13].

paid for in part by a special tax of 18 percent of all wages of non-agricultural firms in 1994 [UNDP, 2002, sections 5.04 ff]. Potential costs due to population removal and loss of assets after contamination by hypothetical spent-fuel pool fires at a range of U.S. sites have been estimated at hundreds of billions of dollars [Beyea *et al.*, 2004].[66]

In both the Three Mile Island accident (in which a reactor core partially melted but there was not a major release of radioactivity from the containment) and the Chernobyl accident, lack of understanding by the operators of what was happening was a key factor. Since that time, operator training has been greatly improved with the use of simulators. A wide range of other steps have been taken to improve safety culture, learn lessons from safety incidents, share best practices and review safety-related aspects of the design and operation of individual plants. The theoretical probability of another core-melt accident has declined significantly as a result. There were about 1500 GWe-years of nuclear power before the Chernobyl accident and about 8,500 since without another major accident.[67]

An incident at the Davis-Besse nuclear power plant (Ohio, U.S.A.) in 2002, in which leaking boric acid almost ate through a reactor pressure vessel head before it was discovered, despite iron oxide in the air and dried boric acid deposits on the outside of the vessel, is a potent reminder, however, that nuclear safety requires constant vigilance [US GAO, 2004].

A major effort also will be necessary to ensure that countries building nuclear power plants for the first time, or rapidly expanding their reactor fleet, put effective safety measures in place, including instilling a strong culture of safety and granting independent regulators the power, resources and expertise to do their jobs.

Given the steps that have been taken in recent decades to improve safety, the probability of a catastrophic release occurring purely by accident may be lower than the probability of such a release occurring as a result of malevolent action. The possibility of terrorism puts an even greater premium on trying to design reactors that are more inherently safe.

In many cases, design for safety and design for security are complementary. Ensuring that redundant control systems cannot all be disabled by one fire or one explosive charge, for example, is important to both safety and security. Protecting against terrorism, however, also requires effective physical protection measures, designed to ensure that major nuclear facilities are adequately protected against attack by small groups on the ground or from the air. Yet there is still today far less systematic attention to reactor security than to reactor safety.

[66] The range of releases of cesium-137 considered was 130–1300 PBq (3.5 to 35 MegaCuries), 1.5 to 15 times the estimated release from Chernobyl.

[67] This does not mean that there have not been worrisome incidents at many nuclear power plants [Schneider *et al.*, 2007].

7 Nuclear-weapon proliferation

Nuclear-weapon acquisition was the first priority of the United States and most other early national nuclear programs. For some later nuclear-weapon programs, civilian nuclear energy programs contributed as a vehicle for acquisition of technology and building infrastructure and expertise for parallel nuclear-weapon programs. Indeed, all of the countries outside the two former Cold War blocs that have acquired nuclear power have done so in the context of nuclear-weapon programs.[68] Fortunately, in most of these cases, the weapon dimensions of the nuclear programs were abandoned.[69]

Will it be possible to extend nuclear power to tens of more countries without spreading the bomb along with it? This will depend on both technological and institutional choices.

The nonproliferation regime

A wide range of proposals to strengthen the nonproliferation regime and reduce the potential proliferation impact of nuclear power have been put forward. International support for these measures will require the nuclear-weapon states—especially Russia and the United States—to live up to their end of the NPT bargain and drastically reduce the numbers, roles and readiness of their nuclear weapons and ultimately eliminate them. [see, e.g., WMD Commission, 2006; ICNND, 2009; Perkovich *et al.*, 2005].

Under the NPT, all non-nuclear-weapon states commit not to acquire nuclear explosives and to accept IAEA inspections of all their nuclear activities to assure that they are peaceful. The traditional safeguards agreement negotiated to fulfill this NPT requirement focuses primarily on accountancy and containment and surveillance to provide "timely detection" of the diversion of "significant quantities" of uranium and plutonium [IAEA, INFCIRC/153, corrected, 1972]. The IAEA has adopted the recommendation of its Standing Advisory Group on Safeguards Implementation (SAGSI) that a "significant quantity" of nuclear material—the amount required to make a first nuclear weapon, taking

68 Defining the regions inside the Cold War blocs as North America/Western Europe/Japan, and the former Soviet Union/Eastern Europe and China. The countries that have nuclear power programs outside these blocs are Argentina, Brazil, India, Pakistan, South Africa, South Korea and Taiwan.

69 Including Argentina, Brazil, South Africa, South Korea and Taiwan.

into account likely losses in processing—should be taken as 8 kilograms of plutonium or uranium-233, or 25 kilograms of uranium-235 contained in HEU [IAEA, 2001, p. 23]. For practical reasons, however, the IAEA set its timeliness objective for detection of the diversion of a significant quantity of material at one month—longer than recommended by SAGSI.[70]

More fundamentally, at a large reprocessing plant such as Japan's Rokkasho Reprocessing Plant, which is designed to separate eight tons of plutonium per year, measurement uncertainties make it impossible to verify that one significant quantity has not been diverted—especially in the case of small diversions occurring over an extended period. Critics argue that safeguards at large bulk-processing facilities are therefore ineffective [Sokolski, 2008]. IAEA experts respond by arguing that a wide range of containment and surveillance measures implemented throughout the plants provide substantial (though unquantifiable) additional confidence that no material has been diverted.

Inspections in Iraq after the 1991 Persian Gulf War dramatized, however, that the focus of traditional IAEA safeguards was too narrow. Iraq had mounted a massive nuclear-weapon-material production program largely at undeclared facilities that were therefore not under safeguards. In response to this wakeup call, member states of the IAEA agreed to take a series of steps to extend the reach of safeguards. Some of these required the negotiation of an "Additional Protocol" to complement the traditional safeguards agreement.

The Additional Protocol [IAEA-INFCIRC-540] requires states to provide the IAEA with more information and access to a broader range of sites, particularly relating to facilities, technology and equipment that could contribute significantly to a capacity to produce plutonium or HEU. The IAEA has been integrating this information with open-source data, including commercial satellite photographs, intelligence provided by member states, and its own inspection activities, into an overall picture of the nuclear activities of each state. This so-called "state-level approach" makes it possible for the Agency to raise questions and focus resources on questionable activities [Cooley, 2003].[71]

Export controls are another critical element of the nonproliferation regime. The NPT requires that states only export nuclear materials or technologies for producing them to non-weapon states if they will be under safeguards. The Zangger

[70] SAGSI estimates of times required to convert various types of nuclear material into nuclear weapons components range down to one week for plutonium or HEU metal [IAEA, 2001, p. 22].

