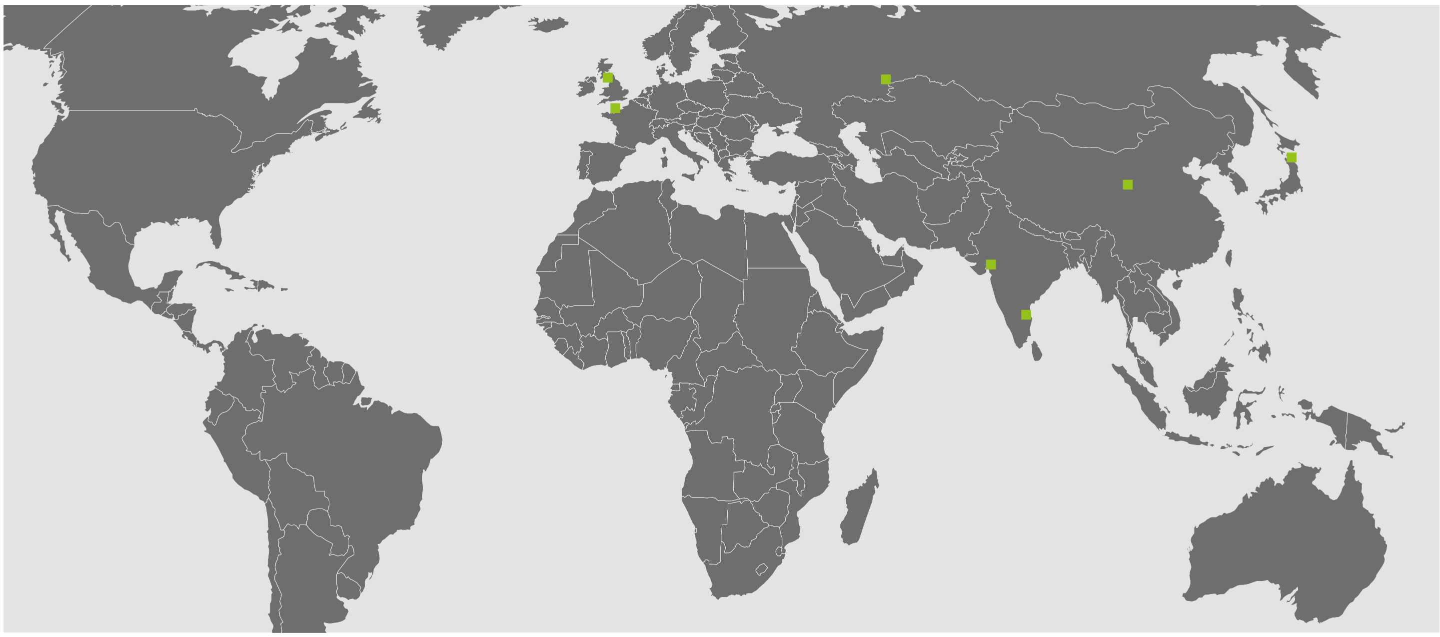

IPFM
INTERNATIONAL PANEL
ON FISSILE MATERIALS

International Panel on Fissile Materials

Plutonium Separation in Nuclear Power Programs

Status, Problems, and Prospects of Civilian Reprocessing Around the World

International Panel on Fissile Materials

Plutonium Separation in Nuclear Power Programs

Status, Problems, and Prospects of Civilian Reprocessing Around the World

This version of the report has been revised on 1 September 2015 correcting the endnote numbering and updating a few web links.

On the cover: the map shows existing plutonium separation (reprocessing) facilities around the world. See Figure 1.5 of this report for more detail

Table of Contents

Country Studies

Technical Background

Tables

Figures

About the IPFM

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

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

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

The panel is co-chaired by Alexander Glaser and Zia Mian of Princeton University and Tatsujiro Suzuki of Nagasaki University, Japan. Its 29 members include nuclear experts from Brazil, Canada, China, France, Germany, India, Iran, Japan, South Korea, Mexico, the Netherlands, Norway, Pakistan, Russia, South Africa, Sweden, the United Kingdom, and the United States. Short biographies of the panel members can be found on the IPFM website, www.fissilematerials.org.

IPFM research and reports are shared with international organizations, national governments and nongovernmental groups. The reports are available on the IPFM website and through the IPFM blog, www.fissilematerials.org/blog.

Princeton University's Program on Science and Global Security provides administrative and research support for the IPFM.

IPFM is supported by grants to Princeton University from the John D. and Catherine T. MacArthur Foundation of Chicago and the Carnegie Corporation of New York.

Summary

Plutonium was first separated by the United States during the Second World War. Uranium was loaded into nuclear reactors, irradiated, cooled, and then chemically "reprocessed" in another facility to recover the plutonium. The reactors and the reprocessing plant were built as part of the secret atomic bomb project. Since then, eight other countries also have produced and separated plutonium for weapons.

