14

Nuclear Energy

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Executive 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 safety requires redundant cooling and control systems, massive leak-tight containment structures, very conservative seismic design, and extremely stringent quality control. As a result, the capital costs of nuclear power plants at least, in Western Europe and North America, proved to be quite high and nuclear power did not become the dominant generator of electrical power.

The routine health risks and greenhouse gas emissions from fission power are small relative to those associated with coal, but there are also high-consequence risks: nuclear weapons proliferation and the possibility of overheated fuel releasing massive quantities of fission products to the environment. The public is sensitive to these risks. The 1979 Three Mile Island and 1986 Chernobyl accidents, along with the high capital costs, ended the rapid growth of global nuclear power capacity (Figures 14.1 and 14.2). After these accidents, the industry improved its overall safety culture, particularly with regard to operator training. This chapter was completed before the large releases or radioactivity from the Fukushima Daichi nuclear power plant that began in March 2011. That event has resulted in reviews of the adequacy of nuclear power safety design and regulation worldwide and, in some countries, a reconsideration of plans for new reactors and/or reactor operating license extensions.

Today, China has 24 GW_e of nuclear capacity under construction (IAEA-PRIS, September 28, 2010) and much more planned. But, Germany has decided to phase out nuclear power; and nuclear power elsewhere in Western Europe and North America, which together account for 63% of current global capacity, is being dogged again by high capital costs and it is not yet clear that new construction will offset the losses due to the retirement of old capacity. Cost escalation is better contained in East Asia, where the International Atomic Energy Agency (IAEA) expects 44–68% of global nuclear capacity expansion by 2030 to occur in China. In Japan, however, following the Fukushima accident, the government has decided to reduce the country's dependence on nuclear power and the debate is ongoing whether to phase it out entirely. Even for its high-nuclear-growth projection which assumes a doubling of current generating capacity by 2030, the IAEA acknowledges that nuclear power's current 14% share of global electric power generation will not increase.

An important societal debate is still ongoing. Do the potential environmental benefits from low-carbon nuclear power outweigh the risks inherent in the technology? These risks occur in reactor operation and possibly in disposal facilities,

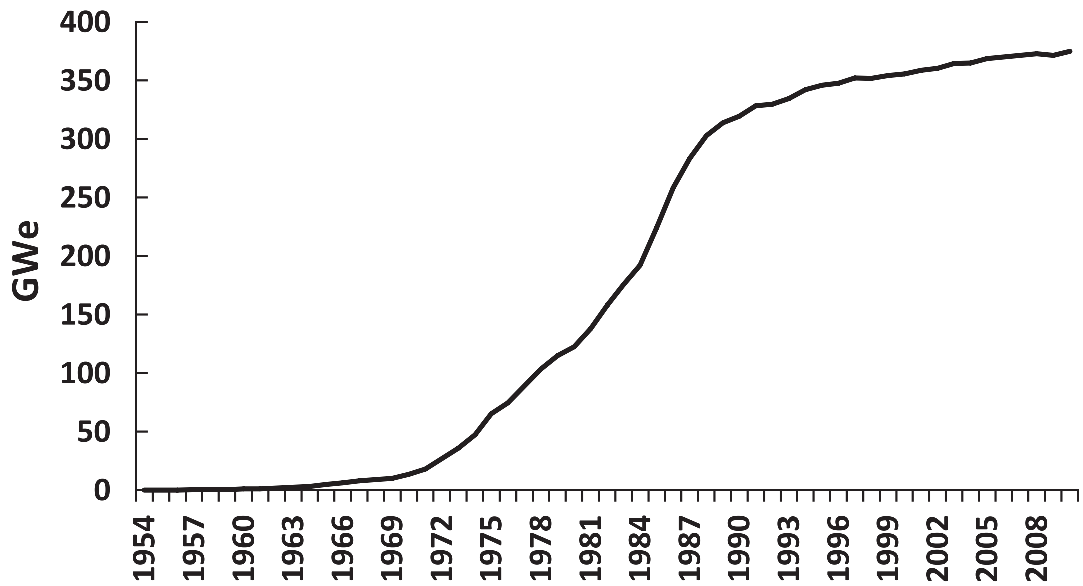

Figure 14.1 | Growth of global nuclear power capacity (GW_e). Source: data from IAEA-Pris, 9 January 2010.

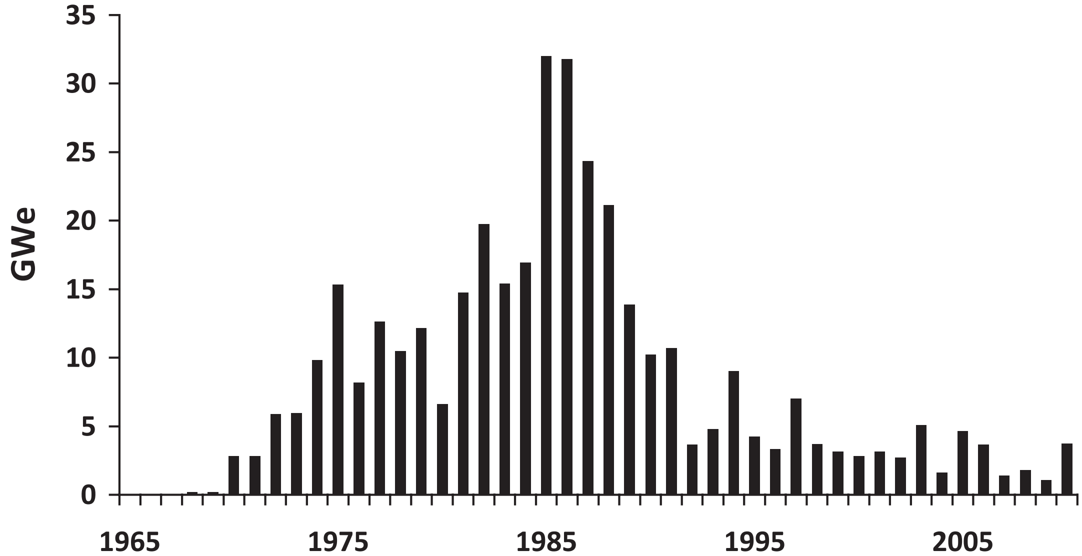

Figure 14.2 | Global nuclear capacity installed by year (GW_e). Source: data from IAEA-Pris, 9 January 2010.

but, in the view of the authors of this chapter, the most important risk from nuclear power is that its technology or materials may be used to make nuclear weapons. Of the 30 nations that have nuclear power today, seven are nuclear weapon states,[1] and most of the non-weapon states have had their non-weapon status stabilized either by being part of the European Union, the North Atlantic Treaty Organization (NATO) or otherwise being under the security umbrella of the United States, or by having been part of the Soviet Union or the Warsaw Pact in the past. The non-weapon states with the weakest security ties to the United States and Soviet Union – Argentina, Brazil, South Africa and Sweden – for a time used their nuclear power programs as covers for nuclear weapon programs. The majority of the countries that have expressed an interest in acquiring their first nuclear power plants (see Introduction, Table 14.2) are similarly not tied to constraining alliances such as NATO and the former Warsaw Pact, and some may have mixed motives for their interest in acquiring nuclear technology. That nuclear weapons may spread with nuclear power technology is therefore a danger that must be taken seriously.

The dominant type of nuclear power reactor in operation 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 1% 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. Given the availability of low-cost uranium and the possibility to dispose spent fuel as waste there is no compelling economic or waste-management reason today to separate out this plutonium.

Much of the leadership of the global nuclear energy establishment, including in France, India, Japan, and Russia, however, continue to promote the uranium conservation and waste-reduction benefits of recovering plutonium from the spent fuel and recycling it. These arguments provided cover for India's nuclear weapon program, which used plutonium produced using a research reactor supplied under the international "Atoms for Peace" program to make its first nuclear explosion in 1974, and also for the weapons dimensions of at least six other nuclear programs.[2] Even when done for

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.

2 Argentina, Brazil, South Korea, Pakistan, Sweden, and Taiwan. Fortunately, all but Pakistan have abandoned their nuclear weapons programs.

peaceful purposes, plutonium recycling is destabilizing because it dramatically reduces the time required for a country to implement a decision to acquire nuclear weapons.

The other route to nuclear weapons involves the enrichment of uranium to a level above 20% uranium-235 (typically to more than 90%). 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 an even smaller scale than that 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 1-gigawatt electric (GW_e) LWR could produce enough material for 25 nuclear weapons per year. Today, members of the nonproliferation community are devoting much of their attention 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 the persistent opposition from a significant portion of the public. As memories of the accidents at Three Mile Island and Chernobyl faded and concerns about the consequences of climate change increased, the trend was toward public opinion that was more favorable. The Fukushima accident has revived concerns about reactor safety, however. Public concern about radioactive waste and opposition to the siting of central spent-fuel storage sites have also helped keep reprocessing plants alive as alternative destinations for spent fuel, despite their poor economics and the proliferation dangers they pose. Of the countries that are most advanced in siting repositories, Finland and Sweden do not reprocess and France does. The radiological hazards from properly designed deep underground waste repositories are small in comparison with those of a Chernobyl-scale release to the atmosphere from a nuclear power plant accident. Perhaps it is due to their recognition of this fact that the communities that have agreed to host radioactive waste repositories already host nuclear power plants.

In the 1970s, nuclear power proponents expected that by 2010 nuclear power would produce perhaps 80–90% of all electrical energy globally (US AEC, 1974). Today, the official high-growth projection of the Organisation for Economic Co-operation and Development Nuclear Energy Agency estimates that nuclear power plants will generate about 20% of all electrical energy in 2050 (NEA, 2008a). Thus, nuclear power could make a significant contribution to the global electricity supply. At the other extreme, it could be phased out, especially if another accident or terrorist incident causes a Chernobyl-scale release of radioactivity. If the spread of nuclear energy cannot be decoupled to a much larger extent from the spread of nuclear weapons, for example, by ending reprocessing and shifting from national to multinational enrichment, it should be considered a last resort energy option.

14.1 Introduction

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

Most current-generation fission reactors are "slow-neutron" reactors.[3] The fast neutrons emitted by fission are slowed by multiple collisions with the nuclei of a "moderating" material before they cause additional fissions (Figure 14.3). Because the probability that fissile nuclei will 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 uranium-235 and is thereby converted into chain-reacting plutonium-239.

Fission power is climate friendly. The emissions of greenhouse gases per kilowatt-hour (kWh) from fission power on a life-cycle basis are on the order of a few percent of those from fossil-fueled power plants.[4] A nuclear capacity of 500–700 GW_e, i.e., 1.3–1.8 times current global nuclear capacity, could forestall the annual release of 10^9 tonnes of carbon to the atmosphere if used to replace coal-fired power plants that do not sequester their carbon dioxide emissions.[5] This would be about one-eighth of the global amount of carbon released into the atmosphere from fossil fuel use and cement production in 2005 (IPCC-PSB, 2007: 139) and 5–12% of the releases projected for 2030 in the full range of IPCC scenarios (IPCC-SRES, 2000: Figure 5–2). The other routine occupational and environmental impacts of nuclear power plants per kWh are relatively low compared with those of fossil power (see Chapter 4). But the potential for catastrophic releases of radioactivity makes the reputation of the global nuclear industry vulnerable to unsafe practices in any country. It is therefore critical to maintain high safety and security standards in design, construction, and operation everywhere.

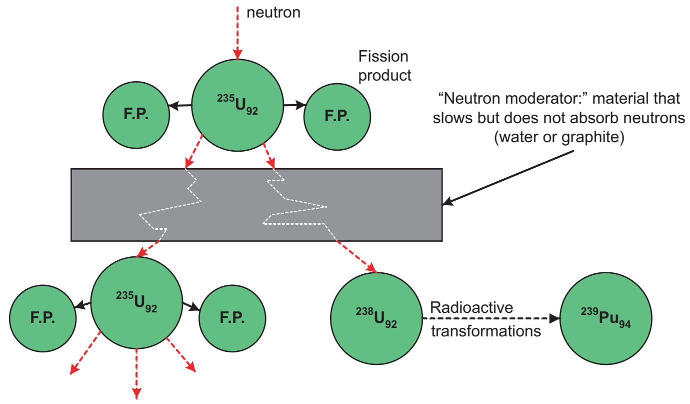

Figure 14.3 | A fission chain reaction in a slow-neutron reactor. Each fission splits a nucleus of a fissile atom (shown here as U-235) into two unequal medium-weight nuclei (fission products, F.P.) and also produces typically two or three neutrons that can go on and cause further fissions. In almost 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 U-238, converting it into U-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.

Although relatively little nuclear capacity has been added in recent years (Figure 14.2), the average capacity factors of nuclear power plants have increased steadily to about 80%.[6] Between 1988 and 2001, they therefore maintained their share of generated electricity at about 17%, before dropping to about 14% by 2009 (IAEA, 2010d: Tables 3 and 4).[7] For nuclear energy to maintain its share of the global electrical power market there will have to be a dramatic increase in nuclear capacity construction – especially as most existing nuclear capacity will have to be replaced during the period 2010–2050.[8]

Given the uncertain capital costs of nuclear power plants, the risks associated with uncertain demand growth projections in North America and Europe, and the possibility of catastrophic accidents, private capital is unlikely to be available to fund nuclear power plant construction without government guarantees. Such support is available, however, in the form

3 "Slow" here is used as a relative term. Ultimately, neutrons are slowed down so that they have the kinetic energy associated with the atoms in the material through which they are passing. At this velocity, they are often called "thermal" neutrons. The velocity associated with the temperature of the water in a light-water reactor (about 300˚C) is about 4 km/s, more than ten times the speed of sound in the atmosphere.

4 Emissions from coal-fired power plants are about 1000 g CO_2/kWh. Emissions estimates for nuclear power plants range from 1.4 to 200 gCO_2/kWh (Sovacool, 2008a). Eliminating incomplete estimates and estimates associated with extremely low grades of uranium ore, and reducing two inexplicably high estimates for the emissions associated with decommissioning, we obtain a range of 38±27 g CO_2/kWh. The uranium ore being mined today typically has concentrations of 0.1% uranium and above (van Leeuwen, 2008, Figure D-3).

5 Assuming that 25.8 kg of carbon are released to the atmosphere per 10^9 J of energy from bituminous coal (World Energy Assessment, 2000, box D.1), an efficiency range for new coal power plants of 35–50% and an average nuclear-power plant capacity factor of 90% (478.5–683.6 GWe). See also Pacala and Socolow (2004).

6 There are substantial variations in these capacity factors, even among those states with the largest nuclear programs. For the period 2007–2009, the average capacity factors for the United States and France were 91 and 95%, respectively, and in Japan and Russia 63% and 81%, respectively (IAEA, PRIS, 11 Nov. 2010).

7 The average capacity factor ("unit capability factor" in the IAEA's terminology) is the ratio of the average output of a power plant as a percentage of its full generating capacity. The "up-rating" of nuclear power plants, i.e. operating them at higher power than their original design capacity, has also contributed to a lesser degree to increasing the number of kilowatt hours being generated by nuclear power during the period when few new plants were being built.

8 Assuming operating lifetimes of 40–60 years (see Figure 14.2).

of direct government funding, loan guarantees, or guaranteed payback of investments through government-regulated markets for electric power.

In China, the construction of nuclear power plants 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 large government-owned companies – AREVA, which sells reactors and fuel-cycle services, and Électricité de France, 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 India, the national government is financing the construction of nuclear power reactors. In the United States, the US Congress passed a major package of incentives and loan guarantees in 2005 to restart reactor orders after a hiatus of three decades. Some state regulators in the United States also 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 nuclear power reactors. Whether the new construction will be significant on a global scale remains to be seen. 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 approximately double by 2030, with nuclear power slightly increasing its current 14% share of the global market for electric power to 16% by 2030. The IAEA's low-growth scenario shows global nuclear power capacity increasing by 47% by 2030 but its market share staying constant (IAEA, 2010d).

Much of the continuing political support for nuclear power stems from the large government nuclear research and development (R&D) establishments in the nuclear weapon states. The first power reactors in the former Soviet Union, the United Kingdom, and France were derivatives of their natural-uranium-fueled, graphite-moderated, plutonium production reactors.[9] 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 in India. Today's most successful power reactor, the low-enriched uranium-fueled light-water reactor (LWR), stems from the compact water-cooled reactors developed for submarine propulsion.

Most of the initial R&D relevant to nuclear power technology was therefore 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. Over the past three decades they have received more than 50% of government expenditures on energy research, development and demonstration (RD&D) projects (Figure 14.4). This bias toward nuclear energy spread to the national R&D establishments of some non-weapon states, most notably that of Japan.

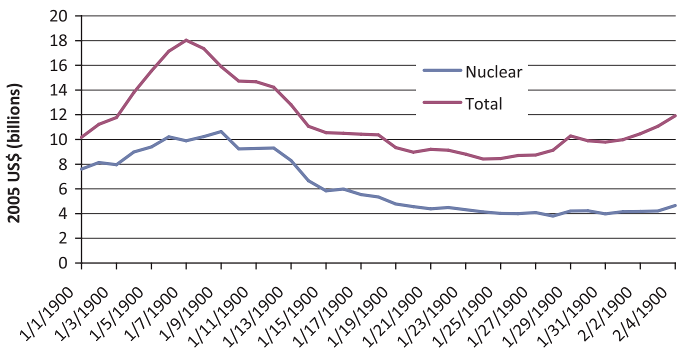

Figure 14.4 | Government energy RD&D expenditures in the OECD countries, 1974–2006. Nuclear includes both fission and fusion. Source: based on IEA, 2008.

Perhaps the most important question with regard to fission power is whether it can grow and spread without spreading nuclear weapons. Various efforts have been undertaken in the past to contain the spread of national spent-fuel reprocessing and uranium enrichment plants that remain the keys to producing nuclear weapon materials. There is reluctance in have-not countries, however, to forgo the option of acquiring a national enrichment plant. And, even though reprocessing and plutonium recycling are uneconomic and have few environmental benefits when used with current nuclear power reactors, many local communities have opposed plans to expand spent-fuel storage facilities at reactor sites or to host central interim storage facilities. This opposition 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.

14.1.1 Global and Regional Nuclear Capacity

Today, 29 countries plus Taiwan have operating nuclear power plants: 18 in Europe (including Armenia, Russia, and Ukraine), five in Asia (plus Taiwan), five in the Americas, and one in Africa (South Africa) (see Figure 14.5).

At the end of 2009, global nuclear generating capacity was 372 GW_e, of which 46% was in Europe (including Eastern Europe, Armenia, Ukraine and Russia), 30% in North America, and 21% in the Far East. The rest of the world – Africa, Latin America, the Middle East and South Asia – accounted for only 3% of this capacity (Table 14.1), but contributed a large part of the controversy over the proliferation implications.

9 Graphite and heavy water are used in reactors fueled with natural uranium to "moderate" (slow down) the typically two or three neutrons emitted by fissions to speeds where a large fraction of them will be absorbed by the U-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, which is why LWRs require enriched uranium fuel.

Figure 14.5 | Capacities of nuclear power reactors in operation by country, end of 2009. Source: data from IAEA-PRIS, January 9, 2010.

14.1.2 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 actually built by 2000 and 2005 (IAEA, 2007a, figures 29, 30). There were few new orders for nuclear power plants and many orders were either cancelled or delayed because of falling electric power consumption growth rates and licensing and construction delays. As a result, projections of growth declined through 2000, and the low projections in 2000 even showed future declines in global nuclear generating capacity as the number of old plants being retired exceeded new builds.

Table 14.1 | Global distribution of nuclear power generating capacity, end of 2009.

Region	Nuclear generating capacity (GW_e)
North America	113.3
Western Europe	122.7
Pacific OECD Far East	46.8
Eastern and Central Europe	11.2
Former Soviet Union	36.4
Centrally Planned Asia and China	8.4
South Asia	4.4
Other Pacific Asia	22.7
Middle East and North Africa	0.0
Latin America	4.1
Sub-Saharan Africa	1.8
World Total	371.9

Source: IAEA, 2010d.

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 IAEA's 2010 projection was for a net increase in global nuclear generating capacity of 174–431 GW_e by 2030 (IAEA, 2010d). The high end of the range corresponds to more than a doubling of the 2009 global nuclear capacity and assumes an average net annual addition of new capacity of 25 GW_e/yr between 2020 and 2030. This corresponds to a growth rate that was only achieved in the past during the late 1980s (Figure 14.2).[10]

Much of the projected increase would be in the Far East (119–189 GW_e) and Eastern Europe (including Russia) (36–63 GW_e), reflecting in particular the ambitious plans of China and Russia (see the country studies in Section 14.3). North America is also projected for an increase (15–53 GW_e). In the low projection, nuclear capacity in Western Europe declines by 37 GW_e, while in the high projection, it increases by 35 GW_e. The other world regions – Latin America, Africa, the Middle East, South Asia, Southeast Asia, and the Pacific – together are projected to add 38–79 GW_e.

The IAEA's low and high growth projections for nuclear power are associated respectively with 2.1 and 3.1% average annual growth rates in global electric power production between 2009 and 2030 (IAEA, 2010d). For comparison, between 1996 and 2006, global electricity consumption increased at an average annual rate of 3.3% (US EIA, 2008b). Given the likelihood of an increase in electricity prices associated with a shift away from fossil-fuel-based generating capacity, global electricity consumption growth rates could decline below the range assumed by the IAEA. On the other hand, if a significant fraction of automobile transport shifts to electric cars or plug-in hybrids, that could help offset the price effect.[11]

Reflecting the revived interest in nuclear power, as of 2010, 61 countries had requested advice from the IAEA about acquiring their first nuclear

10 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."

11 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 total about 10^{13} automobile-km/yr. Assuming that 0.2 kWh would be required per km (Electric Auto Association Europe, 2008) about 2×10^{12} kWh/yr would be required, equivalent to the output of about 250 GWe of generating capacity operating at an average capacity of 90%.

power plants (IAEA, 2010e). Excluding Iran, whose first nuclear power plant is virtually complete, and including Israel, which is the only country that is on a similar list developed by the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency but not on the IAEA list (NEA, 2008a, Table 2.1), the 61 countries are listed in Table 14.2.[12] In 2009, one of them, the United Arab Emirates (UAE), contracted with South Korea to build four 1.4-GW_e LWRs (Reuters, December 27, 2009).

Table 14.2 | Countries that have recently expressed an interest in acquiring a first nuclear power plant (IAEA, 2010e); their GDPs (World Bank, 2009) and rough equivalent generating capacities in 2006, 2007 or 2008 (US CIA, 2010, for kWh generated); and those that pass a screening test for GDPs greater than US$50 billion/year and electricity consumption roughly equivalent to an output of 5 GW_e.