[71] An inadvertent testimonial to the effectiveness of these new approaches was provided by Hassan Rohani, then Iran's nuclear negotiator and secretary of Iran's Security Council, in a speech to the Supreme Council of the Cultural Revolution in 2005. Rohani complained that, as a result of the IAEA finding a dissertation and a journal article that mentioned certain covert nuclear activities, "the IAEA was fully informed about most of the cases we thought were unknown to them" [Rohani, 2005].

Committee was established under the NPT to define what specific technologies should be controlled to fulfill this requirement. After India's nuclear detonation in 1974, the major suppliers established a separate Nuclear Suppliers Group (NSG) under which each participant makes a political commitment to follow much more restrictive export guidelines.

There is an ongoing struggle, however, between states attempting to slow the spread of sensitive technologies and states attempting to acquire them. After the 1991 Persian Gulf War, it was discovered that Iraq had succeeded in illicitly importing a wide range of controlled items for its nuclear weapons program from companies in many countries [Fitzpatrick, 2007]. This provoked many countries to strengthen their nuclear export control systems and, in 1992, the NSG supplemented its rules with restrictions on exports of "dual-use technologies" and a call for states to adopt "catch-all" provisions covering any technology that an exporter suspected was going to an entity involved in proliferation activities.

Nevertheless, in 2003, it was revealed that a global black-market nuclear technology network led by Pakistan's A.Q. Khan had been marketing centrifuge technology and even nuclear-weapon designs, operating in some twenty countries for more than two decades, making clear that far more needs to be done to control the spread of the most sensitive nuclear technologies [Fitzpatrick, 2007].

Controlling enrichment and reprocessing technologies

The most important potential proliferation impact of the civilian nuclear energy system is through the spread of what the 1946 Acheson-Lilienthal Report called the "dangerous" nuclear technologies for uranium enrichment and the chemical "reprocessing" of spent fuel to recover plutonium [Acheson-Lilienthal, 1946]. Concern about the spread of these technologies declined during the late 1950s and 1960s, when the United States and Soviet Union promoted competitive "Atoms for Peace" programs, but India's use of U.S.-supplied reprocessing technology to separate plutonium for its 1974 "peaceful" nuclear explosion convinced the U.S. Government to stop promoting reprocessing both at home and abroad and to organize the NSG as a forum in which it could be agreed that sales of reprocessing and enrichment technology would no longer be used as "sweeteners" in the international competition for sales of nuclear power plants.

Today, there is a similarly catalytic international crisis over Iran's insistence on its "inalienable right," under Article IV.1 of the NPT, to build a national uranium-enrichment plant.[72] The nominal purpose of the plant is to produce LEU for

[72] Article IV.1 of the NPT reads: "Nothing in this Treaty shall be interpreted as affecting the inalienable right of all the Parties to the Treaty to develop, research, production and use of nuclear energy for peaceful purposes without discrimination and in conformity with articles I and II of this Treaty." The debate over Iran's program has concerned whether its intentions are unambiguously peaceful. The IAEA has found that Iran repeatedly failed to comply with its safeguards obligations and the U.N. Security Council has legally obligated Iran to suspend all its enrichment and reprocessing activities and make its nuclear program fully transparent to the IAEA. However, Iran has refused to comply fully.

Iran's future nuclear power plants, but it could potentially be converted to the production of HEU for nuclear weapons or provide a civilian cover for a parallel clandestine enrichment program.

The Acheson-Lilienthal report proposed that enrichment and reprocessing be allowed only at plants owned by an international "Atomic Development Authority." An attenuated version of this idea, multinational instead of international control, was revisited during the 1970s and early 1980s, including the idea of multi-nationally-controlled reactor parks in which spent fuel could be reprocessed and the recovered plutonium recycled only into on-site reactors [see, for example, Chayes and Lewis, 1977 and SIPRI, 1980]. In 2003, IAEA Director General Mohammed ElBaradei proposed another look at multinational control [ElBaradei, 2003] and subsequently initiated a high-level study on multilateral approaches to the fuel cycle [IAEA, 2005b].

In 2004, President G.W. Bush proposed that reprocessing and enrichment plants not be built outside of countries already operating full-scale plants, i.e., the nuclear-weapon states, Western Europe and Japan. A number of leading non-weapon states firmly rejected such a two-class solution,[73] however, and the Bush Administration proposed to make exceptions for some of them.[74] Currently, efforts are underway to give countries such as Iran greater confidence in foreign sources of enrichment services as an alternative to building their own enrichment plants. This includes an IAEA-controlled bank of LEU as a last resort.[75] Over the longer term, IAEA Director-General Mohammed ElBaradei has argued that "the ultimate goal… should be to bring the entire fuel cycle, including waste disposal, under multinational control, so that no one country has the exclusive capability to produce the material for nuclear weapons" [ElBaradei, 2008].

Enrichment. The fundamental issue with enrichment is that the same technology that can be used to produce LEU for civilian fuel can produce HEU for nuclear weapons. Indeed, as enrichment is a highly non-linear process, most of the enrichment work required to produce 90 percent enriched HEU for weapons has

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73 Including Argentina, Brazil, Canada and South Africa.

74 Including Argentina and Brazil, according to a statement by Richard Stratford, Director of the U.S. Department of State's Office of Nuclear Energy Affairs at the June 2004 Carnegie Endowment International Nonproliferation Conference.

75 The U.S.-based Nuclear Threat Initiative and Warren Buffett offered $50 million toward establishing an IAEA fuel bank, and the United States Government, the European Union, the United Arab Emirates and Norway have pledged contributions. The United States and Russia are also establishing supplementary reserves of LEU on their territories (in the U.S. case, to be produced by blending down excess HEU) which individual countries or the IAEA will be able to draw on under circumstances still being negotiated [NAS-RAS, 2008].

already been done in enriching material to four percent for reactor fuel.[76] Gas-centrifuge cascades, now the dominant technology for producing LEU, can be relatively quickly used in a recycle mode or reconfigured to produce weapon-grade uranium [Glaser, 2008].

With regard to the spread of enrichment technology, there are two contradictory trends:

1. Urenco enrichment plants in Germany, the Netherlands and the United Kingdom are being expanded and large new enrichment plants are being built in weapon states based on Urenco (in the United States and France) and Russian (in China) centrifuge technology; and
2. Small national enrichment plants are being built in Brazil and Iran and are being proposed in Argentina and South Africa [*Nuclear Fuel*, 25 Aug. 2008]).

Japan is an intermediate case. It has for a long time had a medium-sized enrichment plant that has not been economically competitive and whose centrifuges have mostly failed but plans to rebuild its enrichment capacity on the same scale [JNFL, 2007].

The small national enrichment plants in Brazil and Iran have different histories. Brazil's program grew out of its Navy's ambition to build nuclear-powered submarines. The primary public rationale for Iran's enrichment plant has been to provide it with fuel security for its nuclear power plants.