Starting in the 1960s, some of the nuclear-weapon states and a few non-weapon states started to separate plutonium for civilian use from spent fuel produced by power reactors. The United States ended its civilian reprocessing program in 1972 and the nuclear-weapon states that are parties to the NPT ended their military reprocessing activities with the end of the Cold War. Today there are only a handful of countries with active civilian reprocessing programs: China, France, India, Japan, Russia and the United Kingdom.

This report looks at the history, current status and prospects of these programs. It also looks at the rise and fall of reprocessing in Germany and the agitation in South Korea for starting a program. There are also three technical chapters at the end assessing: the utility of reprocessing for managing spent nuclear fuel; the economics of reprocessing and plutonium use; and the radiological risk from reprocessing plants.

The original objective of civilian reprocessing was to provide startup fuel for planned "breeder" reactors that would produce more plutonium than they consumed. These plutonium breeder reactors would be much more efficient at utilizing uranium and, throughout the 1960s, the U.S. Atomic Energy Commission promoted them as the solution to concerns that nuclear power would be limited by the availability of low-cost uranium. Large-scale construction of breeder reactors was expected to begin in the 1990s.

In 1974, India, which had acquired reprocessing technology — ostensibly for a breeder reactor program — conducted a "peaceful" nuclear explosion that utilized plutonium produced in a reactor supplied with U.S. heavy water. The U.S. government realized that civilian reprocessing was facilitating nuclear-weapon proliferation and reversed its position on breeder reactors, concluding within a few years that they were unnecessary and uneconomic.

This judgment was borne out during the 1980s and 1990s by experiences with "demonstration" breeder reactors in France, Germany, Japan, Russia and the United Kingdom. The reactors were found to be both more costly than conventional reactors and less reliable, with most operating only a small fraction of the time. Only India and Russia have continued with demonstration breeder reactor programs. Reprocessing continued in France, Japan and the United Kingdom, however, and China built a pilot reprocessing plant that operated briefly in 2010.

In the meantime, much more low-cost uranium was discovered and global nuclear capacity plateaued after the 1986 Chernobyl accident. Uranium only contributes about 2 percent to the cost of electricity from a new nuclear power plant and there is no economic incentive to move to costly breeder reactors, even if they are more uranium-efficient.

France proposed the use of plutonium as supplementary fuel for conventional water-cooled power reactors. Currently fuel made with a mixture of plutonium and uranium oxide (Mixed Oxide or MOX fuel) makes up about 10 percent of the nuclear fuel used by France's power-reactor fleet. A review by France's government in 2000 found that the production of MOX fuel, including the reprocessing of spent fuel to obtain plutonium, cost five times as much as the low-enriched uranium fuel that otherwise would have been used.

For a time, France offset the higher cost of the plutonium fuel by selling reprocessing services to other countries—notably Germany and Japan. The United Kingdom also built a reprocessing plant for foreign customers. But virtually no customers renewed their contracts. As a result, the United Kingdom expects to end its reprocessing program as soon as its existing contracts are fulfilled—around 2020. France is continuing to reprocess for the time being, but its government-owned utility, Électicité de France, has been demanding cost reductions and this has made more gloomy the financial prospects of AREVA, the government-owned company that operates France's reprocessing plant.

Japan, the only non-weapon state that reprocesses today, has built a large reprocessing plant at Rokkasho whose operation has been delayed two decades by various technical problems. It has become hugely costly and, if it operates, is expected to increase the electricity bills of Japan's ratepayers by about $100 billion over the next 40 years. Japan's government insists that the program must continue because the pools at some of its nuclear power plants cannot hold much more spent fuel. It maintains that the prefectures that host Japan's nuclear power plants will not allow on-site dry-cask storage, which has become the standard form of supplementary storage at nuclear power plants in the United States and many other countries. The Rokkasho reprocessing plant therefore is seen as the only available destination for its spent fuel. (Aomori Prefecture, which hosts Japan's new reprocessing plant, also hosts a large empty dry-cask storage facility but says that it will not allow the use of the facility until the reprocessing plant has gone into operation.) South Korea, which does not currently reprocess, made a similar argument for its need to reprocess in its negotiation of a new agreement on nuclear cooperation with the United States but, unlike the 1980s U.S.-Japan agreement, the new U.S.-South Korea agreement does not include U.S. "prior consent" to reprocessing.

In recent decades, an additional rationale has been offered for reprocessing: that it would facilitate spent-fuel management. The argument is that plutonium and the other transuranic elements in spent fuel should be fissioned into mostly shorter half-life radioisotopes to reduce the long-term hazard from spent fuel. The reactors being proposed are modified versions of the costly and unreliable sodium-cooled reactors that previously were proposed for plutonium breeding because they would efficiently fission all these isotopes—not just some, as water-cooled reactors do. This argument for continued reprocessing has been challenged, however, by radioactive waste experts in France and Japan and by a comprehensive study by the U.S. National Academy of Sciences. A risk assessment for Sweden's proposed spent fuel repository found that the radioactive doses on the surface from hypothetical leakage 100,000 years after burial would not be dominated by plutonium because transuranic elements are relatively insoluble in water that is found deep underground where the water's oxygen content is depleted due to chemical reactions with the surrounding rock.