Country	2009 GDP(billion 2005 US$)	Estimated grid capacity (2006, 2007 or 2008) (kWh/5000 h = GW_e)	GDP >US$50 billion/yr and estimated grid capacity >5 GW_e
Albania	12	0.5	
Algeria	156	6	×
Bahrain	20	2	
Bangladesh	72	5	
Belarus	55	6	×
Benin	6	0.02	
Bolivia	15	1	
Cameroon	22	1	
Chile	156	12	×
Columbia	221	10	×
Cote d'Ivoire	21	1	
Croatia	63	2	
Dominican Rep.	42	2	
Egypt	148	24	×
El Salvador	20	1	
Estonia	21	2	
Ethiopia	24	0.7	
Georgia	12	2	
Ghana	26	1	
Greece	319	12	×
Haiti	6	0.1	
Indonesia	465	27	×
Israel	184	10	×
Italy	2090	55	×
Jamaica	13	1	
Jordan	21	2	
Kazakhstan	121	14	×
Kenya	27	1	
Kuwait	135	9	×
Latvia	31	1	
Libya	85	5	×
Madagascar	9	0.2	
Malawi	4	0.1	
Malaysia	202	21	×
Mongolia	5	1	
Morocco	81	4	
Myanmar (Burma)		1	
Namibia	8	0.3	
Niger	5	4	
Nigeria	188	4	
Oman	55	3	
Peru	117	5	×
Philippines	152	11	×
Poland	481	29	×
Qatar	101	3	
Saudi Arabia	432	30	×
Senegal	12	0.4	
Singapore	176	8	×
Sri Lanka	37	2	
Sudan	52	1	
Syria	50	7	×
Tanzania	19	0.2	
Thailand	248	27	×
Tunisia	37	3	
Turkey	664	36	×
UAE	243	14	×
Uganda	13	0.4	
Uruguay	28	2	
Venezuela	283	23	×
Vietnam	74	13	×
Yemen	24	1	

12 A 2008 report by the OECD's NEA lists 25 countries, five of which have "planned or approved projects" and 20 of which have "proposed or intended" projects. "Planned or approved projects": Bangladesh, Belarus, Indonesia, Iran, Turkey and Vietnam. "Proposed or intended projects": Bahrain, Bangladesh, Egypt, Georgia, Ghana, Israel, Kazakhstan, Kuwait, Libya, Malaysia, Namibia, Nigeria, Oman, Philippines, Qatar, Saudi Arabia, Thailand, Uganda, UAE, and Yemen. More detailed information on how serious the interest is in many of these countries can be found in the Survey of Emerging Nuclear Energy States by the Centre for International Governance Innovation (CIGI, 2010).

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. In some countries, nuclear power also is seen as a way to reduce the dependence on imported fuels. There is a concern, however, that a small fraction of countries are also interested in moving toward a nuclear weapon option. Currently, there is special concern that the nuclear weapon option inherent in Iran's uranium enrichment program may stimulate efforts by some of its neighbors to pursue their own nuclear weapon options. In the UAE–US Agreement for Peaceful Nuclear Cooperation, the UAE agreed to forgo the acquisition of uranium enrichment or spent-fuel reprocessing technologies (UAE–US, 2009) but other countries in the region have been unwilling to give up these rights.

Table 14.2 lists the 2007 gross domestic product (GDP) for the 61 countries and the generating capacity in GW_e that would have been required, at a 60% capacity factor, to produce the electric energy that they generated in 2006, 2007, or 2008. In terms of GDP, some countries, such as Mongolia (2009 GDP, US$5 billion) are so poor that it is difficult to understand how they could pay back the US_{2005}\$4 billion cost of a standard 1-GW_e nuclear power plant (World Bank, 2009). The World Bank and Asian Development Bank do not provide loans for the purchase of nuclear power reactors (Schneider et al., 2009: 55). Until recently, South Africa (2009 GDP, US_{2005}\$252 billion) had plans to add 20 GW_e of nuclear capacity by 2025. In December 2008, however, the South African government announced the cancellation of its request for tenders for the first 4 GW_e of capacity because "it is not affordable at this present juncture" (*WNN*, December 5, 2008). It seems unlikely that a country with an annual GDP of less than US$50 billion could afford a US$4 billion nuclear power plant. This situation could be eased if nuclear power plant exporters were willing to provide low-cost loans.

A second issue is that the capacity of many countries' grids may not be large enough to accommodate a standard 1-GW_e nuclear power plant. The IAEA recommends that a single nuclear power reactor not constitute more than 5–10% of the generating capacity on a grid (IAEA, 2007b: 39; 2010f, para. 59).

Of the 61 countries interested in acquiring a first nuclear power plant, listed in Table 14.2, only 24 pass both a US$50 billion annual GDP and a 5-GW_e grid capacity screening requirement (indicated with crosses, ×). Even though the threshold size for a grid required to support a nuclear power reactor has been reduced to 5 GW_e, to allow for the possibility of a doubling of the grid capacity before the first nuclear power plant comes online, the grid requirement appears to be the most stringent. It is mitigated, however, in regions where there is a strong supranational grid. There is an existing grid connecting Malaysia, Singapore, and Thailand, for example, and a proposed West Africa grid that would include Ghana and Nigeria. The grid constraint could also be eased by the use of nuclear power plants with lower generating capacities.

Beyond 2030. The OECD's Nuclear Energy Agency (NEA) has made high, low and phase-out projections of global nuclear capacity beyond 2030

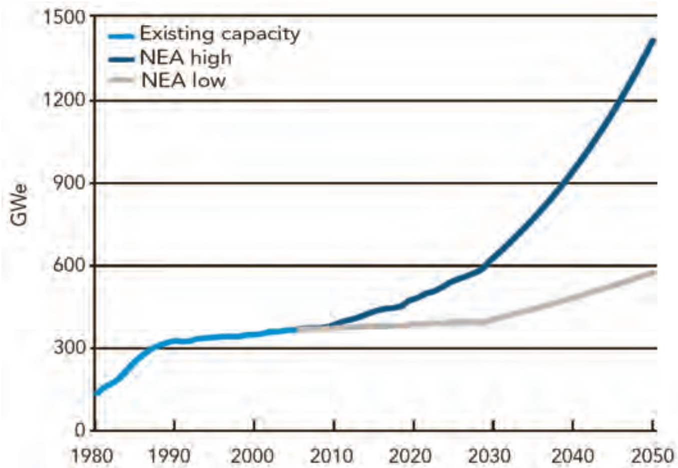

Figure 14.6 | Two Nuclear Energy Agency growth scenarios for nuclear power to 2050. Phase-out scenarios were also considered. Source: NEA, 2008a, Figure 3.11.

(Figure 14.6, 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 online an average of more than 40 GW_e/yr of nuclear capacity during 2030–2050, slightly more than twice the rate of buildup between 1972 and 1987. Even so, the NEA high scenario has nuclear power generating only 22% of global electric energy in 2050 – up from 14% in 2009 (NEA, 2008a: 105).[13] In 2010, the IAEA produced almost identical projections for 2050 (IAEA, 2010d).

14.1.3 Fuel cycles

Nuclear fuel is derived from natural uranium. For use in the dominant reactor type, the LWR,[14] the chain-reacting uranium-235 is enriched from its natural level of 0.7% to between 4% and 5%. Uranium in this enrichment range is called low-enriched uranium (LEU).[15] 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 the uranium-235 has been fissioned. About 2% of the uranium-238 is converted by neutron absorption into plutonium. About half of this plutonium is also fissioned, so that, at the time of discharge, plutonium constitutes about 1% of the heavy elements (uranium plus reactor-produced transuranic elements) in the fuel (Figure 14.7).

13 At the country level, China and India have more ambitious plans than the capacity assumed in the NEA high scenario, which assumes approximately 120 GWe in China and 90 GWe in India in 2050 (see country studies below).

14 The core of an LWR is cooled by ordinary "light" water. The hydrogen nuclei in the water also slow down or "moderate" the neutrons in the chain reaction.

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

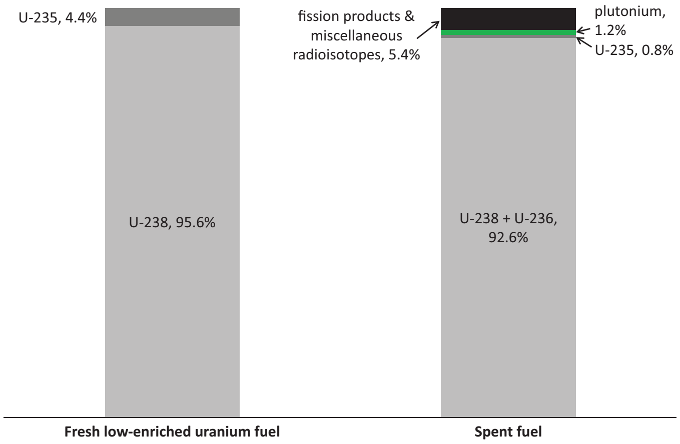

Figure 14.7 | Example of the composition of fresh and spent LWR fuel. Fresh fuel used in standard LWRs is "low-enriched" in uranium-235 (in this case 4.4% U-235) when it is put into the reactor core. Three to five years later, when the fuel is "spent," most of the U-235 has been fissioned, and some has been converted to U-236 by neutron absorption without fission. About 2% of the non-chain-reacting U-238 has been converted to plutonium and heavier "transuranic" isotopes, but more than half of the plutonium has been fissioned. Adapted from: NEA, 1989, Table 9, assuming 53 MW-days/kgU energy release.

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). After about a century, the radiation level from a spent fuel assembly will drop to a level below that considered "self-protecting" by the IAEA.[16]

14.1.3.1 Uranium enrichment

There are two technologies in commercial use for enriching uranium: diffusion and centrifugation of uranium hexafluoride (UF_6) gas. A third technology, based on the 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 to be used on a large scale. It was originally used in the United States, Russia, the United Kingdom, France, and China to produce highly enriched uranium (HEU) for weapons. Because of the compression work involved, gaseous diffusion enrichment is very energy intensive and, because of the thousands of stages involved, economies of scale resulted in enormous plants. A 10-million separative work unit (SWU)[17] gaseous diffusion plant that can supply enrichment services for 65 GW_e of LWR capacity requires about 3 GW_e of electrical power to operate at full capacity (Zhang and von Hippel, 2000, endnote 8). Because of its energy inefficiency, gaseous diffusion is used today only in one plant each by the United States and France, and these are being replaced.

Gas centrifuge. Gas centrifuge enrichment technology is more than ten times more energy efficient than gaseous diffusion, and was first deployed in the early 1960s in the Soviet Union and in the 1970s in Western Europe. UF_6 gas is spun at high speed in a vertical cylinder. Because the molecules containing uranium-238 atoms are slightly heavier, they concentrate near the wall. The fraction of the gas nearest 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).[18] For a separation factor of 1.5, only 15 stages are required to produce low-enriched uranium, and 40 stages to produce weapon-grade uranium. With a smaller number of stages, it is possible to build small plants, and more countries have been able to acquire them – in some cases for weapons purposes (Table 14.3).

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 may now have been overcome, however, 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 the planned capacity shown in Table 14.3 is built, the global enrichment capacity in around 2017 will be about 70 million SWU/yr, enough to support at least 500 GW_e of LWR capacity.

14.1.3.2 Spent-fuel reprocessing

In France, India, Japan, and the United Kingdom, most spent fuel is shipped to "reprocessing plants" where it is dissolved using equipment operated remotely behind thick radiation shielding, and the uranium and plutonium are separated from the fission products. In France, the recovered plutonium is mixed back with uranium (about 7–8% plutonium) to make "mixed oxide" (MOX) fuel for LWRs (Figure 14.8). Since the plutonium from about 7 tonnes of spent LEU fuel is required to make about 1 tonne of MOX fuel (NEA, 1989), plutonium recycling can reduce EU fuel requirements by approximately 15%. This is currently being done in France. Japan has begun to do the same but its program has been delayed by mistakes and public opposition for about a decade (CNIC, November/December 2008). Russia and China reprocess only a small fraction of their spent fuel. Some of the uranium recovered by

16 The IAEA's self-protection standard is more than 1 Gray (100 rad) per hour at a distance of 1 meter (IAEA, 1999: Infcirc-225, Rev. 4, p.11, footnote).

17 SWU is a measure of the output of a uranium enrichment plant. Production of 1 kg of uranium containing 5% U-235 from natural uranium containing 0.72% U-235 with 0.3% U-235 remaining in the depleted uranium requires 7.2 SWUs.

18 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 of the product and depleted "tails" from a single stage of enrichment. For low enrichment, the separation factor can be approximated as e^p/e^t.

Table 14.3 | Centrifuge and laser-enrichment plants, operating, under construction and planned (including planned expansions). All plants, other than the proposed GLE laser-enrichment plant in the United States, are gas centrifuge plants.

Country	Plant (year for projected growth) (reference)	Capacity (10^6 SWU/yr)		
		In operation	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, Faisalabad			0.15
Russia (IBR, 2004)	Novouralsk, Sverdlovsk region (2011)	→ 13.9		
	Zeleznogorsk, Krasnoyarsk region (2011)	→ 8.3		
	Angarsk, Irkutsk region (2015) (WNN, June 25, 2007)	2.5		
	Seversk, Tomsk region (2011)	→ 4.1		
United Kingdom	Capenhurst (URENCO, 2007)	4.2		
United States	URENCO, NM (URENCO, 2008)		5.9	
	AREVA, Idaho			3
	USEC, Portsmouth, Ohio			3.5
	GLE, NC (laser) (GE-Hitachi, 2008)			3.5–6
	Total	→ 45	13.4	10.15–12.65

Sources: Unless stated otherwise, IPFM, 2008, table 4.2.

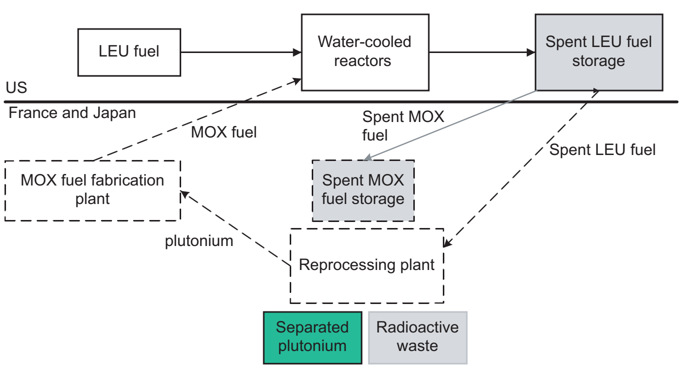

Figure 14.8 | Current spent-fuel disposal strategies. The "once-through" fuel cycle as currently practiced in the United States and many other countries is shown above the horizontal line; LEU fuel is irradiated in a LWR and then stored. The reprocessing and recycling system that is in operation in France and is planned in Japan is shown below the horizontal line. It currently involves the separation of the plutonium for recycling once in MOX fuel. The spent MOX fuel is then stored. Because of the high cost of reprocessing, it is much more expensive to produce MOX fuel than LEU fuel, and most countries have decided that it is not worthwhile. MOX fuel reduces the reactivity safety margins of LWRs somewhat. Except for LWRs specially designed for MOX fuel, the fraction of the core that is made up of MOX fuel is therefore limited to about one third.

reprocessing is also recycled (IAEA, 2007e). If it were all recycled, it could reduce the demand for natural uranium by almost an additional 10%. Similar reductions in uranium demand could also be achieved by reducing the depleted uranium assay for enrichment from the typical value of 0.3% to lower values.

A study for the French Prime Minister in 2000 estimated that reprocessing and plutonium recycling increase the cost of nuclear power by about 0.2 US¢/kWh (Charpin et al., 2000, converting 5 French francs = US_{2005}\$1). A study for the Japan Atomic Energy Commission in 2004 found the cost increase due to reprocessing in Japan to be about three times higher, at ¥0.6/kWh (about US_{2005}¢0.6/kWh) (CNIC, 2004b).

14.1.4 Current Reactor Technology

The dominant power reactor technology today is the LWR, which accounts for 89% of global operating nuclear power capacity (IAEA-PRIS, January

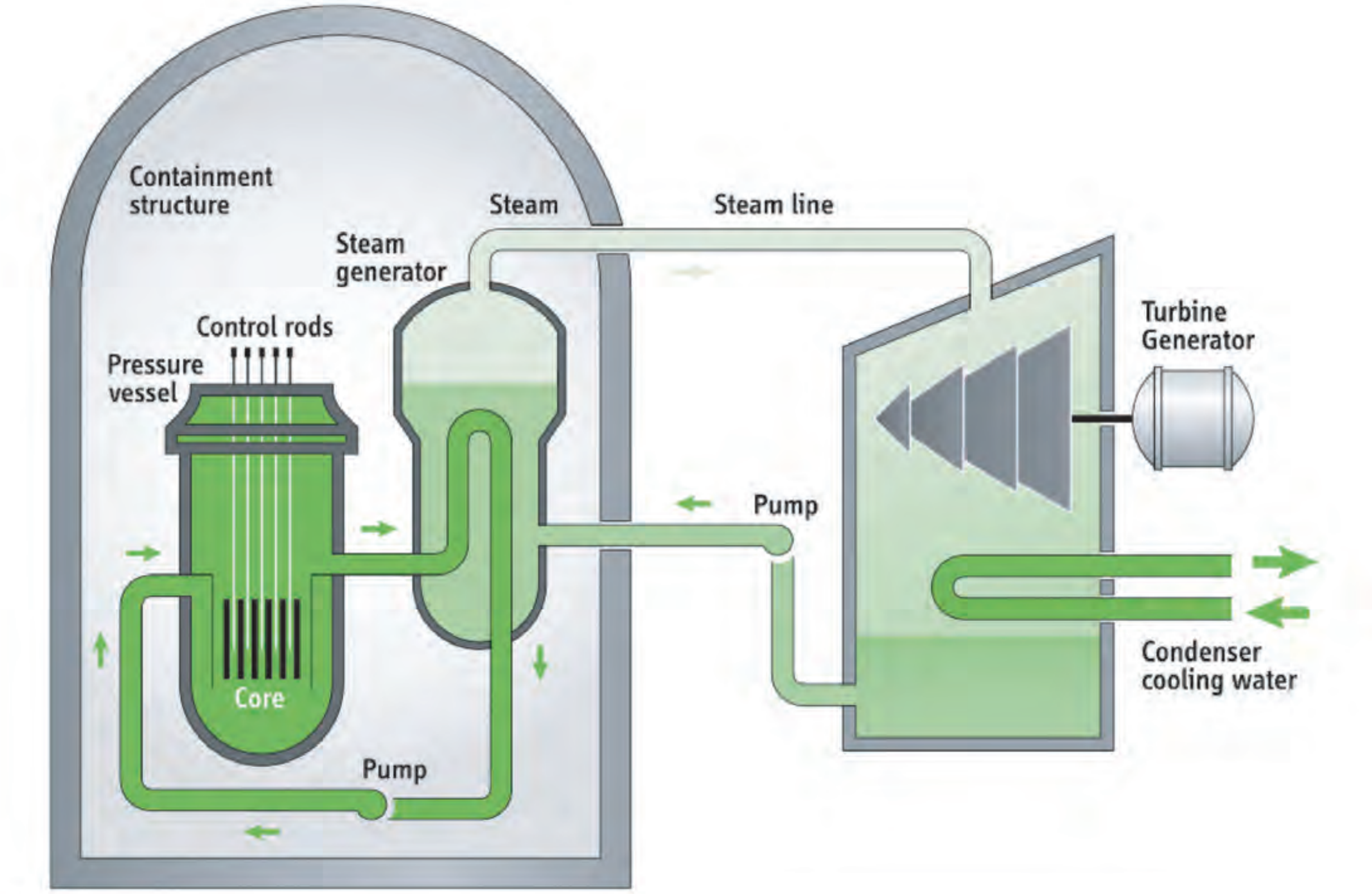

Figure 14.9 | Pressurized light-water reactor. Source: adapted from US Nuclear Regulatory Commission, 2010b.

9, 2009).[19] The fuel is in the form of cylindrical uranium oxide pellets about 1 cm in diameter stacked inside long, thin, sealed zirconium alloy tubes. This fuel is immersed in pressurized water that both slows down ("moderates") the neutrons in the chain reaction as they travel from rod to rod (Figure 14.3) and removes the fission heat from the fuel.

There are two basic types of LWR. In a pressurized water reactor (PWR), the superheated water is not allowed to boil but rather transfers its heat to secondary water that boils in a "steam generator," and the steam then drives a turbo-generator (Figure 14.9). In a boiling water reactor (BWR), the water boils in the reactor and the high-pressure steam goes directly to the turbine.

14.2 The Costs of Nuclear Power

Capital cost. The cost of nuclear power is determined primarily by the capital cost of the plant. For LWRs ordered today, this capital cost is both uncertain and in flux. Based on recent orders worldwide, the median capital costs are around US_{2005}\$4000/kW_e, and projected total generating costs are in the region of US\$0.08/kWh (MIT, 2009). The capital costs, however, can vary by ±US\$2000/kW_e.

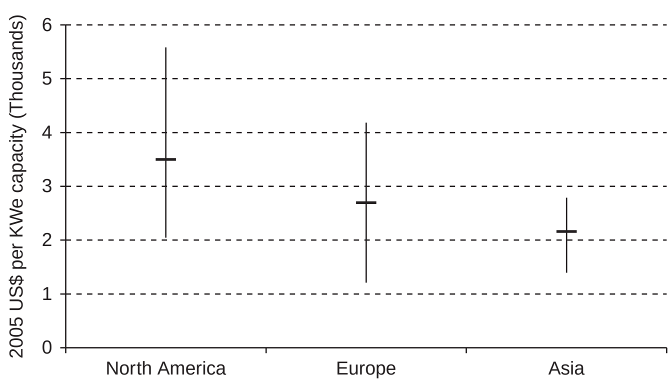

Figure 14.10 | Ranges of 2007–2008 "overnight" construction costs (excluding interest during construction) for plants in North America, Europe (including Russia), and Asia. Source: IAEA, 2009a.

19 Some 6% of global nuclear-power generating capacity is heavy-water-moderated reactors; 5% is graphite-moderated reactors (both water and gas cooled), and two liquid-sodium-cooled fast-neutron breeder reactors constitute 0.2%.

Figure 14.10 shows the results of a compilation of "overnight" costs (most of them are estimated) of the construction of 1 kW_e of nuclear generating capacity for plants in North America, Europe, and Asia in 2007–2008. "Overnight" costs exclude the interest during construction. Over a 4–10 year construction period, a 10% annual interest rate would increase the capital cost by 28–75%.

The large range of costs can be attributed to a number of factors, including:

- Whether costs such as site costs and transmission connections are included.
- Biases in the 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).
- Assumptions about escalating material costs relative to general inflation.

There is a high level of uncertainty about estimates of nuclear power plant construction costs in North America since no new construction has been launched since 1978. Many projects have been announced but cancellations, postponements and cost increases are announced monthly. In Europe, the high end of the cost estimates are based primarily on the only two units that are under construction by AREVA in Finland and France (see Section 14.3.7). The low end reflects costs quoted for Russian-built units. The IAEA lists 15 nuclear power reactors as under construction by Rosatom in Russia and 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 the 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 14.11 shows that during the late 1970s and 1980s, when France and the United States brought most of their current nuclear power plants online, the capital costs of LWR construction in the two countries (measured in constant French francs and US$, respectively) actually increased. There are several reasons why cost savings were not realized from industrial learning:

- Much of the construction of nuclear power plants is on-site, and locally hired workers tend not to benefit from experiences at other sites.
- The lack of standardization. In the United States, designs were customized, while in France, they were standardized across the country but new models were introduced as the program developed.
- Quality standards in the nuclear industry are necessarily very high, and mistakes often require defective work to be torn out and done again.