Iran currently has only one nuclear power plant nearing completion, whose fuel is being supplied by Russia. Iran has announced, however, an ambitious program for bringing 20 GWe of nuclear capacity online by 2025 [IAEA, 2007c]. Given its bad relationship with the United States and its earlier history of being refused enrichment services by EURODIF.[77] Iran states that it is unwilling to depend upon other countries for enrichment services. Its limited resources of natural uranium, however, would require its proposed large nuclear program to depend

[76] One way to understand this is to note that, by the time four percent enrichment has been achieved, the uranium-235 has been separated from over 80 percent of the uranium-238 in natural uranium. A separative work unit (SWU or, more precisely, a kilogram-SWU) is a measure of the amount of work done in isotope separation. To extract 1 kilogram of uranium-235 from natural uranium, which contains about 0.7 percent uranium-235, and concentrate it to 90-percent enriched "weapon-grade" uranium, leaving 0.3 percent uranium-235 in the depleted uranium would require about 200 SWUs. About two thirds of that separative work would be required to concentrate the same quantity of uranium-235 to 4.5 percent enrichment.

[77] Iran still holds 10 percent of EURODIF via a 40-percent interest in SOFIDIF, which holds 25 percent of EURODIF SA. The dividends have not been paid out to Iran since various restrictions have been imposed on Iran following its non-compliance with the U.N. Security Council order of 31 July 2006.

upon imported uranium.[78] It would therefore have to stockpile imported natural uranium to protect itself against uranium supply disruptions. If so, Iran could as well stockpile imported LEU to protect itself from disruptions of uranium enrichment services as well [von Hippel, 2008b].

Argentina's interest in enrichment goes back to the nuclear-weapon program that it abandoned in tandem with Brazil in 1990. South Africa's interest in enrichment similarly goes back to its nuclear-weapon program, which it ended in 1991. Canada's largest uranium company, Cameco, had been considering whether to add value to its exports by acquiring an enrichment plant. In 2008, however, after Urenco refused to sell it a gas-centrifuge enrichment plant, Cameco bought a 24-percent share of a laser-enrichment company whose plant is to be built in the United States [GE-Hitachi, 2008].[79]

Multilateral arrangements. As has been noted, the controversy over Iran's uranium enrichment program has revived the idea of non-national—this time multinational—ownership of fuel-cycle facilities. In 2004, IAEA Director General ElBaradei created an expert group to study the multinational option. In its report, the expert group noted that four multi-nationally-owned enrichment plants already exist: the EURODIF plant in France and the three Urenco plants in Germany, the Netherlands and the United Kingdom [IAEA, 2005b].

In the case of EURODIF, France built and operated a large gas-diffusion enrichment plant and four other countries (Italy, Spain, Belgium and Iran) each invested and, in exchange, obtained rights to a share of the enrichment work. Iran loaned $1 billion for the construction of the plant and prepaid $0.18 billion for future enrichment services. After Iran's 1979 revolution, it temporarily lost interest in nuclear power and requested its money back. After a protracted process, it did get back its $1 billion plus interest in 1991. When it requested delivery of the enrichment services for which it had paid, however, France's position was that the contract had expired. Iran views this refusal as proof of the unreliability of outside nuclear supplies and uses the EURODIF episode to argue that it requires its own enrichment plant [Meir, 2006].

Recently, Russia, in an arrangement very similar to EURODIF, created an International Uranium Enrichment Center (IUEC) at Angarsk as a commercial open joint stock company. The IUEC will buy enrichment services from the Angarsk enrichment plant and, perhaps in the future, a share in the plant itself. Holders of IUEC stock will have a guaranteed supply of enriched uranium and/or a share in the profits. Russia will continue to manage the enrichment plant and have sole access to its technology.

[78] Iran also does not currently have the technology to fabricate fuel for light-water reactors.

[79] The three major suppliers of uranium are Canada, Australia and Kazakhstan. Kazakhstan has become a partner in Russia's Angarsk enrichment facility. Australia has carried out enrichment R&D in the past but is not currently actively pursuing the idea of building its own enrichment plant.

Thus far, Kazakhstan has committed to buy ten percent of the IUEC [*Nuclear Fuel*, 24 Sept. 2007].[80] Ukraine may become part of the IUEC [*Nuclear Fuel*, 30 Nov. 2009] and Armenia also is expected to become a partner [*Nuclear Fuel*, 20 April 2009]. Russia offered Iran a share in the ownership as an alternative to Iran building its own enrichment plant but Iran declined.

This arrangement has been at least partially successful as a nonproliferation initiative, in that it apparently has convinced Armenia, Kazakhstan and perhaps Ukraine that they do not need to have their own national enrichment plants. But it appears that the operation of the plant will be no more transparent to the investors than to non-owner customers. In a non-weapon state such as Iran, therefore, this form of multinational ownership would not provide an additional level of nonproliferation assurance beyond that provided by IAEA inspections.

Urenco provides another model for multinational arrangements. Each of the original partner countries (Germany, the Netherlands and the United Kingdom) has its own technology R&D team and enrichment plant. Obviously, the joint management and sharing of technology within Urenco provides greater transparency among the partners. In the past, however, Urenco has not maintained effective control of the technology. Urenco was the source of the technology that A.Q. Khan used to build Pakistan's enrichment complex and exported to Iran, Libya, North Korea and perhaps other countries. Iraq similarly acquired centrifuge technology through German companies that were supplying Urenco with centrifuge components [Kehoe, 2002].

More recently, Urenco has expanded its business through a joint subsidiary, Enrichment Technology Corporation, to provide centrifuges and design services for enrichment plants in France and the United States. France's nuclear services provider, AREVA, has purchased a 50-percent share of Enrichment Technology Corporation, but without access to the technology. The centrifuges are built in Enrichment Technology facilities in Germany and the Netherlands and are assembled into cascades by Enrichment Technology employees in France and the United States [ETC, 2008]. Russia has similarly built enrichment plants in China [*Nuclear Fuel*, 19 Dec. 2005]. Sometimes the centrifuges are described as "black boxes" as far as the host country is concerned. Since France and the United States are both weapon states, however, Urenco has not yet faced the full challenge of protecting its technology in a non-weapon state.

Canada's uranium company Cameco has been refused a black-box enrichment plant by Urenco and it appears that the United States will not allow export of a laser-enrichment plant to Canada because of doubts about the feasibility of operating this technology in a black-box mode [*Nuclear Fuel*, 25 Aug. 2008]. Urenco also has not been enthusiastic about a proposal to resolve the international crisis

[80] In a separate arrangement, Kazakhstan and Russia have agreed to make equal investments in a new 5-million SWU enrichment plant adjoining the existing Angarsk facility [*Nuclear Fuel*, 28 July 2008b].

over Iran's enrichment program by putting it under multi-national control and replacing Iran's centrifuges with black-boxed Urenco centrifuges [*Nuclear Fuel*, 30 July 2007].