Reprocessing, in fact, *increases* rather than reduces the risk from the radioactivity contained in spent fuel because of routine releases to the environment during reprocessing and the possibility of potentially catastrophic releases from reprocessing plants as a result of accidents or attacks on their huge spent fuel intake pools or the tanks in which the liquid high-level waste from reprocessing is stored. Reprocessing also leaves two costly and dangerous legacies: reprocessing complexes that are contaminated with radioactive materials, and a steady build-up of a global stockpile of separated civilian plutonium that is currently estimated as being sufficient for more than 30,000 nuclear bombs.

As all these problems with reprocessing have become more widely appreciated, there has been a steady decline in the number of countries that reprocess—currently six—and this trend is likely to continue. The decline has not been as rapid as warranted by the magnitude of the problems confronting reprocessing because of resistance from entrenched bureaucracies that have sought to sustain national commitments to separating plutonium and, often, breeder reactors. Nevertheless, as this global overview of reprocessing shows, the world is closer to the end of separating plutonium and the associated security, economic and environmental dangers.

1. Introduction

Reprocessing, that is, the separation of plutonium from irradiated uranium, was developed originally in the United States as a part of its World War II nuclear-weapons program. Some of this plutonium was used on 16 July 1945 in a test explosion in the United States in New Mexico and some in the bomb exploded over Nagasaki in Japan on 9 August 1945. The Soviet Union followed and the two countries built huge plutonium-production complexes to support their Cold War nuclear arms buildups. Britain, France, and China each did the same but on a much smaller scale.

All of the five original nuclear weapon states also eventually built civilian plants to reprocess spent fuel from nuclear power plants to obtain plutonium for startup fuel for an expected new generation of liquid-sodium-cooled "breeder" reactors that would produce more plutonium than they consumed. The four states that subsequently acquired nuclear arsenals, Israel, India, Pakistan and North Korea, also built reprocessing plants to separate plutonium for weapons, and India constructed reprocessing plants to support a breeder reactor development program. Among countries that never acquired their own nuclear weapons, Belgium, Germany, Italy and Japan also constructed reprocessing plants to support breeder reactor programs. Subsequently, they and some additional countries chose to have their spent fuel reprocessed abroad by shipping it to France, Russia and the United Kingdom.

Breeder reactors proved to be uncompetitive with current-generation water-cooled reactors—just as supersonic passenger aircraft proved to be uncompetitive with today's wide-bodied subsonic jets. Over the years, therefore, Belgium, Germany, Italy, and the United States have shut down their reprocessing plants, and the United Kingdom plans to do so. As discussed below, however, France, India, Japan and Russia are, for various reasons, still committed to civilian reprocessing and South Korea has been seeking the right to do so. China's posture with regard to reprocessing is currently ambivalent.

Broadly speaking, the idea that provided the original rationale for reprocessing for civilian nuclear-energy purposes was that the world would soon run short of low-cost uranium. This would be a problem because current-generation reactors are fueled primarily by the chain-reacting isotope uranium-235, which constitutes only 0.7 percent of natural uranium. The advantage of plutonium breeder reactors would be that they would exploit the more abundant uranium-238 isotope (99.3 percent of natural uranium) by converting it into the chain-reacting isotope plutonium-239, thereby increasing the amount of energy that could be extracted from a kilogram of natural uranium by a factor of about a hundred.

A closely related but conceptually separate argument is that the plutonium contained in spent fuel discharged by existing nuclear reactors is valuable because it is potentially useable as fuel; therefore, the argument goes, spent fuel should be reprocessed and the plutonium extracted. Thus, for example, the former head of the Atomic Energy Commission in India maintained that spent fuel should not be considered a waste but "is a resource to extract plutonium from."[1] Likewise, a standard guidebook on nuclear reactors from the 1970s declares: "uranium and plutonium in spent fuel represents a valuable resource for both light water reactors and fast breeder reactors".[2] This idea is often held without consideration of whether the costs of extracting and using the plutonium would exceed the benefits.

This introductory chapter starts with a brief explanation of the technology of reprocessing. Then it discusses why economic considerations do not support breeder reactors. This is why the construction of only a few experimental and "demonstration" breeder reactors have been built, a far cry from the hundreds and later thousands of breeder reactors that had been predicted in the 1970s and earlier. It then turns to the use of separated plutonium in light water reactor spent fuel, which France and Japan resorted to after their programs to commercialize breeder reactors failed. This too has been found to be uneconomic. The relatively new argument, that reprocessing is necessary for radioactive waste management is found to be mistaken too because the benefits of reprocessing for radioactive waste management are small or even negative. Finally, there is a brief overview of the state of the industry and policy in the countries that still practice reprocessing.