Table 14.4 | Civilian spent-fuel reprocessing plants.

Country	Reprocessing plant (Reference)	Level of activity[a] (tonnes of 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 & research reactor fuel)	50[d]
UK	B-205 (Magnox)[e] and Thorp (LWR), Sellafield	B-205 to be shut down; future of Thorp uncertain.

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

b The reprocessing of foreign fuel once constituted about 50% 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 contracts. Thus almost all the spent fuel now reprocessed at La Hague is domestic fuel (Schneider and Marignac, 2008).

c HWR = 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 is to be completed in 2012.

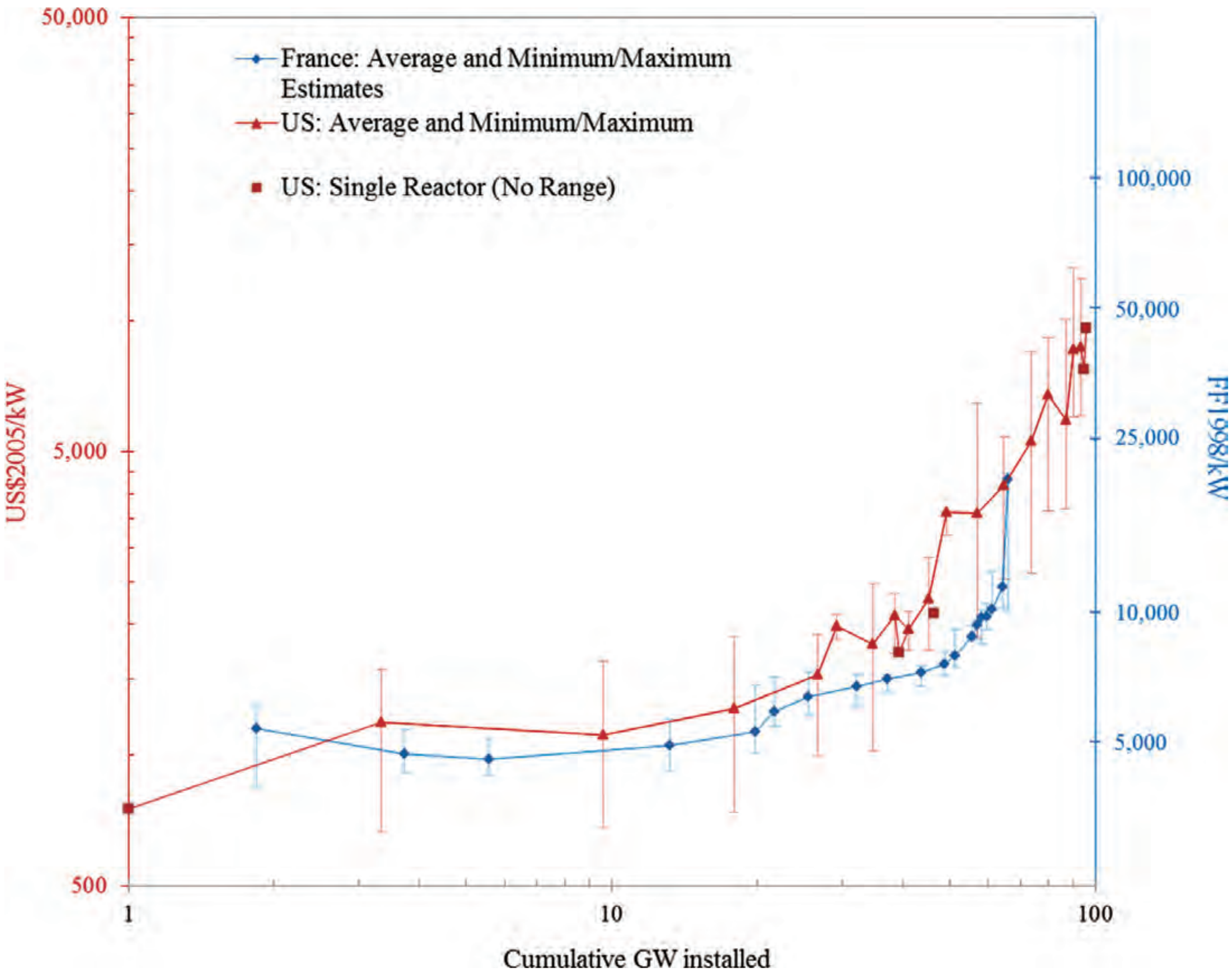

Figure 14.11 | French and US nuclear reactor construction costs (including interest during construction), by completion year, average for all reactors completed in a given year and minimum/maximum (in US_{2005}\$ per kW installed capacity). In the United States, after the 1979 accident at Three Mile Island, there were prolonged delays in licensing plants under construction. The original French cost data (in French Francs 1998) are also shown for comparison. Data sources: US: Koomey and Hultman, 2007; all other data: Grubler, 2010.

- Regulatory requirements become more stringent as the understanding of potential design problems improves.
- Delays in completion result in extra interest charges.

In France, the increase in nuclear power plant construction costs was roughly the same as that of construction costs in general. In the United States, this was true until the 1979 accident at Three Mile Island, after which there were prolonged delays in licensing plants under construction. In France, the duration of construction also increased because of a shift to higher-power reactors with larger components and changes in component designs (Hultman et al., 2007; Grubler, 2010).

Other costs. The costs of decommissioning nuclear reactors are higher than those for other infrastructure because of the neutron-induced radioactivity of the primary pressure vessel and its internal components. The World Nuclear Association cites, without sources, decommissioning costs of US\$190–520/kW_e for water-cooled reactors (WNA, 2007, converted to US_{2005}\$), while the IAEA reports that the costs for decommissioning the 0.4 GW_e LWRs built by the former Soviet Union ranged from US_{2005}\$600–3800/kW_e (IAEA, 2002).[20] Operating and maintenance costs are about US_{2005}\$0.02/kWh (Harding, 2007). For a "once-through" fuel cycle, fuel

20 The large cost range reflects in part the different approaches to decommissioning in different countries. Finland, which had the least costly project, disposed of the waste on site. Germany had the most costly project. Costs in the East European countries fell between these extremes.

costs are only about US$0.007/kWh[21] and interim spent-fuel storage costs are about US$0.00035/kWh.[22] Spent-fuel reprocessing costs in Japan are estimated at ¥0.63/kWh ($US_{2005}$$0.006/kWh; JAEC, 2004).

Because of their high capital costs and relatively low operating costs, nuclear power plants are ordinarily operated in a "baseload" fashion, i.e., at full power whenever they are not down for refueling, inspection, maintenance, and/or repair.[23]

14.2.1 Government Subsidies[24]

Subsidies for nuclear power include government-funded research, development and demonstration projects; limitations on liability for catastrophic accidents; low-cost and guaranteed loans; and guarantees of private investments.

Research, development and demonstration. Between 1974 and 2007, the nuclear weapon states and Japan made huge national investments in fission-energy RD&D. In addition to investments in the development of enrichment and reactors for the production of nuclear weapon materials, and the development of LWRs for naval propulsion,[25] Japan, the United States, France, the United Kingdom, and Germany spent an estimated $US_{2005}$$156 billion on civilian fission-energy R&D (IEA R&D Statistics, 2009). This corresponds to about US$700/$kW_e$ of nuclear capacity in these countries at the end of 2009 (IAEA, 2010d).

Loan and export guarantees. Some governments – notably, France, Japan, Russia, and the United States – are supporting their nuclear power industries with loan and export guarantees. These subsidies are critical 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 in interest on loans (IAEA, 2008b; US NAS, 1996: 427–428).

Guarantees are especially important for nuclear power plants, which are considered risky investments. In 2003, the US 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%" (US CBO, 2003). The US Energy Policy Act of 2005 (Title XVII) provides government loan guarantees up to 80% of the project costs. Congress authorized up to US$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 increasing the limit to US$54.5 billion (US DOE, 2010b: 259). One US utility has estimated that a loan guarantee would reduce the costs of generating electricity from its proposed nuclear power plant by 40% (Schneider el al., 2009: 79).

Limitations on liability for catastrophic accidents. In many countries, nuclear power plants are government owned and the governments would decide after the fact on how much restitution to make for the consequences in the event of a 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 Energy Policy Act. In the current version, plant owners are required to obtain the maximum amount of liability insurance available from private insurers (US$300 million in 2004). Beyond, that, if an accident occurs, each owner is required to contribute up to US$96 million (to be adjusted for inflation) to a pool of about US$10 billion per incident to help cover damages. Beyond that, the government would be responsible (Hore-Lacy et al., 2008). Estimates of the cost savings to utilities from such limitations on liability are highly uncertain (Heyes and Liston-Heyes, 1998; Heyes, 2002).

14.3 Country Studies

This section provides brief case studies of the current nuclear expansion programs of China, India, Japan, South Korea, Russia, the United States, and Western Europe.

14.3.1 China[26]

China's engagement with nuclear power began in 1970. The technology has been drawn from France, Canada, and Russia, with local

21 Assuming a cost of US$150/kg of natural uranium, US$150/SWU, US$11/kg to convert natural uranium to UF_6 or back, and US$300/kg of uranium for fuel fabrication (von Hippel, 2008b, 2005 US$).

22 Assuming a capital cost for interim dry-cask storage of US$150/kg of spent fuel (Alvarez et al., 2003).

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

24 Energy subsidies are discussed more generally in Chapter 6.

25 The United States spent about US$130 billion on the production of plutonium and HEU between 1948 and 1966 and US$51 billion on naval nuclear propulsion between 1948 and 1996 (Schwartz, 1998: 65, 143).

26 Professor Yu Suyuan (Tsinghua University, China) and Dr. Ming Ding (Delft University, the Netherlands), lead authors. The sources for this section include the China National Development and Reform Commission, *State Mid–Long Term Development Plan for Nuclear Power Plants (*2005*–2020),* October 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 would like to thank Dr Yun Zhou, currently with 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*.

development based largely on French designs. The latest technology has been acquired from the United States (the AP1000 reactor) and France (the European Pressurized Reactor (EPR)). As of the end of 2009, China had 9 GW_e 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 huge planned expansion of China's nuclear generating capacity, 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-GW_e PWR, ordered two GW_e-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 initially 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 GW_e version, the CAP1400 (Kubota, 2009).

In March 2008, China's newly formed State Energy Bureau set a target for 2020 of 5% of electricity from nuclear power, requiring at least 50 GW_e to be in operation by then. In June 2008, the China Electrical Council projected 60 GW_e of nuclear capacity by 2020. The total capacity of the nuclear power units under construction as of the end of 2010 was 25 GW_e (IAEA-PRIS, October 12, 2010).[27]

In May 2007, China's National Development and Reform Commission announced that its target for nuclear generating capacity for 2030 was 120–160 GW_e, which corresponds to an average rate of construction of 5–7 GW_e/yr. Sites have been nominated for a potential total nuclear generating capacity of about 155 GW_e. Various tax incentives have been provided for the construction of nuclear power plants.[28]

This projected growth of China's nuclear capacity cannot be dismissed. However, while China has realized extraordinary growth rates in other areas of infrastructure, the rapid expansion of the nuclear industry faces multiple challenges, in particular the lack of trained personnel. The universities are not producing sufficient nuclear engineers, so engineers with other backgrounds have been recruited and given one year of training to familiarize them with nuclear technology. Construction company staff with experience building coal-fired power plants are also 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, director of China's National Nuclear Safety Administration, has warned that, "if we are not fully aware of the sector's over-rapid expansion, it will threaten construction quality and operation safety of nuclear power plants" (*New York Times*, December 16, 2009). He has also indicated that China's nuclear industry faces challenges 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. Much of the equipment used 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 also developed the capability to produce pressure vessels for GW_e-class pressurized water reactors.

Uranium supply. China's known uranium resource at a recovery cost of less than US$130/kg ($US_{2005}$$122/kg) is 70,000 tonnes, but estimates of undiscovered resources in favorable areas exceed 1 million tonnes (NEA, 2008c: 155, Table 2). Domestic production of 840 tonnes/yr provides about half of China's current requirements, and the remainder is reportedly imported from Kazakhstan, Russia, and Namibia. In 2006, China signed a deal with Australia, the world's leading uranium mining country, to buy up to 20,000 tonne/yr, enough to supply about 100 GW_e of LWR capacity (BBC, April 3, 2006).

Fuel cycle – front end. China's original enrichment plants used gaseous-diffusion technology but these have been replaced with gas centrifuge plants imported from Russia under agreements made in the mid-1990s 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 enrichment capacity at two sites in China, based on Russian sixth-generation centrifuges, and work to expand this capacity by an additional 0.5 million SWU/yr is underway.

27 In 2008, China began construction of 6 GWe of capacity; in 2009, 9 GWe; and as of October, 6 GWe in 2010. China's most recently completed nuclear power plants, Tianwan 1 and 2, took eight and seven years to build, respectively.

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

This is enough for about 17 GW_e of LWR capacity. Reportedly, additional capacity expansion is planned (Kubota, 2009). China also buys enrichment services abroad. It has contracted URENCO, an international enrichment company, to supply 30% of the enrichment for the two 0.944-GW_e LWRs at Daya Bay. Tenex, Russia's nuclear materials 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, i.e., one in which plutonium would be recycled from spent to fresh fuel. Accordingly, the 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, in western China, began in 1994. The initial storage capacity is 550 tonnes, which could be doubled. The pilot PUREX reprocessing plant was opened in 2006 with a capacity of 50 tonnes/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 €20 billion (US_{2005}\$25 billion). In mid-2008, the CNNC stated that an 800 tonnes/yr reprocessing plant would start operations in 2025, probably in Gansu province. High-level reprocessing wastes would be vitrified, encapsulated and put into a geological repository 500 m 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.

14.3.2 India[29]

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 el al., 1998).

Most of India's current power reactor capacity is based on 0.22 GW_e heavy-water reactors (HWRs), modified versions of the CANDU reactors that 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 Koodankulam at the southern tip of India, and there are plans to build two to four more such reactors at the same site over the next decade. A 0.5-GW_e prototype fast breeder reactor, to be fueled with MOX (plutonium–uranium) fuel, is under construction at Kalpakkam on the southeast coast.

29 Dr. M.V. Ramana of Princeton University, lead author.

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

1. Heavy-water-moderated reactors are fueled with natural uranium, and the spent fuel is 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 breeder reactors would produce more plutonium than they consumed, and the excess would be used to provide startup fuel for additional 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 bred uranium-233 is to 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 GW_e of installed heavy-water and breeder-reactor capacity by 1987 (Hart, 1983: 61). This was subsequently replaced by the goal of 43.5 GW_e of nuclear capacity by 2000 (Sethna, 1972). At the end of 2009, however, India's nuclear capacity amounted to just 4.5 GW_e, about 3% of the country's total electric power generating capacity (IAEA-PRIS, January 11, 2010).

Prior to the 2008 lifting of the Nuclear Suppliers Group (NSG) ban on uranium and nuclear technology trade with India, the DAE projected a nuclear generating capacity of 20 GW_e by the year 2020 and 275 GW_e by the year 2052 (Grover and Chandra, 2006). Since the NSG waiver, there have been even higher predictions of 40 GW_e by 2020 and 470 GW_e by 2050 (*Financial Express*, October 14, 2008; India, Ministry of Power, 2008). The US Energy Information Administration (US EIA) reference case projection is for India's nuclear power capacity to grow to 20 GW_e by 2030 (US EIA, 2008c).

Uranium constraint. India has known resources of about 60,000 tonnes of low-cost uranium (NEA, 2008c: 207), sufficient for a 40-year-lifetime supply for only about 10 GW_e of HWR capacity. India's relatively small resource base of uranium has been the primary justification for the DAE's plans to focus on breeder reactors designed to have a very high breeding ratio for plutonium.[30] This justification has not

30 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 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).

yet changed despite the recent lifting of the NSG ban on natural and enriched uranium exports to India.

The plutonium supply constraint. The rate at which India can build up its breeder capacity is limited by the rate at which it can produce excess plutonium for the initial cores. The DAE assumes a starting capacity of 6 GW_e of high-breeding-ratio, metal-fueled breeder reactors in 2022. This would require about 22 tonnes 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.[31] Of this inventory, the DAE plans, however, to use at least 15 tonnes for startup fuel (including 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 will therefore be sufficient only to start about 1 GW_e of metal-fueled breeder reactor capacity by 2022.

The DAE's projected growth rates after 2022 are also unachievable. Even with a fuel residence time of two years inside the reactor 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 recycling with some extra bred plutonium that could be used as startup fuel for new breeder reactors. A careful calculation finds that the resulting plutonium growth rate is only 17–40% of the DAE's estimates, depending on whether realistic or optimistic assumptions are used for various parameters (Ramana and Suchitra, 2009). Unless India's nuclear establishment shifts its focus away from breeder reactors, nuclear power 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 and heavy water reactors were the same, electricity from the breeders would be more expensive because of their high fuel-cycle costs. The cost of electric power generated from India's first commercial-scale breeder reactor will be at least 80% higher than from heavy water reactors, mostly because of the high costs associated with reprocessing and fabricating plutonium-containing fuel (Suchitra and Ramana, 2011). Breeders are competitive with heavy water reactors fueled with natural uranium and operating on a once-through fuel cycle only for uranium at prices well above US$1000/kg. In recent decades, the average price of uranium has been around US$50/kg.

14.3.3 Japan[32]

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 53 operational commercial LWRs with a generating capacity of 47 GW_e. Two LWRs (2.7 GW_e) are under construction[33] and 10 (13.6 GW_e) were to be commissioned by 2020. Some of Japan's older reactors are being decommissioned, while others are proposed to have their licenses extended.[34] Prior to the 2011 Tōhoku earthquake and tsunami, a total of 66 LWRs (65.1 GW_e) were expected to be operating in 2020 according to the plans of the electric utilities. These plans now seem likely to be scrapped, at least for the near term. Indeed, Prime Minister Kan, before stepping down, proposed phasing out nuclear power entirely.

Uranium enrichment capacity. Japan Nuclear Fuel Limited (JNFL), the nuclear fuel cycle subsidiary of Japan's nuclear utilities, started operating the country's first commercial enrichment plant with a capacity of 150,000 SWU/yr in 1992. Its capacity was increased every year by one module with a capacity of 150,000 SWU/yr until it reached a nominal capacity of 1.05 million SWU/yr in January 2009. All seven modules have been permanently shut down due to technical troubles, however. Cumulatively, only about 1 million SWUs have been produced.[35]

JNFL launched the 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 are generally opposed to the expansion of on-site storage. Japan's policy is therefore to reprocess its spent fuel. In the late

31 The fissile isotopes of plutonium that chain-react with slow neutrons are plutonium-239 and plutonium-241. The spent fuel of India's pressurized heavy-water reactors contains about 2.6 kg of fissile plutonium per tonne. The amount of plutonium that India can separate is limited by the capacity of its reprocessing plants. It is estimated that India will have separated about 10 tonnes of fissile plutonium by 2018. That is the earliest that India could bring online significantly more reprocessing capacity. Assuming that its reprocessing capacity increases tenfold to 2000 tonne/yr thereafter, and operates at 80% capacity, it is estimated that India could separate out anaother 13 tonnes of fissile plutonium during 2019–2021 (Ramana and Suchitra, 2009).

32 Dr Tatsujiro Suzuki, Tokyo University (now vice chair of Japan's Atomic Energy Commission) and Professor Tadahiro Katsuta, Meiji University, Tokyo, lead authors.

33 Two 1.37-GWe advanced boiling water reactors, Shimane-3 and Ohma, are scheduled to go into operation in 2011 and 2012, respectively.

34 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.

35 Some 1599 tonnes of uranium have been enriched. Assuming 4.4% enrichment with 0.3% uranium-235 in depleted uranium, this would correspond to 1.2 million SWU.

1970s, Japan contracted to ship 5500 tonnes 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, at the northern tip of the main island, with a design capacity of 800 tonne/yr of uranium throughput. Commercial operation of the plant was to begin in 2003 but, due to various technical problems, has repeatedly been postponed, most recently until late 2012 (*Japan Times*, 2010).

As a result of the many years of delays in starting up the Rokkasho reprocessing plant, Japan has a developing shortage of spent-fuel storage pool capacity. As of September 2007, 12,140 tonnes of spent nuclear fuel were being stored at nuclear power plant sites (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 3000-tonne capacity storage pool at the Rokkasho reprocessing plant started accepting spent nuclear fuel in 2000, but was almost full (2817 tonnes 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 under construction and is planned to start operation in 2012. Ultimately, it is to have 5000 tonnes 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).

The reprocessing of spent fuel that Japan sent to France has been completed. Its reprocessing contract with the United Kingdom, which was to have been completed in 2003, has been delayed by problems at the UK reprocessing plant (Forwood, 2008). As a result of its foreign reprocessing program and domestic pilot program, as of the end of 2008, Japan had about 47 tonnes of separated plutonium, most of it in France and the United Kingdom (IAEA, 2009c, Japan).[36] Japan's second commercial reprocessing plant, originally due 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 16–18 LWR power plants with MOX (plutonium–uranium) fuels made from Japanese plutonium in Europe by 2010 has been delayed (CNIC, 2008). The first MOX fuel was finally loaded into a Japanese LWR (Genkai 3) in October 2009 (*WNN*, November 5, 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 10 tonnes of plutonium mixed with 120 tonnes of uranium to make 130 tonne/yr of MOX fuel. Construction was to have started in October 2007, but the plant is still in the pre-construction licensing phase. According to JNFL, commercial operation will start in 2015 (JNFL, 2010).

Breeder reactor R&D. Japan's first experimental breeder was the Joyo (140 megawatt thermal (MW_t), no electricity generation), which has operated about 27% of the time since it achieved first criticality in 1977. Japan's prototype 280 megawatt-electric (MW_e) 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, in May 2010, only to be shut down indefinitely again due to a refueling accident in August 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, Japan passed a "Law Concerning the Final Disposal of Specific Radioactive Waste" that outlines legal responsibilities, cost sharing, and site selection processes. A voluntary site selection process started in December 2002. Thus far, only one application (Toyo Town) has been received and officially accepted, but it was subsequently withdrawn due to local public opposition.

Budget. Japan accounts for almost half of the total nuclear energy R&D carried out in the OECD countries. In 2007, Japan devoted ¥261 billion (US_{2005}\$2 billion) to nuclear energy R&D, about 65% of its budget for energy R&D (IEA, R&D Statistics).

14.3.4 South Korea[37]

The Republic of Korea (ROK) has the world's fifth largest nuclear generating capacity; 20 units with a capacity of 17.7 GW_e, with eight units (9.6 GW_e) under construction as of the end of 2009 and four more (5.6 GW_e) planned for completion by 2021. Except for four heavy-water reactors, all of these are PWRs, 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 US\$20 billion contract from the United Arab Emirates for four 1.4-GW_e reactors to be completed by 2020, and another US\$20 billion contract to jointly operate them for 60 years (Reuters, December 27, 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

36 Since 2007, Japan's government has reported 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 obtain the tonnage of total plutonium.