Director-General ElBaradei has proposed that all future enrichment and reprocessing facilities should be under some form of multinational or international control. The nonproliferation advantages and disadvantages of such approaches have been discussed [NAS-RAS, 2008; and Thomson and Forden, 2006]. If a plant was owned by several countries, or by an international institution, with the plant location designated as extra-territorial (as embassies are, or as the CERN physics laboratory in Switzerland is) this would pose a somewhat higher political barrier to the host state seizing the plant to use it for weapons purposes, as this would require expropriating property of other states or a multinational organization. If the full-time operating staff of such a plant included multinational personnel, this would provide greater transparency into plant operations than IAEA inspections do, and relationships among the foreign and host-state personnel might provide greater insight into whether some of the host state experts were disappearing to work on a covert facility. On the other hand, any multinational approach would have to pay extremely careful attention to technology protection. Access to sensitive technologies should be limited to staff from countries that already possess such technology, with appropriate clearance and screening.

Reprocessing Plants. With regard to reprocessing, there is another option: don't do it. As practiced today, reprocessing and plutonium recycle are not economic and do not significantly simplify spent-fuel disposal [von Hippel, 2007; von Hippel, 2008a; Schneider and Marignac, 2008; and Forwood, 2008]. Reprocessing costs about ten times as much as interim storage of spent fuel in dry casks and recycling plutonium in LWRs once, as is the current practice, does not significantly decrease its long-term radiological hazard. Most countries are abandoning reprocessing (Table 5).

An exception is Japan, where it has been politically unacceptable to allow spent fuel to accumulate indefinitely at the nuclear power plants.[81] A reprocessing plant making tax payments to the local town and prefecture, turned out to be more attractive and is being used to provide a centralized interim destination for Japan's spent fuel and also high-level waste being returned from the reprocessing of Japanese spent fuel in France and the United Kingdom [Katsuta and Suzuki, 2006]. Japan's nuclear establishment also argues that eventually, if fast-neutron plutonium breeder reactors are introduced, plutonium recycle could make Japan independent of uranium imports.

[81] At the end of 2008, however, Chubu Electric Power Company proposed to build a dry-cask storage facility with a capacity of 700 tons of spent fuel in connection with a proposal to build a new 1.4 GWe reactor to replace two old reactors with a comparable amount of generating capacity [CNIC, Jan/Feb. 2009a].

Japan's reprocessing plant, when operating at its design capacity of 800 tons of spent fuel per year, will separate about 8,000 kilograms of plutonium per year. The first-generation Nagasaki bomb contained 6 kilograms of weapon-grade plutonium metal (almost pure plutonium-239), which would be roughly equivalent, in terms of critical masses to 8 kilograms of power-reactor-grade plutonium [Kang and von Hippel, 2005, Table 1].

A shift to more "proliferation-resistant" reprocessing technologies was proposed by the G.W. Bush Administration in 2003 [US DOE, 2003]. Evaluation of the added proliferation resistance of the proposed technologies found, however, that it was it was not significant [see, e.g., Collins, 2005; Hill, 2005; and Kang and von Hippel, 2005]. Ultimately, the Administration proposed to deploy a reprocessing plant very little different from those in France and Japan.[82] The Obama Administration dropped the idea of building a reprocessing plant but is continuing to fund reprocessing R&D.

Risk of nuclear-explosive terrorism

In addition to the problem of proliferation of nuclear weapons to more nations, there is also the risk that terrorists could acquire and detonate a nuclear explosive [Bunn, 2008a]. Repeated studies by the United States and other governments have concluded that, if a well-organized and well-financed terrorist group acquired plutonium or HEU, it might well be able to make at least a crude nuclear explosive. Attempts by groups such as al-Qaeda and the Japanese cult Aum Shinrikyo to acquire nuclear weapons or the materials needed to make them and to recruit nuclear experts have demonstrated that the danger is more than theoretical. Numerous cases of theft and smuggling of at least small quantities of plutonium and HEU have already occurred [Zaitseva, 2007].

Neither HEU nor separated plutonium are present when current-generation nuclear power plants operate on a once-through fuel cycle. The fresh fuel is made from LEU, which cannot support an explosive nuclear chain reaction without further enrichment—a challenge that is beyond plausible near-term terrorist capabilities—and it would be very difficult for terrorists to steal the intensely radioactive spent-fuel assemblies and separate out plutonium for use in a nuclear weapon. For decades, however, there have been concerns that fuel cycles involving plutonium separation and recycle might significantly increase the risk nuclear theft and terrorism [Willrich and Taylor, 1974; Mark *et al.*, 1987].

Weapon-usability of power-reactor plutonium. The Acheson-Lilienthal Report contained a misunderstanding concerning the weapon-usability of power-reactor plutonium. It stated that both "U 235 and plutonium can be de-natured" for

82 The G.W. Bush Administration insisted that pure plutonium not be separated, i.e., that it be mixed with uranium. Since it is trivial to separate plutonium from uranium, this would be of only symbolic significance.

weapon use [Acheson-Lilienthal, 1946, p. 30]. That is correct for uranium-235, which can be diluted down to low enrichment but not for plutonium.[83]

The authors apparently believed that the isotope plutonium-240 could be used to denature plutonium for weapons. Plutonium-240 fissions spontaneously and therefore generates neutrons continually at a low rate. In the implosion design, used in the Nagasaki weapon, these neutrons could start the fission chain reaction before the optimal time for maximum yield. Great efforts therefore were made to keep the percentage of plutonium-240 below a few percent. LWR plutonium contains about 25 percent plutonium-240 [NEA, 1989, Table 9]. In the Nagasaki design, this could have reduced the yield from 20,000 tons of chemical explosive equivalent to as low as 1,000 tons [Oppenheimer, 1945; Mark, 1993]. Such an explosion would still be devastating, however. The radius of total destruction, which was 1.6 km at Hiroshima, would still be 0.7 km for a one-kiloton explosion.[84] For more advanced designs, such as those in the arsenals of the NPT weapon states, there would be no significant reduction of yield [US DOE, 1997, pp. 38-39].

Today, therefore, any mix of isotopes containing less than 80 percent plutonium-238 is considered weapon usable [IAEA, 2001, Table II].[85] Since the amount of plutonium-238 in the world is only one to three percent as large as the total amount of plutonium [NEA-1989, Table 9], it would be impractical to denature a significant fraction of the world's plutonium.