Reprocessing technology

Fuel that has been irradiated in nuclear reactors consists mainly of the uranium that has not undergone fission, fission products, the plutonium that has been produced by the absorption of neutrons in uranium-238, and other transuranic elements such as neptunium and americium. Due to its high level of radioactivity, irradiated fuel generates a large amount of heat. It therefore is first stored in water pools at the nuclear power plants for cooling.

In countries that reprocess, spent fuel is then shipped to reprocessing plants. There, after additional storage in intake pools, the fuel rods are in most cases chopped up and their uranium-oxide "meat", which contains the plutonium and the fission products, is dissolved in hot (about 100 ˚C) nitric acid. Most of the cladding is left unreacted and is separately disposed as high active waste. Both chopping and dissolution release radioactive gases.

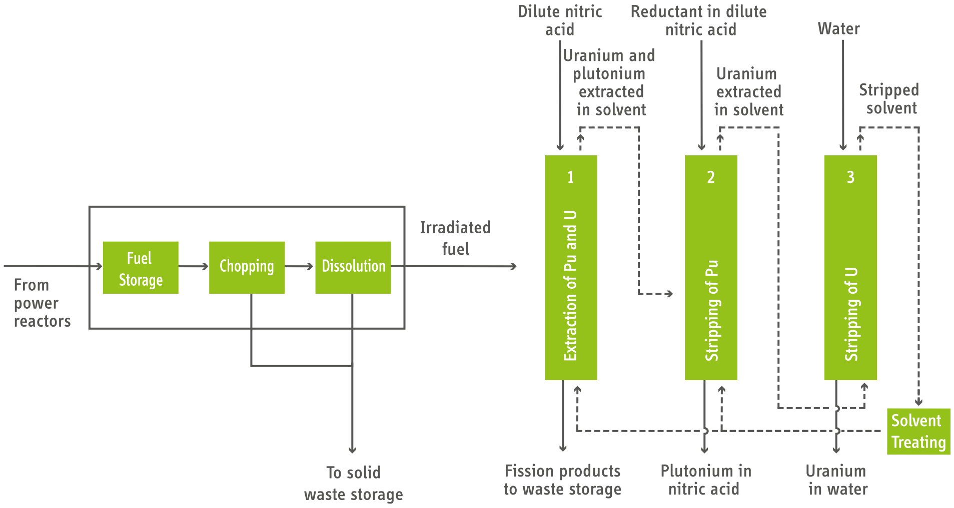

Figure 1.1. The key steps in a basic reprocessing plant. With the current PUREX technology, the spent fuel is chopped into small pieces and dissolved in hot nitric acid. The plutonium is extracted in an organic solvent that is mixed with the nitric acid using blenders and pulse columns, and then separated with centrifuge extractors.

The current standard method of extracting plutonium and uranium from nitric acid solution is called PUREX, an acronym standing for Plutonium and Uranium Recovery by Extraction. The PUREX process separates compounds based on their relative solubility in two different immiscible liquids—aqueous acid solution and an organic solution. The organic solution is tributyl phosphate (TBP) diluted in kerosene. When the two solutions are mixed together, the plutonium and uranium dissolved in the aqueous phase transfer to the organic phase while the fission products and other elements remain in the aqueous phase. If the mixture is then left to settle, the two phases separate out. This process of mixing and settling is repeated multiple times in order to ensure that most of the uranium and plutonium is extracted from the acidic solution. The solutions containing fission-products are radioactive waste (see Figure 3.1).

Plutonium breeder reactors

When the first nuclear power plants were built around 1960, expectations for the future growth of nuclear power were high,[3] while known resources of low-cost uranium were quite limited.[4] The solution suggested by the U.S. atomic-energy establishment — at that time, the world leader — was the construction of plutonium breeder reactors. The ultimate fuel of these reactors would be the isotope uranium-238, which is 140 times more abundant in natural uranium than the chain-reacting isotope uranium-235, whose fissions are the primary source of energy in current power reactors. Another solution that was also explored in the United States and India was to use breeder reactors to convert thorium, which is three times more abundant in the earth's crust than uranium, into the artificial chain-reacting uranium isotope, uranium-233.

Breeder reactors were advocated by leading scientists and engineers in a number of the major industrialized countries. Franz Simon, a British physicist, wrote in 1953:[5]

> "if we had to rely solely on the amount of [uranium-235]…available in the known high-grade ore deposits, large scale power production would not be possible…the real hopes for larger scale power production lie…in the possibility of making use of uranium 238 or of thorium by the process of 'breeding'. While there is yet no absolute certainty that this can be done the probability is nevertheless high."

In the Soviet Union, physicist Aleksandr Ilich Leipunskii made similar arguments and helped launch a plutonium breeder reactor program there that continues in Russia today.[6]

In 1975, International Atomic Energy Agency (IAEA) analysts warned specifically that "the total presently known and estimated resources at < 30$/lb U_3O_8 [$270/kgU in 2014$] will be exhausted by about 2000."[7] The original rationale for the reprocessing plants constructed in the 1960s and 1970s was that the plutonium in the spent fuel of first-generation reactors would be required to fuel the first breeder reactors.