37 This section is mostly based on von Hippel (2010).

resentment within South Korea's nuclear establishment that the United States acquiesced to Japan acquiring these technologies and not South Korea. Following North Korea's nuclear test in May 2009, 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) proposes a form of reprocessing, "pyroprocessing,"[38] the electro-refining of the fuel in molten salt 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 worried about the cost. The G.W. Bush Administration was also interested in pyroprocessing and supported joint R&D between the US Department of Energy's (US 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 US$300 million plus US$600 per waste drum for up to 800,000 waste drums for the local government 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 near the site (Park Seong-won et al., 2010). This is still a small cost, however, compared with Japan's ¥1 trillion (US$10 billion) programmed payments to Aomori prefecture for accepting the Rokkasho reprocessing plant (Takubo, 2008), and the ¥11 trillion ($US_{2005}$$94 billion) estimated cost of building, operating and decommissioning the Rokkasho reprocessing plant (CNIC, 2004a).

14.3.5 Russia[39]

Russia has the world's fourth largest nuclear generating capacity, 22.7 GW_e, provided by 16 PWRs, 11 graphite-moderated, water-cooled RBMK-1000 (Chernobyl-type) reactors and the BN-600 sodium-cooled fast breeder prototype reactor.[40] 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, then President Vladimir Putin consolidated Russia's civilian nuclear activities into one giant state-owned company, Atomenergoprom, under another state-owned company, Rosatom, which also operates Russia's military nuclear programs (*Moscow Times*, May 2, 2007).[41]

Seven 1-GW_e PWRs and a 0.8-GW_e demonstration breeder reactor are currently under construction (IAEA-PRIS, October 8, 2010).[42] According to the Russian government's 2008 long-term plan (Russia Federal Target Program, 2008), starting in 2009, construction was to be initiated each year on two new 1.2-GW_e PWRs. By the end of 2015, 11 new nuclear power units were to be put into operation, and the construction of a further 10 initiated (see Figure 14.12). In late 2009, the schedule slipped, and only eight of the PWRs are expected to be completed by the end of 2015 (WNA, 2010a).[43] Beyond 2015, Rosatom is supposed to find its own funding.[44]

Outside Russia, Rosatom has under construction two VVER-1000 PWRs[45] at the Koodankulam nuclear power plant in India and one at the Bushehr plant in Iran (Rosatom, September 26, 2008). Russia has agreements, but not in most cases binding contracts, to construct: in India, eight more VVER-1200s (four at Koodankulam and four in West Bengal); in China, two more units at the Tianwan nuclear power plant, where two VVER-1000s are already operating, and two BN-800 breeder reactors; in Bulgaria, two VVER-1000 units; in Turkey, four VVER-1000 units; in Armenia, one VVER-1000 unit; and in Ukraine, two VVER-1200 units.[46]

Uranium supply. Russia's confirmed uranium reserves could support about 100 GW_e of LWR capacity for 45 years.[47] All uranium mining activity has been consolidated within Rosatom under Atomredmetzoloto JSC

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

39 Professor Anatoli Diakov, Moscow Institute of Physics and Technology, lead author. This section provides an update of a more detailed chapter in the *Global Fissile Material Report* 2007 (IPFM, 2007). www.fissilematerials.org.

40 The numerical suffixes indicate the approximate gross electric power generating capacity in MW_e. The net capacity is typically about 10% lower (see IAEA-PRIS).

41 See Rosatom's English-language website: www.rosatom.ru/en.

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

43 The reactors under construction at the end of 2010: two VVER-1200 light-water reactors at Rostov nuclear power plant (NPP), two VVER-1200 units at Leningrad-2 NPP, two VVER-1200 units at Novovoronezh-2 NPP, one VVER-1000 unit at Kalinin NPP, and one BN-800 unit at Beloyarskaya NPP (IAEA-PRIS). Rosatom's website also lists two VVER-1200 units under construction at the Baltiyskaya NPP (www.rosenergoatom.ru/rus/development).

44 After 2015, Rosatom plans to build two VVER-1200 units/yr, costing a combined US$4.6 billion (2005 US$). According to Figure 14.12, in 2015, Atomenergoprom would have a capacity of 33 GWe. Assuming that these reactors operate at an 80% capacity factor, they would generate 0.23 trillion kWh/yr. Atomenergoprom therefore would have to be raising capital investments of US$0.02/kWh generated.

45 VVER: Vodo-Vodyanoi energetichesky reactor, the Russian version of the pressurized water reactor.

46 See www.nuclear.ru/rus/press/nuclearenergy/2117970/ (in Russian).

47 Operating at a 90% capacity factor, a 1-GWe VVER would require 140–200 tonne/yr of natural uranium, assuming 0.1–0.3% uranium-235 in the depleted uranium. In 45 years, 100 GWe of VVER capacity would, therefore, require 630,000–900,000 tonnes of natural uranium. Russia is reported to have 545,600 tonnes of uranium

(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 GW_e of LWR capacity. ARMZ is also planning joint ventures with companies in Canada, Armenia, Mongolia, and the Republic of South Africa (Atomenergoprom, 2008).

Reprocessing. Russia has a small reprocessing plant (Mayak) near Chelyabinsk in the Urals, where it reprocesses the spent fuel of the last six of its first-generation VVER-400 reactors along with its naval and research-reactor spent fuel. Russia has declared to the IAEA that, as of the end of 2008, about 45 tonnes of civilian separated plutonium were stored at its reprocessing plants (IAEA, 2009c, Russia).[48] 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 Zheleznogorsk (Russia Federal Target Program, 2006).[49]

Breeder reactors. As shown in Figure 14.12, Russia's nuclear establishment, like India's, is still planning on the near-term, large-scale commercialization of plutonium breeder reactors. One 0.8-GW_e BN-800 liquid-sodium-cooled reactor, on which construction began in 1985, is now scheduled to be put into operation in 2014 (AtomInfo, 2009). China is considering ordering two units (WNA, 2010a). A 1.8-GW_e BN-1800 is being designed to be deployed in the 2020s. In January 2010, the Russian government approved a 10-year, 110 billion ruble (US$3.6 billion) federal target program for the development of fast-neutron reactors and their fuel cycle (Rosatom, 2010).

MOX (plutonium–uranium) 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 tonnes of excess weapon-grade plutonium in parallel to US 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%, as the BN-600 has been since 1980 (Nigmatulin and Kozyrev, 2008).

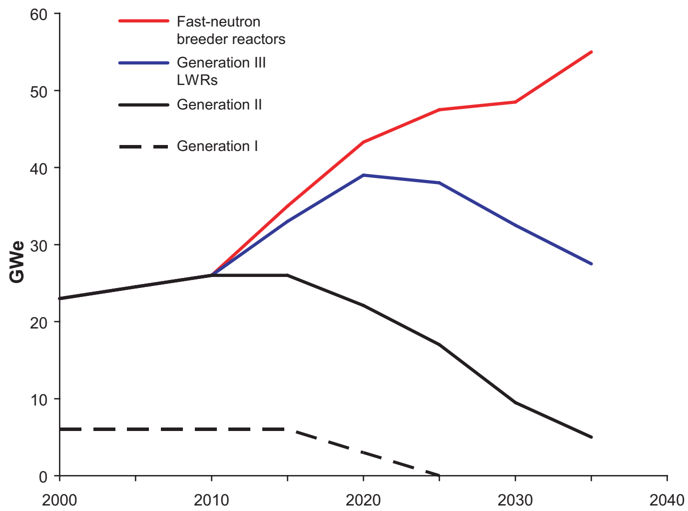

Figure 14.12 | Plans for Russian nuclear power expansion as of 2007. Source: Adapted from Saraev, 2007.

14.3.6 United States

The United States has the world's largest nuclear-generating capacity: 104 power reactors with a net generating capacity of 100.6 GW_e as of the end of 2009 (IAEA-PRIS). The construction of all of these reactors began before 1978, more than three decades ago (US EIA, 2008d). As of the end of 2009, US utilities had applied for 18 combined construction and operating licenses for 28 reactors with a total capacity of 37 GW_e (US NRC, 2010a), but only 12 of these applications were active,[50] and only five had signed engineering, procurement and construction contracts with reactor vendors (for nine reactors) (WNA, 2010c). 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 and was suspended in 1988 when it was about 80% complete because of a reduction in the growth rate of US electric power demand (Reuters, August 1, 2007).

Renewed US interest in nuclear power reflects in part concerns about the future cost of natural gas, following a temporary tripling in real wellhead prices between 1998 to 2008 (US EIA, 2010)[51] and a move away from coal-fired power plants in anticipation of policies aimed at reducing greenhouse gas emissions. It also reflects government incentives. In the

in "reasonably assured resources" plus "inferred" extensions of explored deposits recoverable at up to US$130/kgU, plus 276,000 tonnes in "prognosticated" resources (estimated resources in partially explored geologies) and 714,000 tonnes in "speculative" resources (undiscovered resources based on statistical inferences from geological types) (NEA, 2008c). The price of uranium in 2009 was about US$100/kgU.

48 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 Russia–US "Agreement … Concerning Cooperation Regarding Plutonium Production Reactors," any plutonium separated at these plants after January 1, 1997 will not be used for weapons purposes (Annex III, Subsidiary Arrangement B, Article II).

49 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 (US$65 million at US$24.6/ruble) through 2015 for R&D in support of a pilot reprocessing plant at the Krasnoyarsk Mining and Chemical Combine.

50 The applications for Callaway Unit 2, Grand Gulf Unit 3, River Bend Unit 3, Victoria County Station Units 1 and 2 are shown as suspended, and that for Nine Mile Point Unit 3 has been inactive since 2008. 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).

51 Prices dropped by a half between 2008 and 2009, however, as gas from hydrofracturing shale began to enter the market in large quantities (US EIA, 2010).

Energy Policy Act of 2005, the US government created major incentives to investors to commit quickly to build new nuclear power plants. These included (Title XVII) government loan guarantees equal to up to 80% of project costs. Congress authorized up to US$18.5 billion for this purpose in the Consolidated Appropriations Act of 2008. In June 2008, the US DOE solicited requests for the loan guarantees. The response was applications for US$122 billion in guarantees to cover 65% of the cost of 21 reactors with a total generating capacity of 28.8 GW_e (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 US$54.5 billion (US DOE, 2010b: 259). The four companies that were on the shortlist for the first tranche of loan guarantees were also among the five companies that signed engineering, procurement and construction contracts for new nuclear power plants (Bloomberg, December 17, 2009). (The fifth was responding to state-level incentives; see below). In January 2010, one utility received a loan guarantee for US$8.3 billion ($US_{2005}$$7.6 billion) that reportedly would cover up to 70% of the project costs for two 1.1-GW_e reactors, amounting to at least US$5.4 billion/$GW_e$ ($US_{2005}$$4.9 billion/GW_e). Additional loan guarantees might be provided by the Japanese government because the reactors will be built by Westinghouse, which is now a subsidiary of Toshiba (*New York Times*, February 17, 2010).

The Energy Policy Act also allows for up to US$2 billion to compensate companies building the first six nuclear power reactors for regulatory delays in the startup process. Finally, Title XIII provides for a production tax credit of US$0.018/kWh, up to a total of US$6 billion, for power produced by 6 GW_e of advanced nuclear power capacity during the first eight years of operation.[52]

State-level policy is also important. Out of the 50 states, 36 regulate the investments of utilities in the generation and transmission of electric power.[53] 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.[54] 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 proposing it was unable to obtain the repeal of a state law banning charges for construction work in progress (*Fuel Cycle Week*, April 24, 2009).

In late 2009, the US EIA projected that only 8.4 GW_e of new nuclear electric generating capacity will actually come online in the United States by 2035 (US EIA, 2009). After 2030, US nuclear power plants will reach 60 years at an average rate of about 5 GW_e/yr. US 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 US nuclear capacity is not to decline (US EIA, 2008a).

14.3.7 Western Europe

At the end of 2009, nuclear capacity in Western Europe totaled 122 GW_e, with two new 1.6-GW_e units under construction in Finland and France by the French company AREVA Nuclear Power (IAEA-PRIS).

In seven of the nine WEU 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 since then.[55] Due to retirements, Western Europe's nuclear generating capacity has declined by about 4 GW_e since 2000 (IAEA, 2007a; 2010d). Unless the reactor licenses are extended or the rate of construction picks up, Western Europe's nuclear capacity will continue to decline during the next few decades.

France accounts for a little more than half of Western Europe's nuclear capacity (63.3 GW_e) and for one of the two new units under construction (IAEA, 2010d, Table 1). The equivalent of about 76% of France's electricity is generated by nuclear power (IAEA, 2010a). France is a major net exporter of electric power (Schneider et al., 2009: 101). France's national utility, Électricité de France, is also considering investing in nuclear power plants in China, the United Kingdom and the United States, and possibly also in Italy and South Africa (*WNN*, December 4, 2008). Both of the new 1.6-GW_e EPR reactors being built by AREVA are suffering from serious delays and cost overruns, however. As of the end of 2008, the EPR under construction at Flamanville,

52 The US Congressional Budget Office puts the limit at US$7.5 billion (US CBO, 2008).

53 Some 14 states 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, 2008e).

54 In late 2008, the Florida Public Services Commission authorized two utilities to charge their customers US$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 the cost for completing the building of two Westinghouse AP1000s would be US$5780–8071/$kW_e$ (*Nucleonics Week*, February 21, 2008).

55 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).

France, was expected to cost €4 billion (US$_{2005}$\$5.8 billion) or US\$3600/kW$_e$ (*WNN*, December 4, 2008). In early 2009, the Finland's Olkiluoto EPR was 18 months behind schedule and expected to cost close to €5 billion (US$_{2005}$\$7.2 billion) (*Nucleonics Week*, March 5, 2009). AREVA NP's client in Finland, TVO, was suing for compensation of €2.4 billion (US$_{2005}$\$3.5 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 and filed an arbitration case with the International Chamber of Commerce for about €1 billion in compensation (*Nucleonics Week*, March 19, 2009).

In both cases, a large part of the problem seems to be inadequately trained workers and poor quality control leading to the 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 is met only in China and South Korea.

Of the remaining eight West European countries with operating nuclear power plants, two have laws mandating a phase-out: Belgium (with 54% of electric power generated by nuclear plants in 2008) and Germany (28%) (IAEA, 2010a). Spain's current government favors a nuclear energy phase-out (WNA, 2010g). The Netherlands is currently considering the construction of new nuclear power plants (WNA, 2010f). Despite its experience with AREVA, Finland is considering buying a second new nuclear power reactor from another vendor (*WNN*, February 5, 2009). Sweden had a phase-out law but, in 2010, decided to allow replacement of its current units as they are retired (WNA, 2010e).

The United Kingdom has the third largest nuclear capacity in Western Europe (10 GW$_e$).[56] The last of its first-generation "Magnox" graphite-moderated, gas-cooled nuclear power plants are to be shut down in 2012 (UK NDA, 2010). Its advanced gas reactors (AGRs) have a design life of 35 years, which would have them all shut down by 2024.[57] In early 2008, the UK government, which has an ambitious plan to reduce carbon dioxide emissions, came out in support of the building of new nuclear power plants, but declared that it would not subsidize their construction (*Times*, January 11, 2008). In September 2008, France's government-owned utility, Électricité de France, bought the UK nuclear utility, British Energy, for US\$23 billion with the intention of building four new 1.6-GW$_e$ EPR LWRs on the AGR sites (*International Herald Tribune*, September 24, 2008). Other companies are also considering building new nuclear reactors in the United Kingdom (WNA, 2010d).

56 Germany has the second largest capacity, with 20 GWe.

57 They may have to be shut down even earlier (*New Scientist,* March 25, 2004).

14.4 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. This section first briefly discusses advanced LWRs, and then considers two types of alternative reactors – fast-neutron and slow-neutron[58] – and finally, small and transportable reactors, which may be of interest to countries or regions with small power grids.

14.4.1 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 contain "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 open automatically when the level of water in the reactor falls below a certain level. Emergency cooling water then 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 considerably the probability of a core meltdown accident.

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 backpressure. Also, by giving credit to the passive systems for reducing the probability of a core meltdown, the US Nuclear Regulatory Commission (US NRC), whose 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 uncertain (Lyman, 2008).

58 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-reactor fuel. 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.

14.4.2 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 (Gen IV, 2008) and the IAEA-based International Project on Innovative Nuclear Reactors and Fuel Cycles 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 14.13). 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% of natural uranium, the ultimate fuel of fast-neutron breeder reactors.

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 GW_e (IPFM, 2010). But nuclear capacity plateaued and high-grade uranium ore proved to be much more abundant than previously believed. Enough low-cost uranium has been found to sustain 500 GW_e of capacity for 50 years (NEA, 2008c)[59] 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 US$130/kg or less) would only be about 0.3¢/kWh.

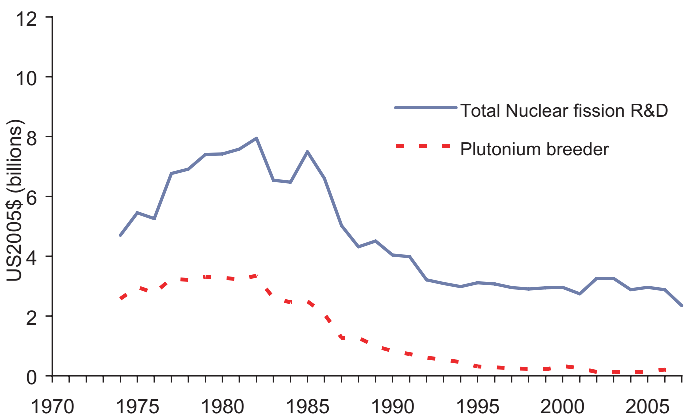

Figure 14.13 | Total fission and breeder research, development and demonstration (RD&D) funding in the OECD countries with substantial breeder programs, 1974–2007 (Belgium, France, Germany, Italy, Japan, Netherlands, UK, and United States). The breeder share is understated because France, which had the world's largest breeder program in the 1980s and 1990s, did not report most of its breeder RD&D activities as such. Source: data from IEA, R&D Statistics, 2009.

Fast-neutron reactors cannot be cooled by water, because (as occurs in the collisions of billiard balls) neutrons are drastically slowed down 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-GW_e 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 briefly 15 years later in May 2010. The largest demonstration liquid-sodium-cooled reactor built to date, France's 1.2-GW_e Superphénix, spent so much time in repair that it had an average capacity factor of only 7% 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 online with an average capacity factor of about 74% (Oshkanov et al., 2004).[60]

There are various ideas for reducing the cost of fast-neutron reactors, including the use of alternative coolants such as molten lead. Helium is also being considered, but has the safety disadvantage that it has little 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.[61] If the capital cost of a commercialized fast-neutron reactor were higher than that of an LWR by only US$1000/$kW_e$, it would require the cost of uranium to rise to about US$1200/kg for the uranium savings from a breeder reactor to offset its extra capital cost (Bunn et al., 2005, Figure 3; MIT, 2003; IPFM, 2010). This is about 10 times the cost of uranium in early 2009.

Most uranium exploration has focused on deposits with recovery costs of less than US$80/kg and finds are reported only when the recovery costs would be less than US$130/kg (NEA, 2008c). These resources range from 0.03–20% uranium (IAEA, 2009b). The concentration at which the amount of electric energy extractable from the uranium in 1 tonne of ore with a once-through fuel cycle would equal the amount of energy extracted from 1 tonne of coal is approximately 0.005–0.02%.[62]

59 Between 160 and 200 tonnes of natural uranium are required annually to fuel a 1-GWe LWR operating at a capacity factor of 90%, assuming 0.2–0.3% uranium-235 remaining in the depleted uranium from enrichment. With a global LWR capacity of 500 GWe, 10 million tonnes of uranium would last 100–125 years.

60 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.

61 The capital cost of the 1.2-GWe Superphénix was FF 34.4 billion (about US$8 billion in 2005 US$) according to France's public accounting tribunal, the Cour des Comptes (*Nucleonics Week*, October 17, 1996).

62 At 0.005% uranium, 1 tonne of ore would contain 50 g of natural uranium. That would produce 6.25 g of 4.4% enriched uranium (assuming 0.2% uranium-235 is left in the depleted uranium). For a burnup of 53 MWt-days/kg, the amount of fission energy released from the 6.25 g of LEU would be 28 × 10^9 J, about the amount of energy released from the combustion of 1 tonne of coal. Van Leeuwen has the breakeven level at 0.02%, in large part because he uses 50% gross thermal efficiency of the coal plant versus 32% for an LWR and a uranium recovery factor of 50% (Van Leeuwen, 2008).

Despite consumption and inflation, known uranium resources with recovery costs less than US$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 and MacGregor, 1980). Figure 14.14 compares the known conventional resources of uranium reported by the OECD's Nuclear Energy Agency (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 Schneider and Sailor's "conservative" and "optimistic" crustal models is assumed to be simply proportional to the amount of rock that must be mined, crushed, and leached to recover 1 kg of uranium. Thus, for ore with half the concentration of uranium, it would cost twice as much to recover 1 kg of uranium.

- The Kim & Edwards cost curve assumes that the recovery cost per kilogram increases somewhat more rapidly than inversely with declining ore concentration. Thus, for example, the cost of recovering a kg of uranium from an ore grade with one-tenth the concentration would be 19 times as high.

- The ocean contains about 4.5 billion tonnes of uranium but at a very low concentration of 3.3 parts per billion by weight. The estimate shown in Figure 14.14 that uranium would be recoverable from seawater at a cost of US$200/kg was developed by the US Department of Energy Generation IV Fuel Cycle Cross Cut Group (see also Tamada et al., 2006).

All the curves in Figure 14.14 are constrained to agree on uranium resources at a uranium recovery cost of about US$40/kg.

If the crustal model approach is correct, 20–60 million tonnes of uranium should be recoverable at a cost of less than US$130/kg. Some 25 million

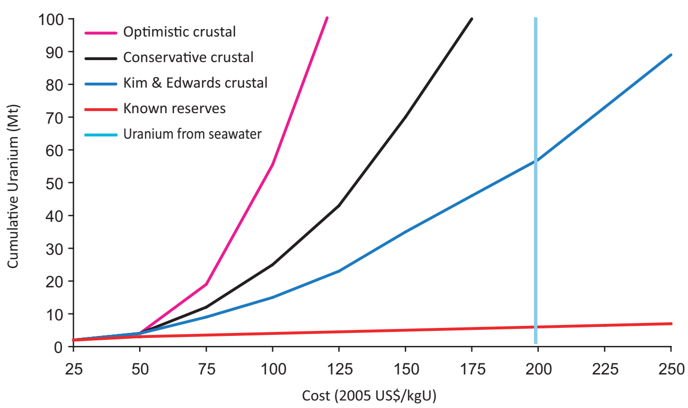

Figure 14.14 | Uranium resource availability. Known conventional reserves as reported in the NEA–IAEA "Red Book" [NEA, 2008c] compared with three geological estimates of crustal abundance as a function of recovery cost and an estimated cost of US$200/kg for recovery of uranium from seawater. adapted from: Schneider and Sailor, 2008.

tonnes of uranium would be required to sustain a once-through LWR economy until the year 2100 if global nuclear capacity increased linearly from 2020 to approximately 4000 GW_e. An LWR capacity of 4000 GW_e would require about 6.4 million tonnes of uranium per decade.[63] 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 GW_e. A recent MIT study has come to a similar conclusion (MIT, 2010).