83 When diluted with uranium-238 to less than six percent concentration, uranium-235 cannot sustain an explosive chain reaction. Indeed, when the percentage is less than 20 percent, the fast critical mass is considered too large for fabrication of a practical nuclear weapon [IAEA, 2001, Table II]. This is the basis for the belief that LEU, defined as containing less than 20 percent uranium-235, is not directly weapon usable.

84 The radius of blast destruction is proportional to the one-third power of the yield [Glasstone and Dolan, 1977, equation 3.61.1].

85 Plutonium-238 is relatively short-lived (88-year half-life) and therefore generates a great deal of decay heat (0.56 kWt/kg). It is used as a heat source for applications such as space probes to the outer planets.

8 Institutional requirements

Because of the safety, security and proliferation risks it poses, the use of nuclear energy requires worldwide vigilance. Each nation operating nuclear facilities is responsible for their safety and security. But all states have an interest in making sure that other states fulfill these responsibilities, creating a need for international institutions.

In the decades since the Chernobyl accident, many countries have substantially strengthened their safety practices and regulations. But there is clearly more to be done. Even in the United States, which has some of the world's most stringent nuclear safety regulations and more reactor-years of operating experience than any other country, critics continue to argue that the Nuclear Regulatory Commission too often subordinates enforcement to the industry's cost concerns [UCS, 2007]. Countries building nuclear power plants for the first time will need to build up adequate groups of trained personnel, put in place effective nuclear regulatory structures and forge nuclear safety cultures [IAEA, 2007b; Acton and Bowen, 2008]. Countries such as India and China, which are rapidly expanding their civilian nuclear infrastructures, will have to take care that the expansion does not outpace capabilities to provide expert personnel to build, operate and regulate these facilities.

The development of regulatory requirements for securing nuclear facilities against sabotage and the theft of fissile and radioactive material is at a much earlier stage. Some countries still have no regulations specifying what insider and outsider threats their nuclear facilities should be defended against, and some do not require armed guards even to protect weapons-usable nuclear material from theft. Substantial steps are needed worldwide to reduce vulnerability [Bunn, 2008a].

National institutions also play a critical role in nonproliferation. Foreign ministries, export controls and intelligence agencies all have key roles. And IAEA safeguards cannot function without each state having an effective state system of accounting and control.

International institutions

International institutions promoting safety, security and nonproliferation include not only the IAEA but also industry organizations such as the World Association of Nuclear Operators (WANO), the Western European Nuclear Regulators Association (WENRA) and professional associations such as the Institute for Nuclear Materials Management (INMM).

Safety. The IAEA's International Nuclear Safety Advisory Group has produced a diagram (Figure 18) showing the international organizations, networks and activities to promote nuclear power plant safety that have grown up in the two decades since the Chernobyl accident.[86] Ultimately, however, decisions on nuclear safety measures are still left to each state. The Convention on Nuclear Safety, for example, does not set specific safety standards and reporting on safety problems is entirely voluntary.[87]

The IAEA plays a critical role by publishing standards, guides and recommendations, and organizing discussions of critical issues and best practices. With the OECD's Nuclear Energy Agency, it manages an Incident Reporting System that collects and assesses information on operating experience and safety-related incidents. It also organizes in-depth, three-week safety reviews of facilities by an international team of safety experts. In those cases where a follow-up mission has been performed,

Figure 18. **The global nuclear safety regime** [IAEA-INSAG, 2006].

[86] A useful overview of international activities related to nuclear safety can be found in [IAEA, 2007f].

[87] For a critique and a suggestion of a more robust approach, see [Barkenbus and Forsberg, 1995].

the IAEA has found that sites either have implemented or are implementing some 95 percent of the teams' recommendations [IAEA 2007f].

IAEA safety peer reviews occur, however, only when a member state asks to be reviewed, and only a minority of the world's power reactors have ever undergone such a review.[88] In 2008, a "Commission of Eminent Persons" appointed by Director-General ElBaradei recommended that states "enter into binding agreements to adhere to effective global safety standards and to be subject to international nuclear safety peer reviews" [IAEA-CEP, 2008].

WANO, a nuclear industry group established after the Chernobyl accident, is another key international nuclear safety institution.[89] WANO is divided into regional groups headquartered in Atlanta, Moscow, Tokyo, and Paris, with reactor affiliations determined by a combination of location and reactor type. All operators of nuclear power reactors worldwide are participants in WANO and accept international peer reviews as a condition of membership. WANO also manages a system for reporting incidents and operating experience and helps organize exchanges of best practices. The reactor vendors also play a key role helping countries to put effective regulations and operating practices into place, and the G8 countries and the European Union both have pursued extensive nuclear safety assistance programs, especially in former Soviet-bloc countries. Finally, there are also several international groupings of nuclear regulators [IAEA, 2007f].

Despite all these efforts, the International Safety Advisory Group has reported important weaknesses in international information sharing and actions. For example, the fact that WANO understandably maintains confidentiality can delay national regulators becoming aware of the incidents being reported [IAEA-INSAG 2006] and some types of incidents continue to recur. In 2006, then-WANO managing director Luc Mampaey complained that some utilities were not reporting at all and WANO chairman, William Cavanaugh III, warned that "another Chernobyl, or another Three Mile Island…would be enough to halt the nuclear renaissance" [*Nucleonics Week*, 27 Sept. 2007].

Security. Most countries shroud their security practices in secrecy and international institutions for promoting nuclear security therefore are substantially weaker than those for nuclear safety. The Conventions on the Physical Protection of Nuclear Material and Facilities and on the Suppression of Acts of Nuclear Terrorism do not set specific standards for how secure nuclear materials or facilities should be, and include no mechanisms for verifying that states are complying with their commitments. The IAEA has published physical protection recommendations, but they too are vague. They call, for example, for having a fence with intrusion

88 The first-ever IAEA Operation Safety Review Team (OSART) review in Russia was held in 2005 at the Volgodonsk plant.

89 The U.S. Institute of Nuclear Power Operations (INPO) was formed to play a similar function at a national level after the 1979 Three Mile Island accident near Harrisburg, Pennsylvania.

detectors around significant stocks of plutonium or HEU, but say nothing about standards of effectiveness.

U.N. Security Council Resolution 1540 legally obligates all U.N. member states to provide "appropriate effective" security and accounting for any nuclear weapons or related materials they may have. A common interpretation of what key elements are required for a nuclear security and accounting system to be considered "appropriate" and "effective" therefore could provide the basis for a legally binding global nuclear security standard [Bunn, 2008b].