In hindsight, it is clear that the belief that the cost of uranium would skyrocket was wrong. Indeed, even in the late 1970s, at least one leading resource geologist, Kenneth Deffeyes, was arguing that, if one were to mine poorer grades of ore, there would be "approximately a 300-fold increase in the amount of uranium recoverable for each tenfold decrease in ore grade".[8]

Over the decades, the IAEA has become much more sanguine about the uranium supply at current usage rates. Its 2014 "Red Book" on global uranium resources, published jointly with the OECD's Nuclear Energy Agency, states: "If estimates of current rates of uranium consumption in power reactors are used, the identified resource base would be sufficient for over 150 years of reactor supply. Exploitation of the entire conventional resource base would increase this to well over 300 years."[9]

The estimates cited in the IAEA's Red Book series are national estimates that are incomplete. Most countries do not include estimates for uranium with recovery costs greater than $130 per kilogram of uranium.

A recent comprehensive review by environmental engineer Gavin Mudd of global uranium resources comes to an even stronger conclusion that "there is a strong case for the abundance of already known U resources, whether currently reported as formal mineral resources or even more speculative U sources, to meet the foreseeable future of nuclear power".[10]

The range of nuclear-energy futures considered by Mudd includes an International Energy Agency scenario that calls for deploying about 2000 GWe (gigawatt-electric) of nuclear power by 2100, a roughly fivefold increase over 2015, as part of a strategy to limit the concentration of atmospheric CO_2 to below 450 parts per million in order to reduce the likelihood of catastrophic climate change.

One indication that the world is not running out of low-cost uranium is the fact that the price of uranium, corrected for general inflation, has risen and fallen due to temporary imbalances of supply and demand but the long-term trend has not been upward (Figure 1.2). At the long-term average cost of about $100/kg, uranium accounts for only about 2 percent of the cost of power from a new light water reactor in the United States.[11] Most of the cost of nuclear power is due to the capital cost of the nuclear reactor. Thus far, all efforts to reduce the capital costs of liquid-sodium-cooled breeder reactors to levels comparable to those of water-cooled reactors have failed.

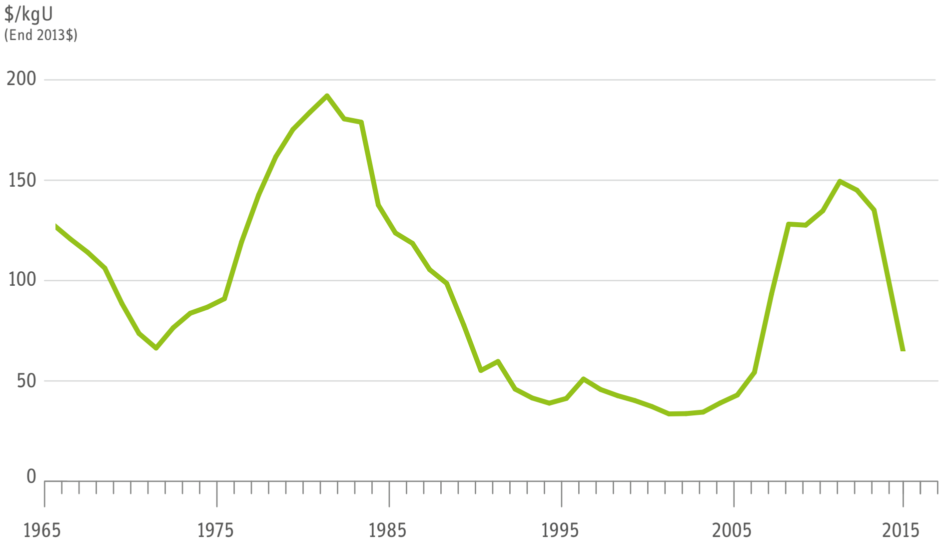

Figure 1.2. Average uranium prices paid by U.S. nuclear utilities, 1965 – 2013. The point for 2014, is the spot-market price, which gives an indication of the direction of the market. Dollar figures from earlier years are converted into 2013 dollars by using the inflator for the U.S. gross domestic product here and elsewhere in this report. For currencies other than dollars, the conversion is first carried out into dollars and then the GDP deflator index is used to convert the amount to present-day dollars. *Sources: For 1965 and 1968 – 1971, Statistical Abstract of the United States 1975, Table 905; for 1975 and 1980, Statistical Abstract of the United States 1991, Table 981; for 1981 – 1993 from the U.S. Energy Information Agency's (US EIA's) Annual Energy Review (2012), Table 9.3; 1994 – 2012 from US EIA Uranium Marketing Annual Report (2012); and, for 2014 spot price, Nuclear Intelligence Weekly, 4 July 2014. Source for GDP deflator index:* research.stlouisfed.org/fred2/series/GDPDEF.

Experience with the breeder reactors that have been built also has shown that most have had persistent reliability problems, primarily because of their use as a coolant of molten sodium, which burns on contact with either air or water.[12] These reliability problems result in breeder reactors operating for a smaller fraction of time, which in turn further increases their capital charges per unit of electricity generated.[13] As a result, forty years after breeder reactors were to have been commercialized, no country has done so and only a few demonstration reactors have been built. Only Russia and India have completed or are constructing new demonstration breeder reactors since 1995.