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 recycling of plutonium because of probably unfounded fears of uranium shortages.

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

This was not a new proposal. In 1992, the US DOE had asked the US National Academy of Sciences (US NAS) to 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 (90–99%) 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% 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

63 Assuming 160 tonnes of natural uranium per GWe-yr, i.e., a depleted uranium assay of 0.2%.

in) LWR spent fuel (the approximate legislated limit on what could be stored in Yucca Mountain before a second US repository came into operation) is uncertain but is likely to be no less than US$50 billion and easily could be over US$100 billion ($US_{2005}$\$120 billion (US_{2005}\$0.3–0.6+¢/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 US Office of Management and Budget requested that the National Academies of Sciences review US DOE's 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: S-8).

14.4.3 Thermal (slow)-neutron Reactors

On its list of reactor types of interest, the Generation IV collaboration 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 US DOE and the US 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 thermochemical processes (US DOE, 2008c). Charles Forsberg, a nuclear engineer at the Massachusetts Institute of Technology, 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 in providing process heat for oil refineries and for extracting liquid fuels from oil shales and tar sands (*Oil and Gas Journal*, August 11, 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 the fission products could be removed and new fuel added by chemically processing a side stream. The problem with this design, however, is the complexity of operating a reactor with an integrated small reprocessing plant (Gen IV, 2008).

14.4.4 Low-power and Transportable Reactors

The IAEA recommends that a single nuclear power reactor should not constitute more than 5–10% of the generating capacity on a grid (IAEA, 2007b). As discussed previously (Table 14.2), gigawatt-scale reactors therefore require large grids. Smaller reactors could provide an alternative for countries and regions with small grids and expensive power. Proponents also claim that economies of scale in factory production could make them less costly than today's reactors, which involve costly field construction. A few relatively low-power LWR designs are available (WNA, 2008).

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

Some small reactor designs emphasize long core life. The tradeoff is that the initial core would be more costly per unit output (IAEA, 2005a, Table 5; IAEA, 2007c; US NRC, 2009).

One transportable nuclear power plant is under construction, a barge carrying twin 0.035-GW_e 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 constructed in St Petersburg with completion projected for 2011 (Bellona, May 18, 2009; IAEA, 2005a, Annex 6.5; Greencross, 2004). In 2006, Rosatom was planning to complete seven floating nuclear power plants by 2015 (Rosatom, 2006a, b). It is believed that, because of Russia's interest in exporting these reactors, they will be fueled with LEU rather than the weapon-usable highly enriched uranium used in Russia's submarines and nuclear-powered icebreakers (Sokov, 2006).

14.4.5 Safer Reactor Designs

Operational safety has been improved and, as discussed above, the new Generation III+ light-water reactor designs have passive safety features that might make emergency cooling independent of the availability of power for days. Nevertheless, the probability of terrorists attempting to cause Chernobyl-scale releases of radioactivity appears to be greater today than it was in the 1980s. This is a major reason why attention should be devoted to less vulnerable designs as well as to improved physical security.

In the case of the high-temperature gas-cooled reactor, attempts to give it inherent safety have been made by putting the uranium into small particles, encapsulated in layers of pyrolytic carbon and silicon carbide, in order 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 GW_e), 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 has found 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 MW_t gas-cooled AVR (Arbeitsgemeinschaft Versuchsreaktor) pebble-bed reactor, which operated between 1967–1988, has called into question the adequacy of its safety design. It was revealed that the reactor had suffered a serious leakage of fission products into the helium coolant. One possible reason 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, appears to have diffused through intact particle coatings. It was therefore concluded that the reactor would require a leak-proof containment similar to that required for modern LWRs, which 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 the possibilities for a truly inherently safe, reliable, and economic design.

14.5 Once-through versus Plutonium Recycling

Today, five weapon states (China, France, India, Russia, and the United Kingdom) plus Japan reprocess at least some of their spent fuel. The Netherlands has contracted with France to have the spent fuel from its single reactor reprocessed (van der Zwann, 2008). Of the reprocessing states, France, India, and Japan currently plan to reprocess most of their spent fuel. The United Kingdom is expected to end reprocessing when it has fulfilled its existing contracts (*Nuclear Fuel*, June 18, 2007, July 28, 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 GW_e (IAEA-PRIS). It also receives and mostly stores spent fuel from Bulgaria and Ukraine. China has built a pilot reprocessing plant.

Of the remaining 21 countries with nuclear energy programs, 11 have not reprocessed their spent fuel[64] and 10 that shipped their spent fuel to France, Russia, or the United Kingdom for reprocessing in the past, have not renewed their contracts.[65] All 21 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 14.5). The percentages shown for some countries in the first column reflect various limitations on the fraction of the spent fuel reprocessed.

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

1. reprocessing and plutonium recycling are much more costly than spent-fuel storage, and

2. countries providing reprocessing services are requiring (or, in the case of Russia, keeping the option to require) 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 politically attractive only for an interim period because it buys a decade or so of respite.

Only Russia has routinely kept its customers' separated plutonium. Among France's and the United Kingdom's former reprocessing customers, Belgium, Germany, Japan, and Switzerland have been recycling their separated plutonium in MOX (plutonium–uranium) fuel in the LWRs that produced it. France is doing the same. India and Russia plan to use their separated plutonium for startup cores for plutonium breeder reactors. France has kept Spain's separated plutonium[66] and presumably will do the same for Italy. It has included that offer in proposed reprocessing contracts to other countries such as South Korea (*Nuclear Fuel*, 13 July 2009).

64 Ignoring US reprocessing prior to 1973.

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

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

Table 14.5 | Civilian spent-fuel reprocessing by country

Countries that reprocess spent fuel (GW_e)		Customer countries that have quit or are planning to quit reprocessing (GW_e)		Countries that have not reprocessed (GW_e)	
Bulgaria (in Russia)	1.9	Armenia (in Russia)	0.4	Argentina	0.9
China (30%)	10.0	Belgium (in France)	5.9	Brazil	1.9
France (80%)	63.3	Czech Republic (in Russia)	3.7	Canada	12.6
India (~50%)	4.2	Finland (in Russia)	2.7	Mexico	1.3
Japan (90% planned)	46.8	Germany (in France/UK)	20.5	Pakistan	0.4
Netherlands (in France)	0.5	Hungary (in Russia)	1.9	Romania	1.3
Russia (15%)	22.7	Slovak Republic (in Russia)	1.8	Slovenia	0.7
UK (ending?)	10.1	Spain (in France/UK)	7.5	South Africa	1.8
Ukraine (in Russia, ~50%)	13.1	Sweden (in France/UK)	9.3	South Korea	18.7
		Switzerland (in France/UK)	3.2	Taiwan, China	4.9
				US (since 1972)	100.6
Total	172.6	Total	56.9	Total	145.2

The United Kingdom is not recycling its own separated plutonium and as yet has no disposal plans. By the time its domestic spent-fuel reprocessing contracts are fulfilled, the UK stockpile of separated plutonium will amount to about 100 tonnes – enough for more than 10,000 nuclear explosives. The UK Nuclear Decommissioning Authority is now examining disposal options (UK NDA, 2009). The storage of separated plutonium and reprocessing waste is significantly more expensive than storage of unreprocessed spent fuel. In addition, after several 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.[67]

Where plutonium is being recycled in LWR MOX, it is 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 recycling in "non-fertile" fuel with LWRs, 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. Achieving a significant reduction in 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. Although about US$100 billion has so far been spent worldwide in efforts to commercialize fast-neutron reactors, no country has yet succeeded. Nor has any country yet been willing to volunteer to take other countries' radioactive waste. The US Congress became skeptical about GNEP; the Obama Administration cancelled the proposal to build a reprocessing plant; and the US reprocessing program has returned to a focus on R&D, and in particular on the feasibility of developing more economic and proliferation-resistant methods of recycling plutonium and other transuranic elements. An evaluation of the resistance of the alternative recycling technologies proposed thus far against national proliferation has been discouraging, however (Bari et al., 2009). Attention has therefore been turning to "breed and burn" concepts in which plutonium is bred and burned in place without separation from fission products (Finck, 2010).

14.5.1 Radioactive Waste[68]

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 100,000 years or more as a result of natural processes or human intrusion is impossible, however. In the United States, Congress mandated in the 1987 amendments to the 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 US$10 billion have been spent on the project and an application for a license was

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

68 Charles McCombie, executive director, Association for Regional and International Underground Storage, adviser.

submitted in 2008 (US DOE, 2008b). In this sense, this repository was the most advanced in the world. It may never be completed, however, because of fierce political and legal opposition from the state of Nevada, now supported by President Obama, who 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 "decide–announce–defend" siting approach 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 become a spent-fuel repository is underway next to a nuclear power plant, following acceptance by the local community and formal approvals granted by the regulator and the parliament (McCombie and Chapman, 2008). More recently, local governments in Spain have competed to provide the site for a national radioactive waste repository. Here again, the finalists are communities that already host nuclear power plants (Deutsche Welle, 2010).

In the design envisioned for the Finnish and Swedish repositories, the spent fuel is to be encapsulated in a 5-cm thick copper cask 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 do 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 an underground facility. Also, if no off-site destination can 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 no country has yet expressed interest in hosting one. In the past, Russia has taken spent fuel back from Eastern Europe and Ukraine. 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 disagrees, however, and, for now, the leadership of Rosatom is not pushing to import foreign spent fuel other than Russian-origin fuel from power reactors exported by the Soviet Union or Russia.

In Europe, the European Commission has encouraged projects aimed at developing shared repositories for its smaller member states (ERDO, 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 5–10% from building one repository instead of two, each with half the capacity. It estimates 60% savings if 14 European countries with small nuclear energy programs share a single repository, but notes that 60% of those savings would 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 US geological repository proposed for Yucca Mountain was as high as or higher per tonne of spent fuel than the costs of the smaller disposal projects being developed in Europe. In 2008, the estimated cost of the US repository, not including transportation costs, was US$76.8 billion [$US_{2005}$$72 billion] for the equivalent of 122,100 tonnes of spent fuel,[69] or about $US_{2005}$$590/kg (US DOE, 2008b). For comparison, the estimated costs for disposing of 9500 tonnes of spent fuel in Sweden was about $US_{2005}$$650/kg;[70] for 5600 tonnes in Switzerland, about $US_{2005}$$500/kg;[71] and for 5800 tonnes in Finland, about $US_{2005}$$365/kg.[72]

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 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.[73]

Interim storage is not immune to controversy, however, because of concerns that interim may become permanent. Indeed, with a few

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

70 46.5 billion Swedish krona (SEK), assuming SEK7.5 (2003) per 2005 US$ (SKB, 2003).

71 Assuming that 2065 packages of spent fuel and 720 packages of vitrified high-level waste are equivalent to 5570 tonnes of spent fuel, and that 4.4 billion Swiss francs (2001 SFR) equal US$2.8 billion (2005 US$) (Chapman et al., 2008, Appendix).

72 Assuming that 2899 spent-fuel containers hold 5800 tonnes of spent fuel and that €2.54 billion (2005 €) equal US$2.12 billion (2005 US$) (Chapman et al., 2008, Appendix).

73 Both France and the UK have accumulated years of production of high-level liquid waste at their reprocessing plants because of technical problems with the vitrification (glassification) process. This waste contains on the order of 100 times the amount of cesium-137 (30 year half-life) that was released in the Chernobyl accident.

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).

The cost of dry-cask interim spent-fuel storage is relatively low (US_{2005}\$100–200/kg, or 0.02–0.05¢/kWh) and keeps open all future options, including deep underground disposal and reprocessing/recycling. 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 kW_t/tonne (Alvarez et al., 2003: Figure 5).[74] Ten tonnes in a typical 100-tonne 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 14.15). 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 fractional release 100 times larger 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).

14.6 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 at Chernobyl, on the border between Belarus and Ukraine, in late April and early May 1986. It was caused by an accidental supercriticality that produced 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 the following:[75]

- The deaths of 28 emergency workers from radiation illness within weeks.
- 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 nearby roads, and in the construction of the temporary "sarcophagus" over the reactor.[76]

Figure 14.15 | Dry cask storage of older spent fuel at a US nuclear power plant. Each year, a 1000-MW_e light-water reactor discharges spent fuel that originally contained about 20 tonne of uranium. Each cask typically holds about half that amount and costs US_{2005}\$1–2 million. Reprocessing spent fuel costs about ten times as much. Source: Connecticut Yankee, 2008.

74 Spent fuel can be placed in dry-cask storage as soon as three years after discharge, when the decay heat is about 6 kW_t/tonne.

75 Unless otherwise stated, the source of information in this section is UNSCEAR, 2000, vol. II, Annex J.

76 The dose limit was 0.25 sieverts (Sv). The average recorded doses were 0.17 Sv in 1986, 0.13 Sv in 1987, 0.03 Sv in 1988 and 0.015 Sv in 1989 (*ibid.,* p. 470).

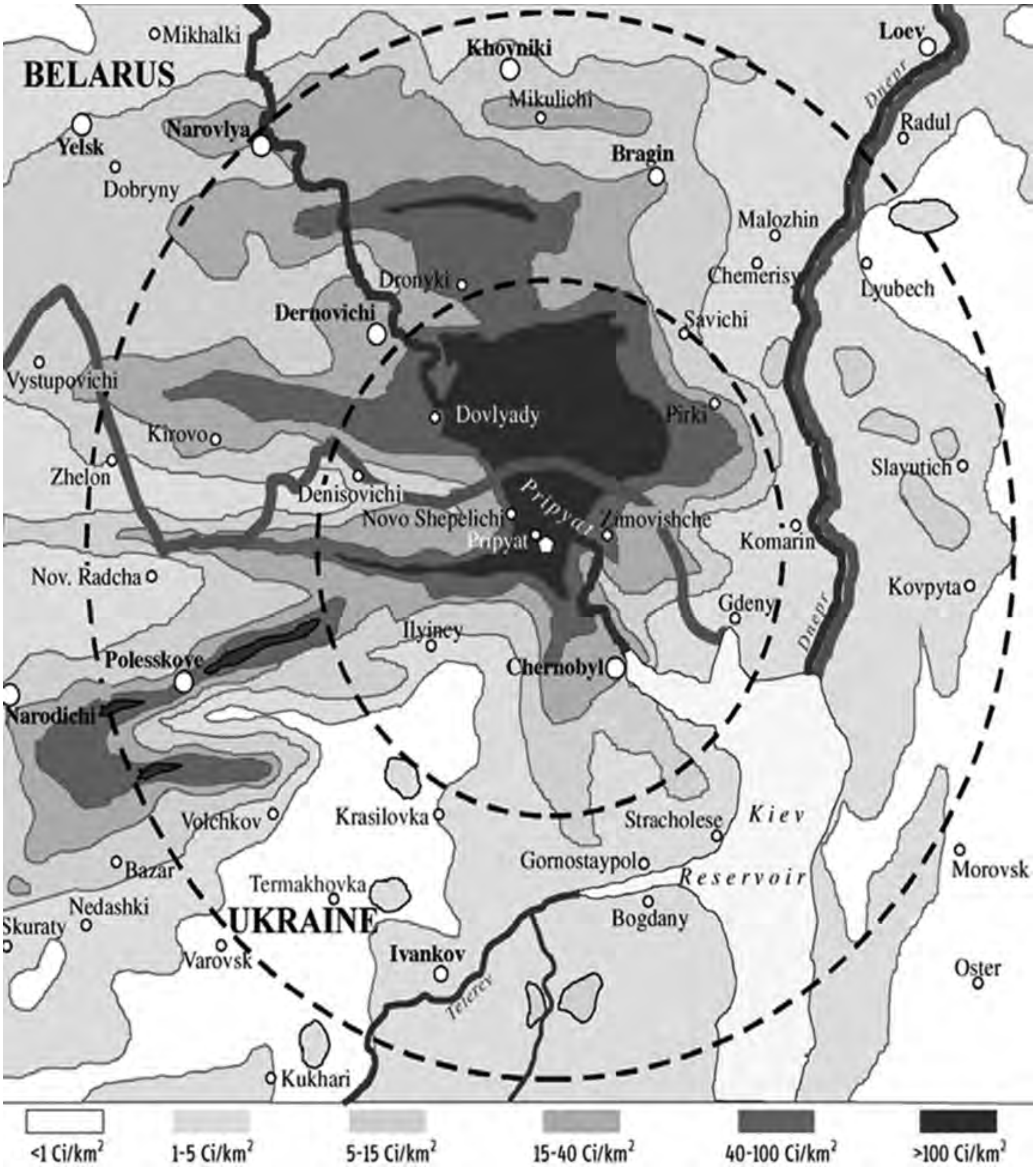

Figure 14.16 | Cesium-137 contamination levels around the Chernobyl reactor measured during the decade after the accident. Source: UNSCEAR, 2000, vol. II, Annex J, Figure VII. About 3000 km^2 contaminated to greater than 1.48 MBq/m^2 (40 Curies (Ci) cesium-137 per km^2) are still officially evacuated. Areas with contamination levels between 0.56 and 1.48 MBq/m^2 (15 and 40 Ci/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 areas has been kept below a level of about 5 mSv/yr – approximately twice the global average natural background rate (UNSCEAR, 2000, vol. 1, Table 1; Annex, para. 108). A population subject to such a dose rate indefinitely would incur an extra cancer risk of about 3.5%, about half of which would be fatal (US NAS, 2006: 4, 8).

- Radioactive contamination of an area of about 3000 km^2 by cesium-137, the 30-year half-life gamma emitter, to levels that resulted in the long-term evacuation of residents (Figure 14.16).[77]

- A still-growing epidemic of thyroid cancer among people in the region who received large doses from ingested and inhaled radioactive iodine (see Figure 14.17).

- Other radiogenic cancers are suspected but undetectable in a much larger background of cancers due to other causes.[78] One recent theoretical estimate, based on dose estimates and dose–risk coefficients derived from Hiroshima and Nagasaki survivors, is typical: 4000 extra cancer deaths among the 600,000 Chernobyl liquidators, 5000 among the 6 million people living in "contaminated areas" (above 37 kBq/m^2 of cesium-137), and about 7000 in the population

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

78 Almost 30% of deaths in developed countries are from cancer (American Cancer Society, 2007).

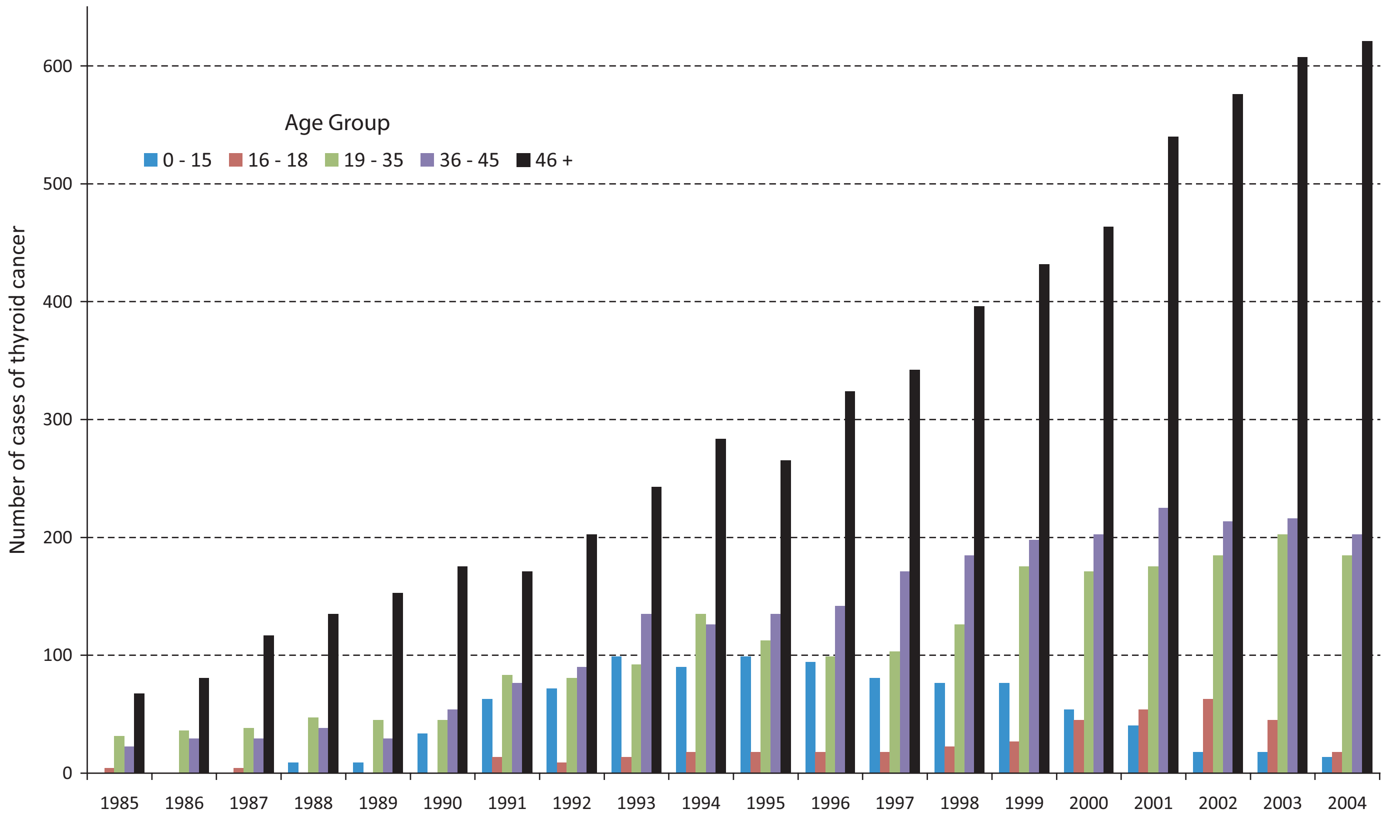

Figure 14.17 | Epidemic of thyroid cancer in Belarus following the 1986 Chernobyl accident. Annual number of cases of thyroid cancer grouped by age at the time of diagnosis. Note that the incidence of thyroid cancer in the youngest group (0–15 years) returned to low levels in 2002 when all the exposed population had graduated into older groups. In the younger groups the death rate due to thyroid cancer has been low. This does not appear to be true, however, for the increasing number of cases among those aged 46 and over. In 2004, this group would have been over 27 at the time of the Chernobyl accident. Source: Bespalchuk et al., 2007.

of 500 million of the rest of Europe who were subjected to lower doses. The total number of extra cancer deaths over the expected lifetime of the exposed population was estimated at 6000–38,000 (95% confidence level) (Cardis et al., 2006).[79]

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

Estimates of the economic cost of the Chernobyl accident range from US$6.7 billion (Sovacool, 2008b) to US$235 and US$148 billion by the governments of Belarus and Ukraine, respectively (years unspecified). In Belarus, the costs of dealing with Chernobyl amounted to 20% of the national budget in 1992, falling to 5% in 2001. These costs were paid for in part by a special tax of 18% on all wages paid by non-agricultural firms in 1994 (UNDP, 2002, sections 5.04ff). Estimates of the potential costs due to the evacuation of the population and the loss of assets due to contamination by hypothetical spent-fuel pool fires at a range of US sites also run to hundreds of billions of dollars (Beyea et al., 2004).[80]

The Chernobyl accident occurred in a reactor type that is now being phased out. The Three Mile Island accident in 1979, where the reactor core partially melted but there was not a major release of radioactivity from the containment occurred in a pressurized water reactor and the three core meltdowns at the Fukushima Daiichi nuclear power plant, which released on the order of one tenth as much radioactivity to the atmosphere as the Chernobyl accident, were in boiling water reactors (von Hippel, 2011). In the Chernobyl and Three Mile Island accidents, the operators' lack of understanding 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

79 An estimated figure of 4000 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).

80 The range of releases of cesium-137 considered was 130–1300 PBq (3.5–35 megacuries, MCi), 1.5–15 times the estimated release from Chernobyl.

improve safety culture, learn lessons from safety incidents, share best practices, and review safety-related aspects of the design and operation of individual plants. There were about 1500 GW_e-yrs of nuclear power before the Chernobyl accident, and about 8500 after than until the March 2011 Fukushima Daichi accident.[81] That accident raised concerns about the possible release of radioactivity from the spent fuel pools. The dangers of loss of water from spent fuel pools and possible remedial actions had been the subject of debate in the United States (Alvarez, 2003; US NAS, 2006b).