Since the mid-1990s, bilateral and multilateral assistance programs have played a critical role in improving nuclear security. The United States in particular has invested billions of dollars in programs designed to help former Soviet-bloc countries install and operate improved security and accounting systems at sites with significant quantities of plutonium and HEU. It has also mounted a global program outside Russia to convert research reactors to use LEU rather than HEU [Bunn, 2008a]. Less attention has been devoted, however, to protecting nuclear power plants, fuel cycle facilities and nuclear shipments against terrorist actions. In 2008, the World Institute of Nuclear Security (WINS) was established, modeled in part on WANO. It is designed to provide a confidential but unclassified forum for nuclear security operators around the world to exchange best practices and discuss issues they have confronted in the hope of improving nuclear security practices worldwide [Howsley, 2008].[90]

Nonproliferation. The 1968 NPT is the foundation for all international efforts to stem the spread of nuclear weapons and has been highly successful. The nonproliferation regime is now under stress, however. Iran's refusal to comply with the U.N. Security Council's demand that it suspend its enrichment program, combined with North Korea becoming the first state ever to withdraw from the NPT and manufacture nuclear weapons, have raised concerns about the ability of the international community to enforce compliance. In addition, the treaty's legitimacy has been undercut by the perception that the NPT nuclear-weapon states have not lived up to their obligation under Article VI of the NPT "to pursue negotiations in good faith on…nuclear disarmament."[91] Many non-weapon states also see efforts by the United States and some other states to prevent the spread of national enrichment and reprocessing plants as undermining the treaty's Article

[90] WINS' first director is Roger Howsley, previously head of security, safeguards and international affairs at British Nuclear Fuel Services Limited. Its web site is at http://www.wins.org.

[91] The entire article, whose interpretation has been clarified by a legal opinion [International Court of Justice, 1996] and subsequent commitments by the weapon states at the 1995 and 2000 NPT Review Conference [UN, NPT Review Conference, 2000], reads as follows: "Each of the Parties to the Treaty undertakes to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament, and on a Treaty on general and complete disarmament under strict and effective control."

IV guarantee of the "inalienable right of all the Parties to the Treaty to develop, research, production and use of nuclear energy for peaceful purposes and without discrimination…"

Of the institutions established to implement the nonproliferation regime, the most important is the IAEA. IAEA safeguards play a critical role in verifying the peaceful use of nuclear energy around the world. The IAEA faces important constraints in access to sites, information, resources and technology, however, and challenges in balancing its efforts to maintain essential positive relationships with states with an appropriate investigatory attitude.

The Additional Protocol is a major advance with regard to access to sites and information, but many issues remain. First, more than a decade after its adoption, there are more than a dozen states with significant nuclear activities or ambitions that have not acceded to the Additional Protocol.[92] Also, despite its expansion beyond the traditional focus on nuclear materials, the Additional Protocol focuses primarily on the IAEA's rights to inspect sites with technologies related to the production of nuclear materials. As a result, when the IAEA wanted to investigate a site in Iran where implosion experiments related to nuclear-weapon design allegedly had taken place, there were no undisputed legal grounds for doing so.[93] Former IAEA Deputy-Director-General for Safeguards Pierre Goldschmidt has suggested that the U.N. Security Council pass a resolution that would require any state found to be in violation of its safeguards agreements to provide access beyond that required by the Additional Protocol and to allow IAEA inspectors to interview, in private, key scientists and other participants in nuclear programs [Goldschmidt, 2008]. The U.N. Security Council has, in fact, backed the IAEA's demand that Iran provide such a level of transparency.[94]

With respect to resources, the IAEA's regular budget for implementing nuclear safeguards worldwide in 2007 is only $100 million or about 0.004 cents per kWh generated by the world's nuclear power plants [IAEA, 2009c]. In the context of renewed hiring in the nuclear industry, the Agency also has increasing difficulty

92 Including Algeria, Argentina, Brazil, Egypt, Iran (signed but not ratified), Iraq (signed but not ratified), North Korea, Mexico (signed but not ratified), Saudi Arabia, Syria, United Arab Emirates (signed but not ratified), Venezuela and Vietnam (signed but not ratified) [IAEA, 2010c].

93 The IAEA asked Iran to voluntarily accept a visit to that site, which Iran eventually did.

94 In its Resolution 1803 of 3 March 2008, the U.N. Security Council ordered Iran to "take the steps required by the IAEA Board of Governors in its resolution GOV/2006/14, which are essential to build confidence in the exclusively peaceful purpose of its nuclear programme and to resolve outstanding questions." IAEA Board of Governors resolution GOV/2006/14 calls on Iran to "implement transparency measures, as requested by the Director General, including in GOV/2005/67, which extend beyond the formal requirements of the Safeguards Agreement and Additional Protocol, and include such access to individuals, documentation relating to procurement, dual use equipment, certain military-owned workshops and R&D as the Agency may request in support of its ongoing investigations."

recruiting and retaining nuclear experts. This is especially serious, given that, in 2008, roughly half of all senior IAEA inspectors and managers were within five years of the agency's mandatory retirement age [IAEA-CEP, 2008]. The IAEA also does not have the resources to do its own R&D to develop new safeguards technologies. It depends on support programs from member states.[95]

The IAEA also plays a major promotional role by helping states acquire and apply nuclear technology for research, medical and agricultural purposes. Overall, by informal agreement among the member states, the IAEA budget for promoting and assisting with nuclear energy and applications of nuclear technology is kept at about the same size as the budget for safeguards.[96]

Despite a call from former IAEA Director-General ElBaradei for negotiation of a universal nuclear export control regime, no progress has been made in that direction. The Nuclear Suppliers Group (NSG) has tried to fill this space but faces ongoing challenges to its legitimacy because it is a self-selected group. Also, the decision to exempt India from the NSG requirement of membership in the NPT has strengthened the impression that economically powerful countries do not have to comply with the rules. The NSG has traditionally operated by consensus but, as more and more states have joined, consensus on strengthening its rules has become more and more difficult to achieve. Most NSG participants, for example, strongly support making the Additional Protocol a condition for nuclear exports from NSG states, but Brazil (which has not accepted the Protocol) has resisted. Canada has similarly refused to agree that enrichment technologies be exported only on a "black-box" basis, i.e., without the recipient being able to have access to the technology [*Nuclear Fuel*, 1 Dec. 2008].

[95] In recent years, however, the IAEA has established an expanded effort to identify new technological approaches to address some of its key safeguards needs, and to work with member states to develop and deploy them [Khlebnikov *et al.*, 2007].

[96] In 2007, the IAEA's base budget was $268 million, of which $103 million went to safeguards, $71 million to nuclear energy and development, and $22 million to nuclear safety and security. An additional $37 million of extra-budgetary funds were contributed by interested countries—mostly for the safeguards, and safety and security programs [IAEA, 2008d].