The failure of programs for large-scale deployment of breeder reactors robbed the current large reprocessing plants in France, Japan and the United Kingdom of their original rationales.

Fuel for light water reactors

France and Japan, however, embarked on programs to use their separated civilian plutonium, mixed with depleted uranium, in mixed oxide (MOX) fuel for use in water-cooled reactors. In MOX fuel, chain-reacting plutonium-239 and plutonium-241 substitute for a similar amount of uranium-235 in low enriched uranium (LEU).[14]

The nuclear properties of plutonium-239 and plutonium-241 are not identical to those of uranium-235, however, and the use of MOX fuel in reactors designed to use low-enriched uranium fuel therefore raises safety issues. The primary concern stems from the fact that the fraction of delayed neutrons released when plutonium-239 fissions is smaller than for uranium-235 fissions. The few tenths of a percent of delayed neutrons provide time for using the movement of neutron absorbing control rods to keep the chain reaction in a reactor's core under control. Because the use of MOX fuel narrows the margin within which such control is possible, most light water reactors are allowed to have only a maximum of a third of their core loaded with MOX fuel.[15]

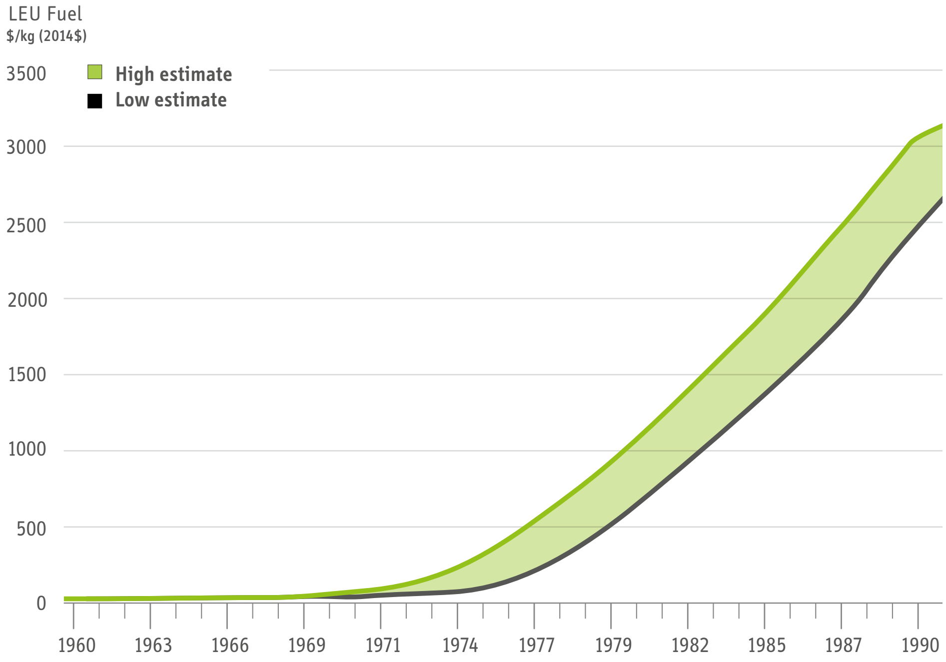

Figure 1.3. Estimated costs for reprocessing. The figure shows estimated costs in constant (2014) dollars of reprocessing in the United States made between 1975 and 1983, and compares these to the cost figure of 2,700–3,200 $/kg-LEU-fuel (2014 dollars) as estimated by the U.S. National Academy of Sciences in 1992 based on data from the United Kingdom and France with financing assumptions appropriate to private industry. *Source: Adapted from Nuclear Wastes: Technologies for Separations and Transmutation, National Academy Press, 1996, p. 117; B. Wolfe and B. Judson, "Fuel Recyle in the U.S. – Significance, Status, Constraints and Prospects," in Proceedings of the Fourth Pacific Basic Nuclear Conference, Canadian Nuclear Association, Toronto, Canada, 1983, pp. 134–38.*

France and a few of its former reprocessing customers in Western Europe are using their separated plutonium in the form of MOX fuel in light water reactors. Japan's utilities planned to do the same but, because of political opposition to MOX at the prefecture level, in ten years of trying before the Fukushima accident, managed to irradiate only 2.5 tons of plutonium out of almost 40 tons of plutonium separated from Japan's spent fuel in Europe.* The United Kingdom has separated over 100 tons of its own plutonium but has yet to use any of it in MOX fuel.

---

* Throughout this report, tons refer to metric tons. One metric ton corresponds to 1000 kg or about 2205 pounds.