In 2002, at the Davis-Besse nuclear power plant (Ohio, United States), it was discovered that leaking boric acid had eaten almost through a reactor pressure vessel head before it was discovered, despite the presence of iron oxide in the air and dried boric acid deposits on the outside of the vessel. The incident was a potent reminder that nuclear safety requires constant vigilance (US GAO, 2004).

Major efforts will also be necessary to ensure that countries building nuclear power plants for the first time, or those rapidly expanding their reactor fleet, as in China and India, put effective safety measures in place. These measures include instilling a strong safety culture and granting independent regulators the power, resources, and expertise they need 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. Yet there is far less focused attention today to reactor security than to reactor safety. The possibility of terrorism puts an even greater premium on trying to design reactors that are more inherently safe than they were in the past.

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 for 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.

14.7 Nuclear Weapon Proliferation

Nuclear weapon acquisition was the first priority of the United States and most other early national nuclear programs. Civilian nuclear energy programs contributed to some later nuclear weapon programs 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[82] that have acquired nuclear power have done so in the context of nuclear weapon programs. Fortunately, most of these countries abandoned the weapon dimensions of their nuclear programs.[83]

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

14.7.1 The Nonproliferation Regime

Today, an extensive regime to limit the spread of nuclear weapons is in place, with the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) as its cornerstone. Only three countries have not joined the NPT – India, Israel and Pakistan – and only North Korea has withdrawn. While this regime has been highly successful, it is now under substantial stress.

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 (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, 1972). The IAEA 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 into account likely losses in processing – should be taken as 8 kg of plutonium or uranium-233, or 25 kg of uranium-235 contained in HEU (IAEA, 2001: 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.[84]

More fundamentally, at a large reprocessing plant such as Japan's Rokkasho, which is designed to separate 8 tonnes of plutonium (1000

81 This does not mean that there had not been worrisome incidents at many nuclear power plants (Kastchiev et al., 2007).

82 The regions included in the Cold War blocs were North America/Western Europe/Japan, and the former Soviet Union/Eastern Europe, and China. Countries with nuclear power programs outside these blocs include Argentina, Brazil, India, Pakistan, South Africa, South Korea, and Taiwan.

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

84 SAGSI estimated the times required to convert various types of nuclear material into nuclear-weapon components as one week for plutonium or HEU metal (IAEA, 2001: 22).

significant quantities) 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 therefore argue that safeguards at large bulk-processing facilities are 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.

The IAEA inspections in Iraq after the 1991 Persian Gulf War dramatically demonstrated that the focus of IAEA safeguards at the time were too narrow. Iraq had mounted a program to produce highly enriched uranium for nuclear weapons, 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, 1998) requires states to provide the IAEA with more information and access to a broader range of sites, in particular relevant facilities with 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 information from 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).[85]

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

There is an ongoing struggle, however, between those states that are attempting to slow the spread of sensitive technologies and those trying 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. In 1992, the NSG supplemented its rules with restrictions on exports of "dual-use technologies" and called 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, and had been operating in some 20 countries for more than 20 years. These revelations made it clear that far more needs to be done to control the spread of the most sensitive nuclear technologies (Fitzpatrick, 2007).

14.7.2 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 former Soviet Union promoted competitive "Atoms for Peace" programs. But India's use of US-supplied reprocessing technology to separate plutonium for its 1974 "peaceful" nuclear explosion convinced the US government to stop promoting reprocessing both at home and abroad, and to organize the Nuclear Suppliers Group 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.[86] The nominal purpose of the plant is to produce LEU for Iran's future nuclear power plants, although Iran has acknowledged that its centrifuge program began in 1985, a time when it had no plans for nuclear power plants and was locked in a war with Iraq, which was using chemical weapons and was suspected of seeking nuclear weapons. The plant could potentially be converted to the production of HEU for nuclear weapons or provide a civilian cover for a parallel clandestine enrichment program.

85 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).

86 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 peaceful. The IAEA has found that Iran repeatedly failed to comply with its safeguards obligations and the UN Security Council has legally obligated Iran to suspend all its enrichment activities and make its nuclear program fully transparent to the IAEA. However, Iran has refused to comply.

The Acheson–Lilienthal report proposed that enrichment and reprocessing be allowed only at plants owned by an international "Atomic Development Authority." Attenuated versions of this idea were discussed during the 1970s and early 1980s, including the idea of multinationally controlled reactor parks in which spent fuel could be reprocessed and the recovered plutonium recycled into on-site reactors (see, for example, Chayes and Lewis, 1977; SIPRI, 1980). In 2003, former IAEA Director-General Mohammed ElBaradei proposed another look at multinational control (ElBaradei, 2003) and subsequently initiated a high-level study of 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,[87] however, and the Bush Administration proposed to include states with pilot-scale facilities.[88] 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.[89] Over the longer term, ElBaradei has argued, "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 material for nuclear weapons. Indeed, most of the enrichment work required to produce 90% enriched HEU for weapons has already been done in enriching material to 4% for reactor fuel.[90] Gas-centrifuge cascades, now the dominant technology for producing LEU, can be used or relatively quickly reconfigured to produce weapon-grade uranium (Glaser, 2008).

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

- URENCO, an international enrichment group, is expanding its enrichment plants in Germany, the Netherlands, and the UK, and is building large new enrichment plants in France and the United States while Russia is doing the same in China.

- Small national enrichment plants are being built in Brazil and Iran and are being proposed in Argentina and South Africa (Nuclear Fuel, August 25, 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, whose fuel is being supplied by Russia. Iran has announced, however, an ambitious program for bringing 20 GW_e of nuclear capacity online by 2025 (NEA, 2008c). Given its bad relationship with the United States, and its earlier history of being refused enrichment services by the European Gaseous Diffusion Uranium Enrichment Consortium (EURODIF),[91] 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 upon imported uranium.[92] It would therefore have to stockpile imported natural uranium to protect itself against uranium supply disruptions. If so, why not 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 military nuclear 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, was interested in adding value to its exports by acquiring

87 Including Argentina, Brazil, Canada, and South Africa.

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

89 American billionaire Warren Buffett offered US$50 million through the US-based Nuclear Threat Initiative toward establishing an IAEA fuel bank, and the US government, European Union, 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 US case, to be produced by blending down excess HEU), upon which countries in good standing with regard to their nonproliferation commitments will be able to draw (US NAS-RAS, 2008).

90 One way to understand this is to note that, by the time 4% enrichment has been achieved, the uranium-235 has been separated from over 80% of the uranium-238 in natural uranium. A separative work unit (SWU or, more precisely, a kg-SWU) is a measure of the amount of work done in isotope separation. To extract 1 kg of uranium-235 from natural uranium, which contains about 0.7% uranium-235, and concentrate it to 90% enriched "weapon-grade" uranium, leaving 0.3% 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% enrichment.

91 Iran still owns 10% of EURODIF via a 40% interest in Sofidif (Société franco–iranienne pour l'enrichissement de l'uranium par diffusion gazeuse), which holds 25% of EURODIF SA. The company has not paid out dividends to Iran since various restrictions were imposed on Iran following its non-compliance with the UN Security Council order of 31 July 2006.

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

an enrichment plant. In 2008, however, after URENCO refused to sell it a gas-centrifuge enrichment plant, Cameco bought a 24% share of a laser-enrichment company whose plant is to be built in the United States (GE-Hitachi, 2008).[93]

Multilateral arrangements. As noted above, 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 multinationally 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 in which other countries (Italy, Spain, Belgium, and Iran) invested, in exchange for rights to a share of the enrichment work. Iran loaned the consortium US$1 billion for the construction of the plant and prepaid US$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 US$1 billion plus interest in 1991. When it requested delivery of the enrichment services for which it also 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 (Meier, 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.

Thus far, Kazakhstan has committed to buy 10% of the IUEC (*Nuclear Fuel*, September 24, 2007).[94] Ukraine (*Nuclear Fuel*, November 30, 2009) and Armenia (*Nuclear Fuel*, April 20, 2009) also are expected to become partners. Russia offered Iran a share as an alternative to Iran building its own enrichment plant, but the offer was declined.

This arrangement has been at least partially successful as a nonproliferation initiative, however, in that it has apparently convinced the partner countries 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) had 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, the consortium has not maintained effective control of the technology. URENCO subcontractors were the source of the technology that A. Q. Khan used to build Pakistan's enrichment complex and to export centrifuge enrichment technology 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 Company (ETC), 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% share of ETC, but without access to the technology. The centrifuges are being built in ETC facilities in Germany and the Netherlands, and are assembled into cascades by ETC employees in France and the United States (ETC, 2008). Russia has similarly built enrichment plants in China (*Nuclear Fuel*, December 19, 2005). The centrifuges are described as "black boxes" as far as the host country is concerned, though regulators in the countries where these plants operate inevitably have to understand some aspects of the technology to be able to confirm its safety. Since France, the United States and China are all weapon states, however, URENCO and Russia have not yet faced the full challenge of protecting their technologies 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 black-box mode (*Nuclear Fuel*, August 25, 2008). URENCO has rejected a proposal to resolve the international crisis over Iran's enrichment program by putting it under multinational control and replacing Iran's centrifuges with black-boxed URENCO centrifuges (*Nuclear Fuel*, July 30, 2007). Such an arrangement would not likely be of interest to Iran either.

Former IAEA 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 (US NAS-RAS, 2008; Thomson and Forden, 2006). If a plant were owned by several countries, or by an international institution, with the plant location

93 The three largest suppliers of uranium are Kazakhstan, Canada, and Australia. Kazakhstan has become a partner in Russia's Angarsk enrichment facility. Australia has supported enrichment R&D but is not currently actively pursuing the idea of building its own enrichment plant.

94 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).

designated as extra-territorial – as are embassies and the laboratory of the European Organization for Nuclear Research (CERN) in Switzerland – 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 the 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, the simplest alternative would be to forgo the practice. As practiced today, reprocessing and plutonium recycling are not economic and do not significantly simplify spent-fuel disposal (von Hippel, 2007, 2008a; Schneider and Marignac, 2008; 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 reduce its long-term radiological hazard. Most countries are abandoning reprocessing (see Table 14.5).

An exception is Japan, where it is politically unacceptable to allow spent fuel to accumulate at nuclear power plants and prefectures have been reluctant to host centralized spent-fuel storage facilities.[95] A reprocessing plant, with large 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 for 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 recycling could make Japan independent of uranium imports.

Japan's reprocessing plant, when operating at its design capacity of 800 tonne/yr of spent fuel, will separate about 8000 kg/yr of plutonium. The first-generation Nagasaki bomb contained 6 kg of weapon-grade plutonium metal (almost pure plutonium-239), which would be roughly equivalent, in terms of critical masses, to 8 kg 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). An evaluation of the added proliferation resistance of the proposed technologies found, however, that it was not significant (see, e.g., Collins, 2005; Hill, 2005; Kang and von Hippel, 2005). Ultimately, the Administration proposed to deploy a reprocessing plant very little different from those in France and Japan. It insisted that pure plutonium would not be separated, i.e., that it would be mixed with uranium. Since it is not difficult to separate plutonium from uranium, however, this would be of only modest significance.

14.7.3 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, 2010). Repeated studies by the US 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. A number of 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 terrorist capabilities in the near term – 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 recycling might significantly increase the risk of 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 weapon use (Acheson–Lilienthal, 1946: 30). That is correct for uranium-235. When diluted with uranium-238 to less than 6% concentration, uranium-235 cannot sustain an explosive chain reaction. Indeed, when the percentage is less than 20%, 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% uranium-235, is not directly weapon-usable.

The authors of the Acheson–Lilienthal report 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 Nagasaki weapon implosion design, these neutrons could start the fission chain reaction before the optimal time for maximum yield. In the Manhattan Project, great efforts therefore were

95 At the end of 2008, however, Chubu Electric Power Company proposed to build a dry-cask storage facility with a capacity of 700 tonnes of spent fuel, in connection with a proposal to build a new 1.4 GWe reactor to replace two old reactors with a comparable generating capacity (CNIC, 2009).

made to keep the percentage of plutonium-240 below a few percent. LWR plutonium contains about 25% plutonium-240 (NEA, 1989, Table 9). In the Nagasaki design, this could have reduced the yield from 20,000 tonnes of chemical explosive equivalent to as low as 1000 tonnes (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-kilotonne (1 kt) explosion.[96] For more advanced designs, such as those in the arsenals of the NPT weapon states, there might be no significant reduction in yield (US DOE, 1997: 38–39).

Today, therefore, any mix of plutonium isotopes containing less than 80% plutonium-238 is considered weapon usable (IAEA, 2001, Table II).[97] Since the amount of plutonium-238 in the world is only 1–3% as large as the total amount of plutonium (NEA, 1989: Table 9), it would be impractical to attempt to use it to denature a significant fraction of the world's plutonium.

14.8 Institutional Requirements[98]

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. For nuclear power to grow enough to make a significant contribution to mitigating global climate change, stronger institutions at both the national and international levels will be required.

In the decades since the Chernobyl accident, many countries have strengthened their safety practices and regulations substantially, but there is clearly more to be done. The Fukushima accident has provoked a global discussion concerning what national and international institutions and approaches need to be changed. 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, both internal and external critics continue to argue that the Nuclear Regulatory Commission too often subordinates enforcement to the industry's cost concerns (US NRC, 2002; 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 the growth of 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 should be defended against, and some do not require armed guards even to protect weapon-usable nuclear material from theft. Substantial steps are needed worldwide to reduce vulnerability (Bunn, 2010).

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.

14.8.1 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 and professional associations such as the Institute for Nuclear Materials Management.

Safety. The IAEA's International Nuclear Safety Group (INSAG) has produced a diagram (Figure 14.18) 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.[99] Ultimately,

Figure 14.18 | The global nuclear safety regime. Source: IAEA-INSAG, 2006, Fig. 1.

96 The radius of blast destruction is proportional to the one-third power of the yield (Glasstone and Dolan, 1977, equation 3.61.1).

97 Plutonium-238 is relatively short-lived (88-year half-life) and generates a great deal of decay heat (0.56 kW_t/kg). It therefore would be difficult to fabricate into a nuclear explosive. It has been exempted from safeguards because it is used as a heat source for applications such as space probes to the outer planets, but the exemption has been drawn as narrowly as possible.

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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.[100]

The IAEA plays a critical role by publishing standards, guides and recommendations, and organizing discussions of critical issues and best practices. It manages an incident reporting system with the OECD Nuclear Energy Agency 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, the IAEA has found that sites either have implemented or are implementing some 95% of the teams' recommendations (IAEA, 2007d).

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.[101] 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, an industry group established after the Chernobyl accident, is another key international nuclear safety institution.[102] WANO is divided into four regional groups with headquarters in Atlanta, Moscow, Tokyo, and Paris. A reactor's affiliations with one or more of these headquarters is determined by a combination of its 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 experiences, 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. Also both the G8 countries and the European Union have pursued extensive nuclear safety assistance programs, especially in former Soviet-bloc countries. Finally, there are also several international groupings of nuclear regulators (IAEA, 2007d).

Despite all of these efforts, INSAG has reported important weaknesses in international information sharing and actions. For example, the fact that WANO 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, Luc Mampaey, then WANO managing director, complained that some utilities were not reporting at all (*Nucleonics Week*, September 27, 2007).

Security. Most countries shroud their security practices in secrecy, and international institutions for promoting nuclear security are therefore 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 having a fence with intrusion detectors around significant stocks of plutonium or HEU, for example, but say nothing about standards of effectiveness.

UN Security Council Resolution 1540 legally obligates all UN 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, 2008).

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, 2010). 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 forum for nuclear security managers around the world to exchange best practices and discuss issues they have confronted in the hope of improving nuclear security practices worldwide (Howsley, 2008).[103]

In April 2010, leaders from 47 countries gathered in Washington D.C. for the first nuclear security summit and endorsed the objective of securing all vulnerable nuclear material worldwide within four years. They agreed on a broad communique and modestly more specific work plan, and some countries made important national commitments, such as Ukraine's commitment to eliminate all the HEU on its soil by 2012. A second nuclear security summit was scheduled in Seoul for March 2012. This summit process has elevated nuclear security to the top levels of government.

99 For a useful overview of international activities related to nuclear safety, see IAEA (2007d).

100 For a critique and a suggestion of a more robust approach, see (Barkenbus and Forsberg, 1995).

101 The first-ever IAEA Operation Safety Review Team review in Russia was held in 2005 at the Volgodonsk plant. The plant prepared for months and received a very positive review (M. Lipar, Head, Operational Safety Section, IAEA, personal communication, April 2008).

102 The US Institute of Nuclear Power Operations was formed to play a similar function at the national level after the 1979 Three Mile Island accident near Harrisburg, Pennsylvania.

103 WINS' first director is Roger Howsley, previously head of security, safeguards and international affairs at British Nuclear Fuel Services Limited: www.wins.org.

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 UN Security Council's demand that it suspend its enrichment program, combined with North Korea having become 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."[104] 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 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 IAEA is the most important. 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, as well as challenges in balancing its efforts to maintain essential positive relationships with states with an appropriate investigatory attitude.

The Additional Protocol to the NPT 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 a number of non-weapon states with significant nuclear activities or ambitions that have not acceded to the Additional Protocol.[105] 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.[106] Pierre Goldschmidt, former IAEA Deputy Director-General for safeguards, has suggested that the UN 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 UN Security Council has, in fact, demanded that Iran provide such a level of transparency.[107]

With respect to resources, the IAEA's regular budget for implementing nuclear safeguards worldwide in 2007 is only US$100 million, or about 0.004¢/ kWh generated by the world's nuclear power plants (IAEA, 2010d). In the context of renewed hiring in the nuclear industry, the Agency also has increasing difficulty recruiting and even 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.[108]

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 other applications of nuclear technology is kept at about the same size as the budget for safeguards.[109]

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 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.

104 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 Conferences (UN, NPT, 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."

105 Including Algeria, Argentina, Brazil, Egypt, Iran (signed but not ratified), Iraq (signed but not ratified), Mexico (signed but not ratified), Syria, United Arab Emirates (signed but not ratified), Venezuela and Vietnam (signed but not ratified) (IAEA, 2010c).

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

107 In its Resolution 1803 of 3 March 2008, the UN 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 research and development as the Agency may request in support of its ongoing investigations."

108 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).

109 In 2007, the total IAEA budget was US$268 million. Excluding central management and information services, it was US$199 million, of which US$103 million went to safeguards, US$71 million to nuclear energy and development and US$22 million to nuclear safety and security. An additional US$37 million of extra-budgetary funds were contributed by interested countries – mostly for the safeguards, safety and security programs (IAEA, 2008c).

14.9 Public Acceptance[110]

Historically, 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 18 countries done for the IAEA in 2005, on average 62% of the respondents did not want existing nuclear power plants to be shut down, although almost the same percentage opposed building new ones (Figure 14.19). In Western Europe and 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; EC, 2007). As memories of the accidents at Three Mile Island (1979) and Chernobyl (1986) faded and concerns about the consequences of global warming increased, however, the trend prior to the 11 March 2011 accident at Japan's Fukushima Daiichi nuclear power plant was toward more pro-nuclear public opinion, and government policies were moving even more rapidly in that direction. Public opposition also diminishes when new nuclear power plants are built at existing sites, as is often the case. In China, where many new sites are being established, public opposition was relatively limited, at least prior to the Fukushima Daiichi accident (WISE, 2007).

Individuals oppose nuclear power for different reasons. Some feel that the technology is too expensive, while others are concerned about the fact that nuclear energy technologies can be used to produce nuclear weapons. The main source of opposition, however, is the public concern about the production of radioactive waste and the potential for high-impact accidents.

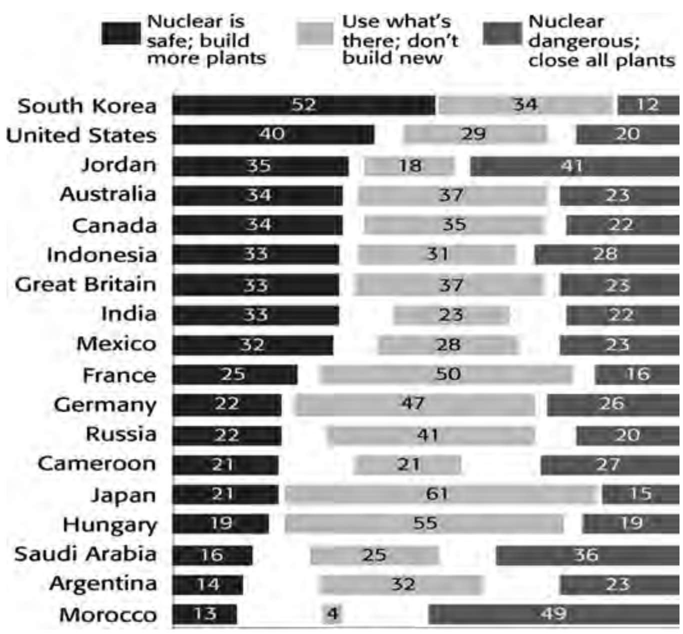

Figure 14.19 | Attitudes to nuclear power by country. The white spaces represent "don't know," "none of the above," "other" or "no answer." Source: Globscan, 2005.

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.[111] Technical experts often assess risk probabilistically through injuries and deaths per GW_e-yr of nuclear energy generated. On this scale, nuclear power does not seem particularly dangerous.

Public perceptions are the result of various psychological, social, and cultural processes, however, that can heighten or attenuate risk signals (Kasperson et al., 1988). Typically, attenuation occurs with everyday hazards such as indoor radon, smoking, and driving. In the case of nuclear power, in contrast, the risks are often amplified. Indeed, some scholars studying public perceptions have argued that nuclear energy is "subject to severe stigmatization" (Gregory et al., 1995).