9 Public acceptance

As memories of the accidents at Three Mile Island (1979) and Chernobyl (1986) fade and concerns about the consequences of global warming increase, the trend has been toward more favorable public opinion of nuclear power. Fission power has inspired more public opposition than any other energy source except possibly hydropower in India and a few other countries. According to a survey of public opinion in eighteen countries done for the IAEA in 2005, although on average 62 percent of the respondents did not want existing nuclear power plants to be shut down, almost the same percentage opposed building new nuclear power plants (Figure 19). In many countries, such as the United States, a majority of the population has consistently opposed the construction of new nuclear reactors since the early 1980s [Rosa and Dunlap, 1994; Bolsen and Cook, 2008]. An April 2007 analysis for the European Commission concluded that "the European public is still strongly opposed to the use of nuclear power; those who are worried about climate change are even more fiercely opposed." Two thirds of the respondents favor a decrease of the share of nuclear energy in the European Union electricity mix while only one third would like to see it grow [EC, 2007].

Individuals oppose nuclear power for different reasons. One abiding concern has been the connection with nuclear weapons

> "Nuclear energy was conceived in secrecy, born in war, and first revealed to the world in horror. No matter how much proponents try to separate the peaceful from the weapons atom, the connection is firmly embedded in the minds of the public" [Smith, 1988].

Some feel that the technology is too expensive. The main cause for opposition, however, is the public perception that, aside from the connection with nuclear weapons, nuclear power is a very dangerous technology in its own right.

This public perception of risk has been something of a puzzle to many technical experts, since they do not view the risk to the public from nuclear power plants as especially high.[97] Technical experts often assess risk probabilistically through

[97] Enrico Fermi, who designed the first chain reacting "pile," apparently anticipated the public's concerns, however, well before the U.S. nuclear-power program was launched. He is reported to have commented (as paraphrased by Alvin Weinberg) that it "is not clear that the public will accept an energy source that produces this much radioactivity and that can be subject to diversion of material for bombs" [Weinberg, 1994, p. 41].

injuries and deaths per GWe-year of nuclear energy generated. Much of the public, however, is more sensitive to other characteristics. For decades, psychometric studies based on detailed opinion surveys have shown that

> "Nuclear power...risks were seen as involuntary, unknown to those exposed or to science, uncontrollable, unfamiliar, catastrophic, severe (fatal), and dreaded…These results have since been replicated with many different populations in numerous countries" [Slovic, 1994].

Public perceptions are also the result of various psychological, social and cultural processes that can heighten or attenuate risk signals [Kasperson *et al.*, 1988]. Typically, attenuation occurs with everyday hazards such as indoor radon, smoking and driving without a seatbelt. In contrast, nuclear power risks are typically amplified. Indeed, scholars studying public perceptions argue that nuclear energy is "subject to severe stigmatization." The term stigma is used to denote a technology that is not just considered hazardous but "something that is to be shunned or avoided not just because it is dangerous but because it overturns or destroys a positive condition" [Gregory *et al.*, 1995].

Faced with public antipathy, the nuclear industry and some governments have carried out campaigns to persuade the public to accept nuclear power. Many of the campaigns have centered on efforts to get the public to see risk the way experts see it through, for example, statements such as "the risk from living near a nuclear power plant is equivalent to the risk of annually riding an extra three miles in an automobile." But such comparisons do not address the qualities of the risk that people believe to be important and often produce more anger than enlightenment [Slovic, 1996].

Also, the implicit assumption that public opposition results from ignorance may not be correct [US OTA, 1984]. An analysis of the debate over the risks from the Diablo Canyon nuclear plant in California, U.S.A. found that

> "proponents and opponents were equally knowledgeable about nuclear power factual information, but those who supported nuclear energy expressed more trust in the credibility of information received from government and industry officials and were more trusting that the officials would protect the public" [Levi and Holder, 1988].

Indeed, many studies reveal a widespread belief that the social institutions that manage nuclear power are untrustworthy as sources of information [Wynne, 1992]. A 2001 survey by the European Commission found that only twelve percent of Europeans trusted the nuclear industry [EC, 2008].

Both trust and distrust tend to reinforce and perpetuate themselves [Slovic, 1993]. A nuclear reactor accident such as the 1979 accident at Three Mile Island, which did not result in the release of a significant amount of radioactivity, can be seen either as proof that safety through defense in depth works or that catastrophe was averted only by sheer luck. Distrust is also reinforced by evidence of suppression of negative information. Examples are the revelations of the falsification of quality-control data on MOX fuel manufactured by British Nuclear Fuels Limited [UK-HSE, 2000] and that accidental control-rod withdrawal events during shutdowns at nuclear power plants in Japan had been covered up for years [Japan-NISA, 2007].

Today, concerns about nuclear power are confronted by another great concern: the consequences of global warming. The nuclear industry, some independent scientists, and some governments are increasingly reframing the debate into one over whether public fears about nuclear power have to be subordinated to the need to limit climate warming. In a 2005 survey, this argument resulted in an increase in public support for building new nuclear power plants averaging about 10 percent [Globscan, 2005].

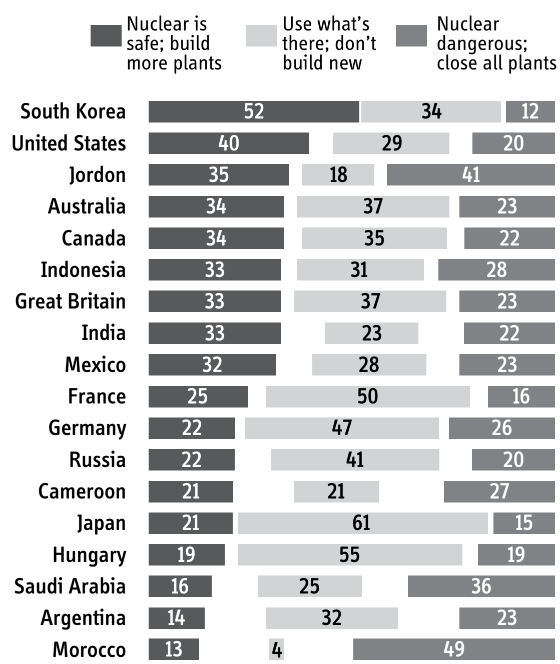

Figure 19. **Attitudes toward nuclear power by country.** The white space represents "don't know," "none of the above," "other" or "no answer" [Globscan, 2005].