France, Japan and the United Kingdom all decided to build reprocessing plants on the basis of cost estimates that were an order of magnitude too low (Figure 1.3). The cost of producing MOX fuel, including the cost of reprocessing LEU fuel to obtain the plutonium, is an order of magnitude higher today than the cost of the equivalent amount of low-enriched uranium fuel.[16] The cost of spent-fuel reprocessing also is about ten times the cost of the alternative option for managing spent fuel, dry-cask spent-fuel storage.[17]

Continued plutonium separation through reprocessing despite the failure of breeder reactor commercialization programs and the poor economics of plutonium use in light water reactor MOX has resulted in a buildup of stocks of separated plutonium. Even in France, despite its technically (if not economically) successful program that fabricates about 10 tons of plutonium a year into MOX fuel, the stock of unirradiated plutonium has been increasing steadily and reached 60 tons at the end of 2013 — up from 30 tons at the end of 1995.[18] In 2012, eighteen years after the end of its breeder program, the United Kingdom finally decided that the appropriate response would be to discontinue reprocessing.

In the mid-1990s, nine countries with different interests in civilian reprocessing programs met to hold discussions on plutonium management.[19] The United States pressed for an agreement to reduce stocks but succeeded only in getting a vague agreement that each of the nine countries "will take into account [along with a long list of other considerations] the importance of balancing supply and demand, including demand for reasonable working stocks for nuclear operations, as soon as practical."[20]

The nine countries also agreed to report their stockpiles of civilian plutonium annually to the IAEA. The United States has not separated civilian plutonium since 1972. The declarations of the other eight — all of which either were reprocessing power reactor fuel or were having it reprocessed in France and the United Kingdom during this period — are plotted in Figure 1.4. It will be seen that the stockpiles owned by the four reprocessing countries: France, Japan, Russia and the United Kingdom have all increased while the stockpiles of the four customer countries shown as "other" (Belgium, Germany, Italy and Switzerland) plateaued and then declined dramatically after they ended their plutonium separation programs and began to work down their backlogs.

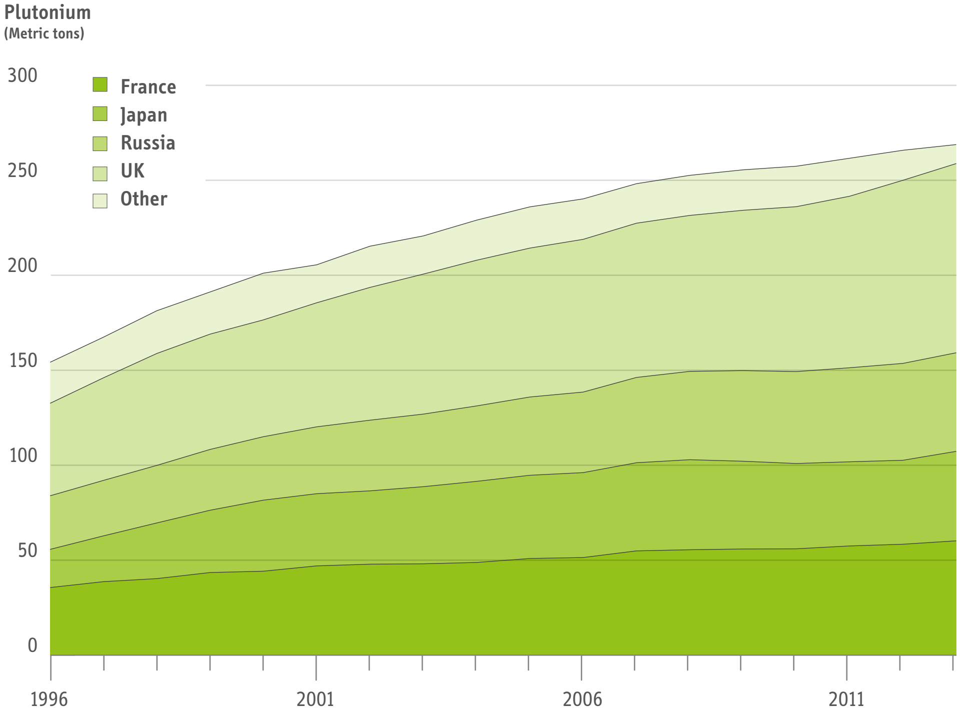

Figure 1.4. Growth of stocks of separated civilian plutonium, 1996 – 2013. These figures are based on annual declarations to the IAEA starting from 1996. The stocks of the "other" (customer) countries — Belgium, Germany, Italy and Switzerland — are held in France and the United Kingdom and are included in "other." China had negligible stocks during this period.[21]

Transmutation

Given the disastrous economics of breeder reactors and plutonium use in light water reactors, the final argument for reprocessing has been that it would be beneficial to separate and eliminate plutonium and other long-lived transuranic isotopes that otherwise would be buried with the spent fuel. Plutonium-239, for example, has a halflife of 24,000 years. Since the slow neutrons in water-cooled reactors are not effective in fissioning all plutonium isotopes,[22] the argument is that it is important to continue to develop and eventually deploy sodium-cooled fast-neutron reactors to "transmute" (fission) the plutonium in spent MOX fuel.[23]

These arguments are misleading. In fact, plutonium is relatively insoluble in water that is found deep underground because the water's oxygen content is depleted due to chemical reactions with the surrounding rock. All calculations that we are aware of indicate that it is the long-lived fission and activation products in the spent fuel that will dominate the doses from any leakage from the repository that reaches the surface.