Faced with public antipathy, the nuclear industry and some governments have tried to persuade the public to see risk the way experts see it, such as through campaigns pointing out that the annual risk from living near a nuclear power plant is equivalent to the risk of riding an extra three miles in an automobile (Slovic, 1996). But such comparisons do not address the aspects of the risk that people believe to be important, and often produce more anger than enlightenment.

The assumption that public opposition results from ignorance may not be correct (US OTA, 1984). One analysis of the debate over the risks from the Diablo Canyon nuclear plant in California 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 institutions that manage nuclear power are untrustworthy as sources of information (Wynne, 1992). A 2001 survey by the European Commission found that only 12% of Europeans trusted the nuclear industry (EC, 2008). Both trust and distrust tend to reinforce and perpetuate themselves (Slovic, 1993). Today, however, concerns about nuclear power are confronted by another major concern: the consequences of global climate change. The nuclear industry, some independent scientists, and some governments are increasingly reframing the debate as one about whether public fears

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111 Enrico Fermi, who designed the first chain reacting "pile," apparently anticipated the public's concerns, however, well before the US nuclear power program was launched. He is reported to have commented (as paraphrased by Alvin Weinberg) that it "is not certain that the public will accept an energy source that produces vast amounts of radioactivity as well as fissile material that might be diverted by terrorists" (Weinberg, 1994).

about nuclear power have to be subordinated to the need to limit climate change. In a 2005 survey, this argument resulted in a 10% increase in public support for building new nuclear power plants (Globescan, 2005).

In the United Kingdom, the debate has been particularly intense because of the national commitment to reduce carbon dioxide emissions, the declining supplies of North Sea gas, and the retirement of the country's first-generation Magnox reactors. The government, the nuclear industry, major scientific leaders and professional societies have all been promoting a "new build" of nuclear capacity. One study 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, and found "reluctant acceptance" (Bickerstaff et al., 2008). The study found, however, that radioactive waste was regarded with even greater dread than climate change, and there was great mistrust of the competence of the nuclear power establishment and the government to manage nuclear power safely. The respondents were also concerned about the possibility of terrorist attacks on nuclear facilities. If it were feasible to make a more rapid shift to renewable sources of energy, that would attract greater support. In the United States, a national poll in 2008 found that 42% of the population supported an increased commitment to nuclear power, compared with 93% for solar, 90% for wind, 52% for natural gas, 33% for coal, and 22% for oil (Greenberg, 2009).

14.10 Policy Recommendations

Throughout its history, the debate on nuclear power has focused on two questions: is it necessary, and to what extent 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. This is the subject of several chapters in this volume, especially Chapter 17 (Global and Regional Scenarios). 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, of alternative means of matching energy supply and demand.

With regard to the second question, the greatest dangers that need to be minimized are Chernobyl-scale releases of radioactivity into the environment and the possibility that nuclear power facilitates the proliferation of nuclear weapons and nuclear terrorism. There are a number of initiatives that could help to reduce but not eliminate both of these risks.

14.10.1 Reducing the Risk of Catastrophic Releases of Radioactivity

The light-water reactors (LWRs) that dominate nuclear power today, and will continue to do so for the foreseeable future, were originally developed for naval propulsion. The primary design consideration was therefore that they be compact. When they were adapted for use as power reactors, that constraint was loosened and redundant emergency cooling systems and a containment building were added. These additions helped, but as the recent Fukushima Daiichi accident showed, a core meltdown accident with a large release of radioactivity to the human environment is still possible. Indeed, the successful containment of the 1979 Three Mile Island melt-down was to some extent a matter of luck. Some US 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 have made significant improvements in operator training since 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, after the US NRC acceded to the operator's insistent demands and allowed the Davis-Besse nuclear reactor to continue to operate in what was later established to be an extremely dangerous condition, the US NRC Inspector General commented that "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 criterion for selecting among 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: 54). In any case, Gen IV industry representatives have repeatedly stated 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 the design could be optimized economically, rather than the other way around.

Given license extensions to 60 years and perhaps beyond,[112] many of the existing plants are likely to be operating for a very long time. In the aftermath of the Fukushima Daiichi accident, national regulations and international standards should be tightened, to ensure that nuclear facilities are prepared for the full spectrum of foreseeable earthquakes, floods, blackouts, and other disasters – and for terrorist attacks of the

112 In its 2009 projections for US nuclear capacity, the US Energy Information Administration assumed that the licenses of US nuclear power plants will be extended to 80 years (US EIA, 2009).

scale and sophistication of the September 2001 aircraft hijackings. Reactor operators should be required to protect against spent fuel burning if a spent fuel pool loses water and fuel that is sufficiently cool should be moved into safer dry casks. They also should be required to retrofit reactor containments with robust filtered vents that could greatly reduce the amount of radioactivity released in a severe accident (Beyea and von Hippel, 1982; Schlueter and Schmitz, 1990). Operators and nearby agencies such as police and fire departments must have effective emergency plans in place and regularly exercise them, so they all know what to do in the event of a crisis. The role and capabilities of the IAEA and WANO also should be significantly strengthened, including expanded and more transparent peer reviews.

14.10.2 Increasing Proliferation Resistance

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

1. phase out reprocessing as quickly as possible,
2. place enrichment plants under multinational ownership and management, and restrict them to politically stable regions, and
3. establish regional spent-fuel storage and repositories.

1. Phase out reprocessing as quickly as possible. In the fuel cycle of an LWR fueled with LEU, weapon-usable material becomes directly accessible only 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 that, 10 or more years after discharge, are dominated by cesium-137, with a half-life of 30 years. 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 countries, such as Japan and South Korea, political obstacles would have to be overcome to the extended interim storage of spent fuel on nuclear power plant sites or at a central site.

2. Place enrichment plants under multinational ownership and management and restrict them to politically stable regions. 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 to divert expertise and components to the construction of a clandestine national enrichment plant. Multinational ownership does not necessarily mean ownership by multiple governments. It could include ownership by companies that are owned by or answerable to multiple governments. An arrangement intermediate between that of URENCO, which involves technology sharing, and that of EURODIF and Angarsk, in which non-host countries are passive investors, might be optimal. This could include multinational teams of operators in the enrichment plant control room. Indeed, the black-box model that has been adopted by URENCO in France and the United States, and by Russia in China, might be near the correct balance. In this arrangement, management of the plant can be shared, making operations, but not the technology, more transparent among the partners.

In order to make this approach politically feasible, it will probably be necessary to convert existing national facilities in the weapon states into multinational facilities. This could be done without significantly disrupting existing commercial arrangements, for example, if companies from other countries bought shares of ownership in existing facilities, and ultimately began participating in the staffing of those facilities. It will also be desirable to agree that new facilities not be built until a minimal level of contracted demand exists to make it economically viable (at least the equivalent of 10 GW_e of LWR capacity, corresponding to an enrichment capacity greater than 1 million SWU/yr).

It would be desirable that such facilities be built in politically stable regions. If, as in the case of Iran, neighboring countries feel that their security would be threatened by a proposed enrichment plant, that perception should be regarded as a major argument against the facility.

Finally, it would be important to have arrangements to reduce the danger that new enrichment plants will be used to justify the host countries mastering enrichment technology. Today, URENCO's ETC and Russia's Rosatom make the most cost-effective gas centrifuges.

3. Establish regional or international spent-fuel storage facilities and repositories. In the not too distant future, perhaps 50 countries, many with only a few nuclear power reactors, will be accumulating spent fuel. This may create the danger that countries will begin to "reprocess" their spent fuel as a "solution" to their spent-fuel problem as is being urged in South Korea today. Also, after about a century, the radiation field around spent fuel declines to a level where it is no longer considered self-protecting and "quick-and-dirty" reprocessing would become easier.

Interim spent-fuel storage facilities and geological repositories should be established in countries willing to host them for a price lower than the cost of reprocessing and national disposal of the associated reprocessing wastes. This puts quite a high ceiling on the price and, given the minimal risks involved from a well-designed spent-fuel storage facilities and repositories, could make hosting them economically attractive. The designs of the spent fuel storage facilities and repositories should be subject to international standards and oversight in order to ensure that the import of spent fuel does not create environmental hazards in countries with less well developed regulatory infrastructures. The repositories should also be designed to be retrievable for a period of a century or so in order to keep options open for alternative disposal strategies.

14.11 Fusion Power[113]

Nuclear fusion may be an alternative to a longer-term commitment to fission energy. In nuclear fusion, energy is produced by fusing together the nuclei of deuterium and tritium, the two heavy isotopes of hydrogen, to form helium and a neutron.[114] Effectively unlimited quantities of the primary fuels, deuterium and lithium (from which tritium is produced), are easily available. (The quantity of uranium is also effectively unlimited, when used in fast breeder reactors.) Due to the low fuel inventory and the high heat capacity of a fusion reactor, an explosive runaway reaction or a meltdown of a fusion energy system are not possible. Radioactive waste products from fusion decay with half-lives of decades. The proliferation risk from fusion is greatly reduced since the introduction of "fertile" materials from which fissile materials such as plutonium could be produced could be made easily detectable in a pure fusion system under safeguards. In a "breakout" scenario, fissile material would not become available until after significant operation of the fusion power plant, and could be prevented by international action.

Current fusion energy research is focused on the confinement of hot ionized gas, called a plasma, in a toroidal (doughnut-shaped) magnetic field. Substantial progress has been made in developing a quantitative understanding of the physical processes that determine the behavior of fusion plasmas. Laboratory experiments have now produced about 10 MW_t of heat from fusion for about one second. The international thermonuclear experimental reactor (ITER) project, under construction in France by a consortium that includes China, Europe, India, Japan, Russia, South Korea, and the United States, is expected to produce 300–500 MW_t of heat from fusion for hundreds of seconds. It is designed to be able to produce about 100 MW_t averaged over a period of weeks.

An alternative route to fusion power production is to heat a small pellet of fuel to high temperature so rapidly that it burns and produces significant fusion energy before it disassembles. The disassembly time is set by the mechanical inertia of the fuel, so this approach is called "inertial fusion energy." It is being pursued today predominantly for its value in providing understanding of the physics of nuclear weapons, but it presents an alternative approach to commercial fusion energy as well. The National Ignition Facility (NIF) has recently begun operation at the Lawrence Livermore National Laboratory in California.

ITER and NIF are fusion research facilities at the scale of fusion power plants. They are first-of-a-kind facilities, and have proven to be expensive, more so than originally planned. Critics of fusion tend to focus on specific technological issues such as the production of tritium fuel or the development of neutron-resistant materials (Moyer, 2010), for which solutions are under development (Hazeltine et al., 2010). There is an appropriate overall concern, however, that fusion power plants will be large and complex high-tech facilities, and as a result their economic practicality cannot be assured despite favorable projections (Maisonnier et al., 2005; Najmabadi et al., 2006). Very considerable R&D is required to move from scientific feasibility to technological feasibility to practical demonstration (FESAC, 2003; US BPO, 2009). In parallel with ITER, supporting research is planned in each of the national fusion R&D programs to facilitate progress toward higher power and continuous operation, and to qualify advanced materials and components to withstand the heat, particle and neutron fluxes from fusion plasmas. Some national programs anticipate demonstration fusion power plants in the 2035–2040 timeframe, with commercialization starting in mid-century.

While fusion will not provide a solution to reducing carbon emissions in the near term, energy needs will continue to grow in the second half of the 21st century, and carbon emissions will need to continue to decline. Fusion energy, if it is indeed developed by mid-century, could in principle obviate the need for reprocessing and fission breeder reactors, which carry with them significant safety and severe proliferation risks.

14.11.1 Resources

The current focus is on producing fusion energy from the two heavy isotopes of hydrogen, deuterium (D) and tritium (T).[115] Tritium is not available in significant quantities in nature, because it has a half-life of only 12.3 years. However the D–T reaction produces a neutron:

$$D + T \rightarrow {}^4He + n + 17.6\ MeV$$

This neutron, multiplied moderately through (n, 2n) reactions with beryllium or lead can be used to produce tritium through the reaction:

$$n + {}^6Li \rightarrow T + {}^4He + 4.8\ MeV$$

Thus the basic fuels for D–T fusion energy are deuterium and lithium-6. Deuterium is present in water at 154 atoms per million hydrogen atoms, and lithium-6 comprises about 7.5% of natural lithium. Other materials used in the construction of fusion systems are not considered to limit the expansion of fusion power.

113 Robert Goldston, Princeton University, USA, lead author.

114 The nucleus of deuterium contains a proton and a neutron and that of tritium a proton and two neutrons, as distinct from an ordinary hydrogen atom, whose nucleus contains no neutrons.

115 The power density achievable for a given plasma pressure is about 35 times higher for the D–T reaction than for any other potential fusion fuel system. This ratio is appropriate for comparison with the D–D reaction, assuming that all T and ^3He produced in the D–D reaction is subsequently burned as well.

Three gigawatt-years (GW-yr) of thermal energy from fusion, including the 4.8 MeV produced in generating the needed tritium, requires the burning of 90 kg of deuterium and 265 kg of lithium-6. Therefore, the natural resources required for a year's operation of a 1 GW_e fusion power plant would be the deuterium in 5000 tonnes of natural water and the lithium-6 in 4 tonnes of natural lithium. Deuterium is already being separated from water on an industrial scale to produce the moderator for heavy-water reactors. Assuming US_{2005}\$300–600/kg for heavy water (Miller, 2001; Ramana, 2007) and ignoring the relatively minor cost of recovering deuterium from heavy water by electrolysis, the cost would be US\$3000/kg of deuterium or US\$0.003/kWh of electric energy generated from fusion, assuming an efficiency of one-third in the conversion of thermal to electrical energy. At the year-2000 price of about US\$20/kg (US_{2005}\$23/kg), world resources of lithium are estimated at more than 12 million tonnes (USGS, 2007; Fasel and Tran, 2005). This corresponds to a cost of about US\$300/kg of lithium-6, which, at that price, would contribute only about 0.001¢/kWh to the price of fusion-generated electricity. Increasing lithium-6 enrichment to the levels proposed for fusion reactors (up to ~80%) would cost approximately US_{2005}\$3000/kg of lithium-6, or 0.01¢/kWh (Rhinehammer and Wittenberg, 1978).

Lithium reserves of 12 million tonnes would allow the full-power operation of 2000 1- GW_e power plants for 1500 years. It should be economically possible to extract an additional 200 billion tonnes of lithium from seawater for this purpose.[116] The reserves of deuterium in seawater are effectively unlimited.

14.11.2 Technologies

14.11.2.1 Magnetic confinement fusion

The primary approach to developing fusion energy is to use strong magnetic fields to confine a very hot, circa 100 million °C, ionized deuterium–tritium gas, or plasma. Ions and electrons spiral along magnetic fields and magnetic field lines can be contained within a closed volume, specifically, a torus. The hot plasma can therefore be suspended in a vacuum while it is at fusion temperature. The main toroidal magnetic field (i.e., going around the torus the long way) is provided by toroidal field (TF) coils (see Figure 14.20). Shielding these coils from the fusion neutrons are the first-wall components that face the hot plasma and lithium-bearing blankets in which the neutrons are absorbed and the tritium fuel is produced. Some of the heat energy from the plasma flows in the form of energetic ions, directed by magnetic field lines into localized "divertor" regions at the top and/or bottom of the vacuum chamber.

The overall D-shaped cross-section of the plasma is produced by the interplay between the magnetic field produced by a strong electrical current that flows within the plasma around the torus (in the tokamak configuration shown in Figure 14.20) and the magnetic fields produced by currents flowing in poloidal field coils. (These coils produce magnetic fields with no component in the toroidal direction; their fields face only the short way around the torus.) The toroidal current is initiated by a pulsed central solenoidal magnet that creates a toroidally directed electric field and is sustained by external means such as radio-frequency waves. D–T fuel is injected through ports in the form of frozen pellets. Coolant is supplied and tritium is removed through pipes connected to the blankets.

14.11.2.2 Inertial confinement fusion

An inertial fusion energy system would consist of four major components:

- A large laser, ion beam, or other means to provide megajoules (1 megajoule = 1 MW-s) of energy to a millimeter-sized target in about 10 ns, in order to compress and heat the fusion target to high temperature before it disassembles.
- A factory to produce precision cryogenic D–T targets at low cost, at a rate of 5–15 per second.
- A system to inject a new target accurately and rapidly into the target chamber 70–200 ms after each explosion.
- A target chamber capable of withstanding repetitive explosions (and being cleared rapidly thereafter), converting the fusion power to heat, and with a lithium blanket to capture the neutrons and produce replacement tritium.

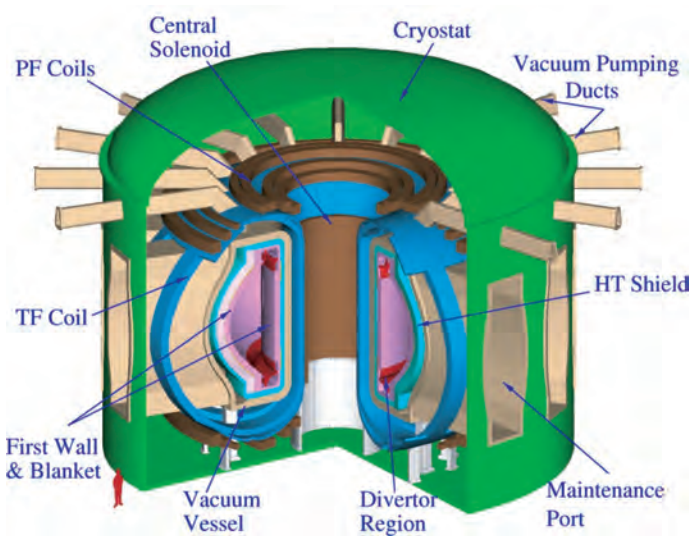

Figure 14.20 | Schematic of the ARIES Advanced Tokamak fusion power core. Source: Najmabadi et al., 2006.

116 Seawater contains 0.18 ppm lithium by weight; the concentration of uranium by weight is 56 times lower, while the requirement for power production in LWRs is 50 times higher.

14.11.3 Comparison of Fusion and Fission Power

14.11.3.1 Safety

A magnetic fusion reactor cannot undergo the equivalent of a prompt criticality accident, such as occurred at Chernobyl. The time constant for a thermal excursion is set at about 5 s by the ratio of the heat content of the fuel to the heating rate of the plasma by the 3.5 MeV helium nuclei from fusion. This time constant is much longer than the approximately10 ms characteristic time constant of a prompt-critical thermal neutron fission reactor. Were the plasma density and fusion rate to rise on this a 5-second scale, the limits to the pressure of the plasma, set by the underlying plasma physics, would rapidly extinguish the reaction. Most likely, before this occurred the increased heat flux to the plasma-facing components would erode their surfaces with a resulting influx of impurities into the plasma that would also quench the reaction. The most energetic physically possible excursion could damage internal components, but could not massively breach the vessel containing the fuel, as happened at Chernobyl.

Like fission reactors, fusion reactors could have loss-of-coolant or loss-of-coolant-flow accidents. Even after the fusion reaction stopped, the decay heat released by radioactive isotopes created by transmutation of the materials of internal components would continue to heat the reactor's structure. The structure of a fusion reactor is more massive than that of a fission reactor core, however, and with appropriate choice of reactor materials, the radioactive decay heat source would be reduced to the point where, even with no active cooling, the heat could be conducted and radiated away from the hottest components as fast as it was generated without a risk of breaching the vessel containing the fuel (Petti et al., 2006).

Fusion systems have significant radioactive inventories because of the large flux of energetic fusion neutrons through the reactor structure facing the plasma, which transmutes non-radioactive atoms into radioactive species. There is also a significant inventory of tritium within the vacuum vessel. While the physical mechanisms that could massively breach the vessel of a fission system do not exist in a fusion system, it is still important to determine the biological hazard potential of all components of the reactor, and to examine how much radioactivity in the structure could be mobilized and released into the atmosphere if the largest credible leak in the vessel were sustained. Figure 14.21 compares the amount of air that would be required to dilute the amount of tritium in a fusion reactor to permissible concentrations with that required to dilute the amount of radioactive iodine in a fission reactor.

In one study of a hypothetical reactor, designed with a silicon carbide structure to reduce the inventory of long-lived activation products, it was found that the hazard was dominated by tritium absorbed into the surface of the plasma chamber, activation products in the molten lead coolant, and activation products in structural tungsten.[117] If the full

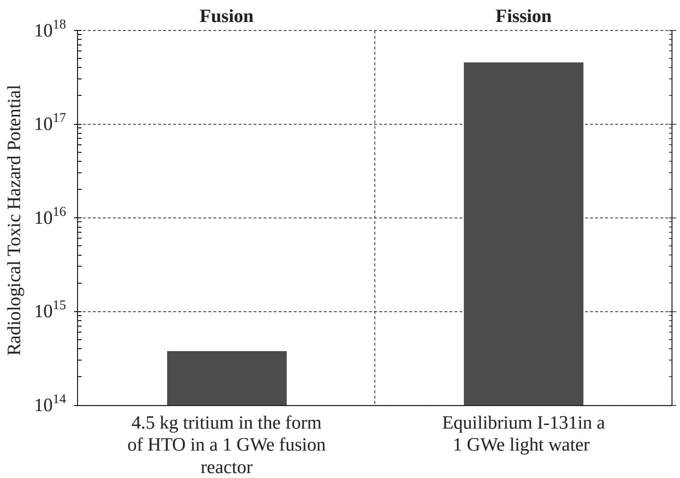

Figure 14.21 | Comparison of biological hazards from potential releases of tritium and iodine-131 from nuclear fusion and fission reactors, respectively, measured in terms of the volume of air required to reduce their concentrations to maximum allowed levels. Source: Kikuchi and Inoue, 2002.

"mobilizable inventory" were released during average weather conditions, doses of more than 1 sievert (Sv) could result at the site boundary 1 km away, and 10 Sv for worst-case meteorology. A dose of a few sieverts within a period of a few weeks could be lethal. Such a release would require a massive breach of the containment vessel, however, which the authors of the study found physically not credible. They found that, for the worst credible leak, the reactor structure and containment building would reduce the releases to a level where the site boundary dose would be below the 0.01 Sv threshold at which evacuation would be required (Petti et al., 2006).

In summary, nuclear fusion has the safety advantages over fission that the primary fission accident initiators of a prompt criticality event (Chernobyl) or meltdown (Three Mile Island, Fukushima-Daichi) are absent. Furthermore, the biological hazard potential of the mobilizable inventory is far below that of a fission reactor. The consequences of an accident are thus reduced to levels dramatically below those of worst-case fission accidents by the choices of structural materials and coolants. Calculations of reductions in releases due to the performance of the reactor containment and other measures below the level required for an evacuation plan would nonetheless likely be controversial and require rigorous regulatory review.