The U.K. debate has been particularly intense because of a national commitment to decrease carbon emissions, a decline in the availability of North Sea gas and the retirement of the United Kingdom's first-generation Magnox reactors. The government, nuclear industry, major scientific leaders and professional societies all have been promoting a "new build" of nuclear capacity. One study that used a survey and focus groups to evaluate the impact on public attitudes of a reframing of the issue of nuclear power around the need to reduce carbon emissions found "reluctant acceptance" [Bickerstaff *et al.*, 2008]. Radioactive waste was regarded with even greater dread than climate change, however, and there was great mistrust of the competence of the nuclear-power establishment and government to manage nuclear power safely. There were also concerns about the possibility of terrorist attacks on nuclear facilities. If a more rapid shift to renewable sources of electricity were identified as feasible, it would attract greater support. In 2008, a U.S. national poll, found 42 percent supported an increased commitment to nuclear power versus 93 percent for solar, 90 percent for wind, 52 percent for natural gas, 33 percent for coal and 22 percent for oil [Greenberg, 2009].

10 Policy recommendations

Throughout its history, two questions have been debated about fission power:

1. Is it necessary?
2. How much can the dangers that it poses be reduced?

The first question can only be answered in the larger context of an examination of the alternatives, the rates at which they can be deployed and their costs—both economic and external.

If public attitudes are to be respected, however, nuclear power should be introduced or expanded in a country only after a comparative assessment with public review and participation has been carried out of alternative means of matching supply with demand.

With regard to the second question, the largest dangers that should be minimized are Chernobyl-scale releases of radioactivity into the environment and the facilitation by nuclear power of nuclear-weapon proliferation and nuclear terrorism. There are a number of initiatives that could reduce but not eliminate both risks.

Reduce the Risk of Catastrophic Releases of Radioactivity

The LWRs that dominate nuclear power today and will do so for the foreseeable future were originally developed for naval propulsion. The primary design constraint therefore was that they be compact. When they were adapted to be power reactors, that constraint was loosened and redundant emergency cooling systems and a containment building were added. These additions helped but, as the 1979 Three Mile Island accident showed, a core melt-down accident is still possible. Also, some containment buildings would not have been able to withstand the pressure increase from the hydrogen burn that occurred during the Three Mile Island accident while others would be over-pressured by the carbon dioxide that would be released if a molten core began to eat its way through the concrete floor of the containment [Beyea and von Hippel, 1982].

The owners of LWRs made significant improvements in operator training after the Three Mile Island accident and the "Generation III+" LWRs that are being introduced today have significant improvements in safety design. The pressure to increase safety has not been so effective in the regulatory area, however. In 2002, the U.S. Nuclear Regulatory Commission's (NRC) Inspector General commented, after the NRC had allowed the Davis Besse nuclear reactor to continue to operate in what was later established to be an extremely dangerous condition, "NRC appears to have informally established an unreasonably high burden of requiring absolute proof of a safety problem, versus lack of reasonable assurance of maintaining public health and safety…" [US NRC, 2002].

And what of the alternatives to the conventional LWR that are currently being examined in the Generation IV (Gen IV) reactor R&D effort? Although safety is a desideratum, relative safety does not appear to be a selection criterion between the different types of reactors under consideration. Rather, safety studies are being pursued with the objective of making each existing design type as safe and licensable as practicable [Gen IV 2008, p. 54]. In any case, it has been stated repeatedly by Gen IV industry representatives that, whatever the design type, commercial operation is still decades away.

An effort should therefore be mounted, with a higher priority than the Gen IV efforts, to design a reactor for safety, including associated spent-fuel storage, and then to see how it could be optimized economically rather than the other way around.

Proposals for safety improvements that could be retrofitted into existing nuclear power plants, such as a filtered vent in case of containment overpressure, should also be considered and has, in fact, been implemented in some plants [Beyea and von Hippel, 1982; Schlueter and Schmitz, 1990]. Given license extensions to 60 years and perhaps beyond,[98] many of the existing plants are likely to be operating for a very long time. Dense-packing of spent-fuel pools should also be reconsidered because of the possibility of a loss of coolant leading to a spent-fuel fire and a release of cesium-137 to the atmosphere potentially many times larger than the Chernobyl release [Alvarez et al, 2003; US NAS, 2005].

The importance of designing more inherent safety and physical security into nuclear power plants increased after the events of September 2001, which made indisputable the existence of sub-national groups willing to commit mass murder.

Increase Proliferation Resistance

There are two obvious steps by which the proliferation resistance of civilian nuclear energy could be increased:

1. Phase out reprocessing as quickly as possible; and
2. Place enrichment plants under multinational ownership and management.

98 The most recent projection for U.S. nuclear capacity by the U.S. EIA assumed that the licenses of U.S. nuclear power plants will be extended to 80 years [US EIA, 2009a].

Phase out reprocessing as quickly as possible. The only place in which directly weapon-usable material becomes accessible in the fuel cycle of an LWR fueled with LEU is as a result of spent-fuel reprocessing, i.e., the separation of plutonium (possibly mixed with other transuranic elements) from the intensely gamma-emitting fission products—dominated ten or more years after discharge by 30-year half-life cesium-137. As discussed above, there is general agreement that, for the foreseeable future, fuel cycles involving reprocessing and plutonium recycling will not be economically competitive with “once-through” fuel cycles in which the spent fuel is stored. Proliferation resistance is therefore aligned with economics in this case and there would only be economic benefits from phasing out reprocessing. In some cases, such as Japan and South Korea, political obstacles would have to be overcome to extended interim storage of spent fuel on nuclear power plant sites or at a central site.

Place enrichment plants under multinational ownership and management. Multinational ownership and management, if well designed, could make it more difficult for a host government to convert an enrichment plant to the production of HEU for weapons or divert expertise and components to the construction of a clandestine national enrichment plant. An arrangement intermediate between that of Urenco, which involves technology sharing, and EURODIF and Angarsk, in which non-host countries are passive investors might be optimal. Indeed, the black-box model that has been adopted by Urenco in France and the U.S. and by Russia in China, might be near the correct balance. In this arrangement, management of the plant can be shared, making operations more transparent among the partners, but the technology is not.

In order to make this approach politically feasible, it would probably be necessary to convert existing national facilities in the weapon states into multinational facilities. It also would be desirable to agree that new facilities should not be built until a minimal level of contracted demand exists to make it economically viable (at least the equivalent of ten GWe of LWR capacity, corresponding to an enrichment capacity greater than one million SWUs per year).

The selected technology should be one of the two or three most economically competitive available, as judged by an international bidding process and (as already noted) supplied on a black-box basis if the host nation is not an owner of such competitive technology. This would reduce the danger that every new enrichment plant would be used to justify the host country developing its own enrichment technology. Today, Urenco’s Enrichment Technology Company and Russia’s Rosatom make the most cost-effective gas centrifuges.

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