14.11.3.2 Proliferation

The proliferation risk from fusion energy systems is much smaller than that from fission systems because no chain-reacting fissile material

117 The most important neutron-activation products in lead are polonium-210 (138-day half-life) and mercury-203 (47 days). The most important activation products in tungsten are: rhenium-184 (38 days), rhenium-184m (165 days), rhenium-186 (4 days), and rhenium-188 (17 hours); and tungsten-181 (121 days), tungsten-185 (75 days), and tantalum-182 (114 days) and tungsten-187 (24 hours) (Petti et al., 2006).

or fertile material that could be converted to fissile materials by neutron absorption need to be present in a fusion power plant at any time (Glaser and Goldston, 2011b). Thus, while an inspection regime would be required, it would only need to detect the presence or absence of heavy fissile or fertile isotopes.[118] Fairly simple detection schemes could very sensitively detect small quantities of fertile materials or fission products in a fusion system whose neutrons are being used to breed fissile material.

One could be concerned about a "breakout" scenario for fusion, in which a nation expelled IAEA inspectors or unplugged remote monitoring devices and then reconfigured a fusion power system to breed fissile material. There is a very important qualitative difference between fission and pure fusion in the breakout scenario, however. In the fission case, such as occurred in North Korea, the reactor owner already has in hand spent and cooled fuel containing plutonium at the moment that the inspectors are expelled. There is nothing that can be done, short of military invasion, to prevent the separation of this plutonium for use in nuclear weapons. Bombing a fission reactor and its spent fuel storage facilities risks spreading radioactivity, or, if highly controlled, leaves the plutonium available to be mined from the rubble. Neither bombing nor invasion was considered practical in the case of North Korea, nor would they likely be considered practical in many other cases.[119]

By contrast, in the case of a fusion power plant, at the time of "breakout," no fissile material is yet in hand, so the challenge becomes the prevention of the operation of a reconfigured version of the power plant, capable of fissile material production. A fusion power plant could be rendered inoperable quickly and easily by a conventional cruise-missile strike on any of a number of support facilities: cryogenic systems, power conversion systems, or even cooling systems, without risk of a significant release of radioactivity.[120]

A fusion power plant consumes – and so must replace – about 130 kg of tritium per full-power year. Access to grams of tritium to "boost" the yield of nuclear weapons would be harder to prevent if many fusion power systems were in operation around the world. Tritium is not now controlled under the Non-Proliferation Treaty, whose focus is on preventing the diversion of fissile materials for use in weapons. Consideration should be given to strengthening international controls over tritium (Kalinowski and Colschen, 1995).

One might also be concerned that the science associated with inertial confinement fusion would be proliferated along with inertial fusion energy systems, and that key tests relevant to nuclear weapons could be undertaken on these facilities, as they will be at the NIF in California. Classified radiation-hydrodynamics codes are used to predict the performance of nuclear weapons. Their equivalents in the non-classified world could be calibrated against inertial fusion experiments, and could become widely available. A second concern is that if plutonium or other nuclear materials were used in the target of an inertial fusion R&D facility, critical information could be gained about relevant equations of state. The design of first-generation fission weapons, however, does not require experimentally validated advanced design codes, nor information on the equation of state of materials under such extreme conditions. In principle, these could help in the design of advanced weapons, but further review is required (Goldston and Glaser, 2011a).

Some researchers have considered "hybridizing" fusion and fission; these ideas have recently been reviewed and evaluated (Freidberg and Finck, 2010). In principle, the neutrons from fusion can be used for three purposes related to fission power:

- multiplying the 20-MeV energy output from each fusion reaction by using fusion neutrons to induce fission reactions (200 MeV each) in a sub-critical fission blanket surrounding the fusion system;
- breeding fuel for fission systems by transmuting uranium-238 or thorium-232 to plutonium-239 or uranium-233, respectively; and/or
- using the energetic neutrons from fusion to "burn" plutonium-239 and other transuranics recovered from the reprocessed spent fuel of fission power plants.

The advantages are that the fusion system could operate at lower gain and possibly lower neutron wall loading, and the fission system could operate sub-critically, reducing some of the accident potential compared with fast-neutron breeders. It also appears, however, that fusion-fission reactors would combine the majority of the scientific and technological development issues of the fusion systems with the majority of the proliferation risks of fission systems with reprocessing.

It should be noted that even if fusion comes into large-scale use after mid-century, plutonium and other transuranics will remain from LWRs and will constitute a potential proliferation risk. In case 3, where fusion-fission hybrids are used to burn transuranics, possibly more efficiently than "burner" fast reactors, one would have to balance the diversion

118 Uranium-238 and thorium-232 are both termed fertile isotopes because the addition of a neutron followed by radioactive decay produces artificial chain-reacting or fissile isotopes: plutonium-239 and uranium-233, respectively.

119 Attacks on reactors have happened. Iran and Israel both bombed Iraq's Osiraq reactor, in 1980 and 1981 respectively, while it was under construction, because they thought that Iraq would try to use it or its fuel to make nuclear weapons. Similarly, Iraq repeatedly bombed Iran's Bushehr reactor while it was under construction during the period 1984–88. The Unites States was on the verge of bombing North Korea's power reactor at Yongbyon in 1994 because it was being used to make plutonium, but was deterred in part because of concern about the international reaction to the first attack against an operating reactor and the associated radiation release.

120 See, for example, the layout of the ITER complex, www.iter.org/gallery/com_image_download.

risks from reprocessing this material multiple times as it is consumed, versus those of placing it in monitored underground repositories.

14.11.3.3 Radioactive waste

Fusion radioactive waste, unlike that from fission, does not originate from the burning of the fuel, but rather from neutron irradiation and consequent activation of the structural and blanket materials that face the reacting fuel. In typical designs, the first 20 cm or so of the chamber wall would need to be replaced approximately every four years. Neutron activation products can have half-lives of millennia, just like long-lived transuranic elements and fission products.[121] Power plant studies indicate, however, that structural materials can be selected that reduce the radiological hazard from the fusion reactor waste to as low as one-hundred thousandth that of fission-reactor waste (Fetter, 1987) or even one-millionth, as shown in a more recent Japanese study (Kikuchi and Inoue, 2002; see Figure 14.22). The concentration of the radioactivity would be low enough so that the material could be classified as Class C low-level radioactive waste and shallow burial (less than 30 m deep) would be permitted by US regulatory standards (Henderson et al., 2000; US Federal Code of Regulations, Part 61.7(5)).[122] It has also been proposed that the waste from fusion systems could be stored on site, and/or that a significant fraction could be recycled. Nevertheless, despite the potential for greatly reduced waste production, fusion power could still face significant public concerns about the disposal of its wastes.

14.11.3.4 Cost

At this point in the R&D process, it is difficult to project the costs of constructing and operating a fusion power plant. Based on simple consideration of the mass of the major technical components of a 1- GW_e fusion system relative to that of a fission system, and the complex materials required for some components, it appears unlikely that, without accounting for externalities, electricity produced by fusion systems would be less expensive than that from light-water reactors. Studies of magnetic fusion-power systems have been undertaken in the United States (Najmabadi et al., 2006) and in Europe (Maisonnier et al., 2005). Assuming success with the R&D issues discussed below, they conclude that the cost of electricity from a 1- GW_e magnetic fusion power plant would be in the range of US_{2005}\$0.05–0.13/kWh, for a tenth-of-a-kind power plant. The cost of electricity is estimated to be reduced by 20% for 1.5- GW_e plants, due to economies of scale. These estimates should, however, be treated with extreme caution, due to the distance of extrapolation.

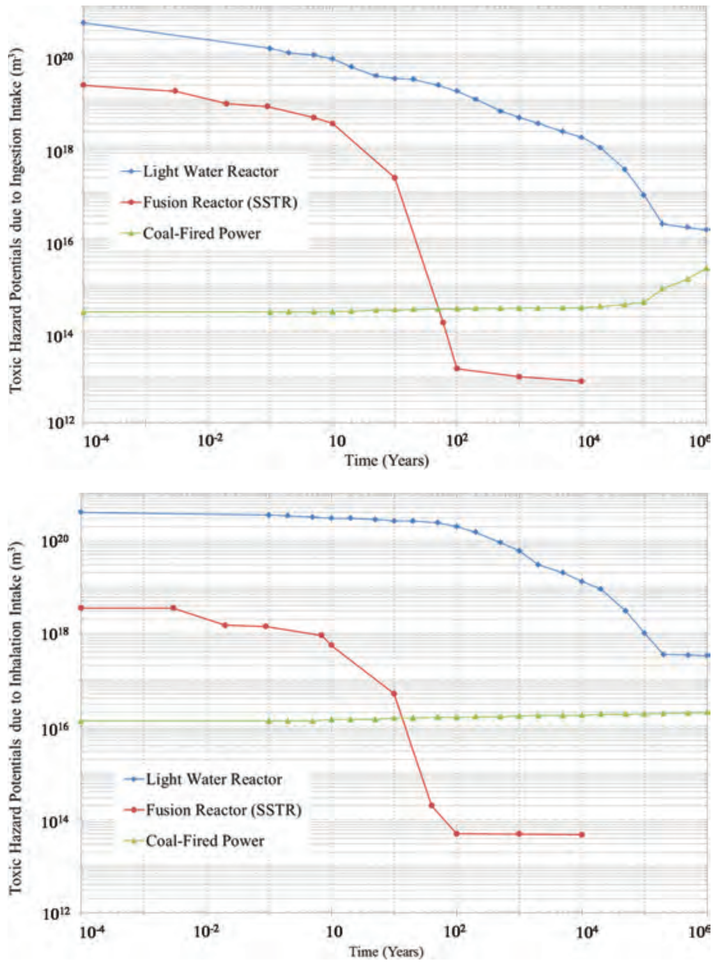

Figure 14.22 | Comparison of radioactivity hazard potential from lifetime operation of fission and fusion reactors. Based on the tritium inventory and the calculated lifetime production of radioactive transmutation products by the Japanese-designed Steady State Tokamak Reactor fusion reactor compared with that of the spent fuel discharged over the lifetime of a light-water reactor, and the uranium and decay products in the ash from a coal-fired power plant accumulated over its operating lifetime. Source: Kikuchi and Inoue, 2002.

Integrated cost projections have not been undertaken recently for inertial fusion energy, but the extrapolation distance to a cost estimate for inertial fusion energy is even greater with respect to the repetition rate of the driver beams, the lifetime required for high-power final optics for systems involving laser-driven pellet implosion, and the required cost reduction for target fabrication.

14.11.4 R&D Status

14.11.4.1 Magnetic confinement fusion

The basic concept behind magnetic fusion is that strong magnetic fields are used to contain a plasma, so that it can be heated to high temperature and can burn in a sustained manner. The two central scientific challenges are:

1. thermally insulating the plasma sufficiently well so that the fusion process itself can provide most of the needed plasma heating,

121 Important long-lived activation products in fusion-reactor studies are: carbon-14 (half-life: 5700 years), aluminum-26 (710,000 years), and three activation products of molybdenum, molybdenum-93 (3500 years), niobium-94 (24,000 years), and technicium-99 (213,000 years) (Henderson et al., 2000).

122 US Code of Federal Regulations, Part 61.55 gives the limits in Ci/m³ for a small number of relevant nuclides for waste to qualify as Class C waste: carbon-14 (8); nickel-59 (220), and niobium-94 (0.2).

allowing a high power gain (energy output divided by energy input) to be sustained; and

2. containing a high enough pressure plasma that it can provide sufficient fusion power density to justify the cost of the magnetic "bottle."

Very substantial scientific progress has been made in addressing both of these challenges. The basic mechanisms that allow heat to escape across magnetic fields have been identified and modeled computationally.

While issues remain for scientific confirmation, the overall experimental picture is consistent with the presence of fine-scale turbulence driven largely by the gradient in the temperature between the center of the hot plasma and its cooler edge. This results in an overall energy confinement time (energy stored in the plasma divided by power required to heat it) that scales consistently across the many experimental devices that have been operated around the world (Figure 14.23). Scaling from these experiments gives a projection that the international ITER project will have a gain of 10, meaning that 10 times more fusion power will be produced than the heat input from microwaves or other inputs from outside of the plasma required to sustain it at fusion temperature. Since 20% of the heat from fusion stays within the plasma in the form of energetic helium nuclei, this means that two-thirds of the power heating the plasma will come from the fusion reactions themselves. Demonstrating this self-sustaining plasma heating is the primary scientific goal of ITER. A magnetic fusion power plant will require a gain of about 25.

Substantial progress has also been made in identifying the limits to the plasma pressure that can be contained in a magnetically confined fusion

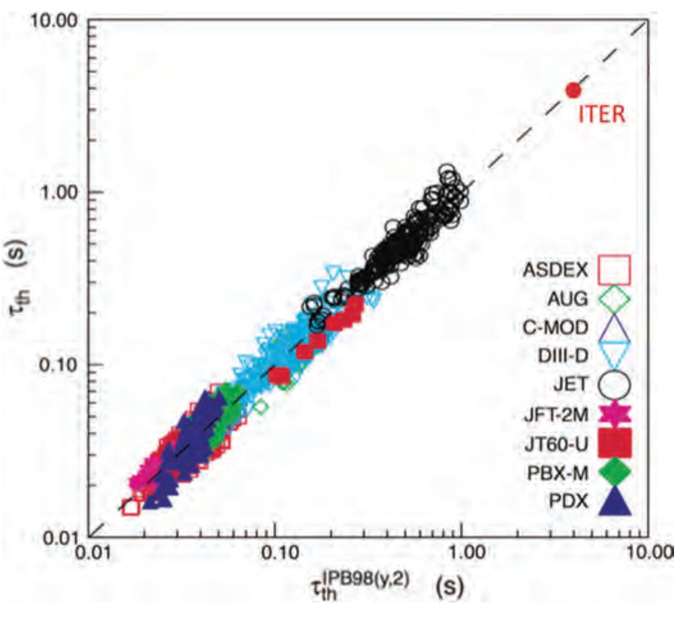

Figure 14.23 | Experimental confinement time of thermal energy vs. regression fit [IPB98(y,2)] to experimental results from nine tokamak experiments world-wide. Source: Shimada, 2000

plasma. Indeed, these pressure limits, as determined by limits of the ratio of plasma kinetic pressure to the pressure of the magnetic field, are now accurately predicted on the basis of theory. Since the fusion rate is approximately proportional to the square of the plasma pressure, this sets the power production capability of fusion systems. ITER is predicted to be able to produce at least 500 MW_t of fusion power. Fusion power production multiplied by the pulse length gives the energy released per pulse from fusion systems. In the 1970s, the toroidal magnetic confinement configuration called the "tokamak" achieved fusion power production of 1/10 of 1 W for one-hundredth of a second. ITER, also configured as a tokamak, is planned to operate for at least 300–500 s at a gain of at least 10, with a goal of effectively steady-state operation at gain of 5. Because ITER will produce significant power levels from fusion for significant periods of time, many of the technologies for ITER are similar to those that would be used in a fusion power plant. Thus the mission of ITER is to "demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes."

14.11.4.2 Inertial confinement fusion

The concept underlying inertial fusion is that a small pellet of D–T fuel is compressed to very high density, but mostly at low temperature. A few percent of the fuel is heated to fusion temperature, however, and, as it burns, it "ignites" a fraction of the remaining fuel, which burns as well, igniting more fuel and ultimately providing adequate gain for net power production. The key recent scientific advances have been in the development of fully three-dimensional codes that can predict the evolution of the fundamentally unstable compression process, as well as the unstable burn process. These calculations define the requirements on the manufacturing precision required for the spherical fusion targets, and on the timing and uniformity of the laser or other beams used to compress and heat the targets. Furthermore, new ideas are being developed on means to heat the "hot spot" that initiates the burn, for example using special very short-pulse lasers (called "fast ignition") or carefully timed shocks. These may allow higher gain or lower laser driver energy for fusion energy systems.

A second issue, particular to inertial fusion driven by lasers, is laser–plasma interaction. The very high power laser light can interact with the plasma it produces in the vicinity of the target, with the result that the laser beam is steered away from the target, and/or energetic electrons are produced that heat the target and impede implosion. This is an active topic of research at the National Ignition Facility.

In inertial fusion, gain is defined as fusion yield divided by the laser light energy input. It is reduced by the relatively low efficiency (~20%) of conversion of laser light to X-rays which actually impinge on the pellet and implode it, in the geometry used at the NIF. To set a clear goal, a US NAS (1997) report defined ignition at the NIF as gain of unity. The total fusion energy released per pulse at the NIF will, at gain of unity, be 1–2 MW-s, 100,000 less than anticipated in ITER. The pulse repetition rate at high gain will be of the order of a few per day, as compared with ~50/day in ITER.

While magnetic fusion needs a gain of about 25 for a practical power plant, the low overall efficiency of the pulsed system in laser-driven inertial fusion requires a gain of about 150. The NIF will perform pellet shots at a rate of a few per day, as compared with a fusion power system that would need to perform shots at a rate of order 5–15 per second. Since the technologies used at the NIF are quite different from those to be used in a fusion power plant, it is viewed as demonstrating the scientific feasibility of inertial fusion, but not its technological feasibility.

14.11.5 R&D Needs

14.11.5.1 Magnetic confinement fusion

The key R&D needs for magnetic fusion (FESAC, 2007) are in support of:

1. higher power gain than ITER (25 versus 10) at higher total power output (~2500 MW_t versus 500 MW_t) in fully continuous operation;
2. efficient techniques to handle the power and ion flux from such a plasma; and
3. efficient techniques to handle the neutron flux from such a plasma while producing the needed tritium fuel.

Major new experimental facilities in China, South Korea, Japan, and Europe are now under construction or are beginning operation to investigate advanced operating modes and plasma configurations to address the first issue. These are superconducting tokamaks and "stellarators," comparable to the size of current experiments, but capable of very long pulse operation. To avoid irradiation problems, these experiments are designed to use hydrogen and deuterium "fuel" for physics studies, not DT for power production. Stellarators are more complex to construct than tokamaks, having a cross-section that rotates and distorts around the torus. They have the advantage, however, that they do not require external energy inputs to sustain internal plasma current and so can operate more efficiently in steady state than tokamaks. Results from these experiments are anticipated in parallel with ITER operations, and ITER itself will explore higher-performance operating modes once its basic goals are achieved.

Figure 14.24 | Laser beam lines at the National Ignition Facility at Livermore National Laboratory, California. Source: FESAC, 2003.

In the Unites States, experiments with D–D fuel are also being considered that could cost-effectively address the issue of how best to handle the power and ion flux from the plasma (OFES, 2009).

The European Union and Japan are working together on the design and engineering validation of a facility to address the issue of qualifying materials to handle the high fluence (time-integrated neutron flux) of very high-energy neutrons from fusion plasmas. This would be based on an intense deuterium ion beam penetrating a liquid lithium target to produce energetic neutrons. Material tests are to be done with displacements per atom and volumetric helium production expected for fusion power plant plasma-facing structures. Promising experimental results have already been achieved with nano-composited ferritic alloys, tested using ion beams to simulate energetic neutrons.

ITER will provide a test bed for tritium breeding modules at relatively low neutron fluence. Integrated testing in a pilot plant or demonstration power reactor would be needed before commercialization could be undertaken.

14.11.5.2 Inertial confinement fusion

The key R&D needs for inertial fusion are:

1. higher gain than the NIF's base mode of operation (150 versus 1);
2. cost-effective, repetitively pulsed driver systems (about 5–15 per second, versus a few per day for the NIF), perhaps using beams of heavy ions that can be produced with smaller energy conversion losses than laser light;
3. cost-effective, very-high-throughput, precision D–T target manufacture;
4. techniques to place targets in the fusion chamber with high accuracy and speed; and
5. target chambers and final beam focusing systems that can handle repeated 400 MJ explosions (the equivalent of 100 kg of TNT) while providing the required precisely controlled environment quickly after each explosion.

The National Ignition Facility itself will likely investigate higher-gain operation, as will a fast ignition experiment, called FIREX, in Japan. The Omega-EP experiment at the University of Rochester in the United States will also study fast ignition. Small efforts are underway in the United States, Japan and Europe to investigate other technological issues, such as the development of ion beams as a more efficient alternative to lasers (allowing lower pellet gain). But the main purpose of the large inertial fusion studies in the United States and France (Laser Mega Joule facility) has been to support nuclear-weapon science.

14.11.6 Possible Deployment Scenarios

Progress toward fusion energy depends on funding as well as scientific and technological success. In the United States, the Magnetic Fusion Engineering Act of 1980 projected a demonstration power plant by 2000, and authorized funding for magnetic fusion of US_{2005}\$34 billion. The actual level of funding appropriated was about one-third of this.

A study was undertaken (FESAC, 2003) to determine the program that would be required to bring on line a fusion demonstration power plant within 35 years. The scientific and technological issues listed above were considered in detail, and it was estimated that the United States could be one of several leaders worldwide in the development of fusion if an investment of about US_{2005}\$27 billion were made over the 35-year period. This would include aggressive R&D in both magnetic and inertial fusion, until a down-selection before construction of major new DT facilities.

If a number of successful demonstration fusion power plants were brought online around the world in the time frame of 2035–2040, one could imagine the commercial construction of fusion power plants beginning in 2050. Whether this is practicable will depend on whether the significant R&D issues discussed above can be resolved. Fission power, during its period of growth in 1975–1990, increased its share of electricity production at a rate of 1.2%/yr. If we posit fusion energy growth at 0.9%/yr of total electricity production, it could achieve about a 30% share of world electricity production by 2100. Assuming world electricity consumption of 12 TW_e in 2100, this would correspond to the construction of an average of 50 1.5- GW_e power plants per year, worldwide.

14.11.7 Policy Recommendations

Fusion is clearly attractive from the points of view of waste, safety and proliferation, particularly when compared with fission based on reprocessing and breeding. At the same time, it should be recognized that success with the technical development of fusion energy is not assured, and that the cost of fusion energy is difficult to project. Each of the major candidates for baseload electric power in the next decades – coal with carbon sequestration, major expansion of fission, and renewables with large-scale energy storage and transportation – faces serious challenges, however. Thus the availability of fusion energy could be important for stabilizing CO_2 levels in the atmosphere as energy demand continues to grow in the latter half of the 21st century (Goldston, 2011).

Further opportunities for international collaboration/coordination should be pursued. As the goal is to determine whether commercialization of fusion can be achieved by mid-century, however, it will be prudent to continue to pursue the development of fusion energy science and technology in the world's domestic fusion programs, in parallel with international participation in the ITER project and other projects, perhaps a neutron irradiation facility.

Taking at face value the development plan articulated in the United States, and perhaps multiplying by four to obtain a global figure, an investment in the range of US\$100 billion over the next 30 years would be required to bring fusion online on the timescale discussed above. This corresponds to a worldwide investment rate of US\$3.3 billion/yr, comparable to the investment rate in fusion R&D in the 1970s. Thus, once ITER construction is well under way, the world level of investment in fusion research will need to approach US\$3 billion/yr to sustain healthy domestic research efforts as well as construct ITER. If the yearly level of investment were to remain at about that level after completion of ITER, this could provide the needed resources for the R&D and demonstration projects needed to support the beginning of the commercialization of fusion by mid-century. Because of the large size of the energy market, investments of this scale in energy R&D can be justified on a purely economic basis (Goldston, 2006).

In the opinion of the present authors, diverting current fusion research towards fission–fusion hybrids could be counter-productive. The destruction of wastes from fission might be an application of fusion energy, but the primary attraction of fusion is its high level of safety, low level of waste, and, especially, its low proliferation risk when compared with fission. A fusion-fission hybrid likely would not have those advantages.

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