At the same time, the gaseous fission products routinely released by reprocessing plants as well as possible large releases from explosions in liquid high-level waste tanks or evaporators could result in far higher population doses than any future leakage from deep repositories. A comprehensive U.S. National Academy review of a proposal to revive reprocessing and sodium-cooled fast reactor programs in the United States to reduce the quantities of plutonium and other transuranic elements requiring deep burial, concluded in 1996 that "none of the dose reductions seems large enough to warrant the expense and additional operational risk of transmutation."[24]

Implications of reprocessing for international security

The most important reason to be concerned about the practice of reprocessing is that plutonium can be used to make weapons. Barring plutonium that contains more than 80 percent of the rare isotope, plutonium-238, just about any other mix of plutonium isotopes is considered weapon usable. Some make the distinction between "weapon-grade" plutonium that contains more than 90 percent of plutonium-239, and "reactor -grade" plutonium that has larger fractions of the higher isotopes of plutonium. A commonly cited problem with the use of reactor-grade plutonium is the increased likelihood of a "fizzle" of a Nagasaki-type weapon design where a premature initiation of the fission chain reaction by neutrons emitted by fissioning of plutonium-240 leads to pre-detonation of the weapon and an explosive yield only a few percent of the design value. U.S. nuclear-weapon designers have stated:[25]

> "At the lowest level of sophistication, a potential proliferating state or sub-national group using designs and technologies no more sophisticated than those used in first-generation nuclear weapons could build a nuclear weapon from reactor grade plutonium that would have an assured, reliable yield of one or a few kilotons (and a probable yield significantly higher than that). At the other end of the spectrum, advanced nuclear weapon states such as the United States and Russia, using modern designs, could produce weapons from reactor grade plutonium having reliable explosive yields, weight, and other characteristics generally comparable to those of weapons made from weapons-grade plutonium."

The International Atomic Energy Agency assumes that 8 kilograms of plutonium would suffice for a first-generation Nagasaki-type nuclear weapon. The 8-kilogram number takes into account inevitable losses during the production of a first weapon. Using this yardstick, more than 30,000 warheads could be produced from the stocks of separated civilian plutonium shown in Figure 1.4. More than twice as many could be made if advanced nuclear warhead designs were used.

Historically, the connection between civilian reprocessing and international security became a widely-shared concern after India carried out a "peaceful nuclear explosion" in 1974. India had primarily justified its separation of plutonium as being necessary for its breeder-reactor development program. The United States, which had been promoting reprocessing and breeder reactors through the 1960s and had provided India with Atoms for Peace Program assistance, was especially shocked. The Ford Administration (1974 – 1977) and then the Carter Administration (1977 – 1981) requested reviews of whether or not breeder reactors and reprocessing really were essential to the future of nuclear power. After studying these reviews, the Carter Administration decided to suspend the licensing of a large commercial reprocessing plant that was under construction in Barnwell, South Carolina and the construction of a demonstration breeder reactor near Oak Ridge, Tennessee.

When it took office in 1981, the Reagan Administration (1981–1989) reversed those decisions. It also made clear, however, that it would not subsidize reprocessing. In 1982, U.S. nuclear utilities concluded that direct disposal of spent fuel would be much less costly than reprocessing and persuaded the federal government to take responsibility for the siting and construction of a deep underground spent fuel repository in exchange for a fee of 0.1 cents per nuclear kilowatt-hour.[26] Since that time, the U.S. government has worked to discourage additional countries from launching civilian reprocessing programs. For most of this period, its argument has been, in essence, "we don't reprocess, you don't need to either."[27] That policy has reinforced the economic arguments against reprocessing. No new country has begun reprocessing and, as already noted, three countries have stopped and a fourth (the United Kingdom) has decided to do so.

Reprocessing today

Ten countries have built civilian reprocessing plants and a further ten have shipped their spent fuel to another country and had it separated (Table 1.1).

Country	Facility	Design capacity (metric tonsU/yr)	Years of operation
Belgium	Eurochemic	30	1966–75
China	Jiuquan pilot plant	50	2010–
France	UP1 UP2 UP3	400 1000 1000	1958–97 1966– 1989–
Germany	WAK	35	1971–90
India (heavy water reactors [HWRs])	Tarapur I Tarapur II Kalpakkam	100 100 100	1982– 2011– 1996–
Italy (research & HWR)	EUREX	Pilot plant	1970–83
Japan	Tokai Rokkasho	200 800	1977–2014 2006–8, 2016 ?–
Soviet Union / Russia	RT1	200–400	1976–
United Kingdom (B204 and B205 for graphite-moderated reactors)	B204 B205 THORP	300 1500 1200	1952–73 1964–2020? 1994–2020?
United States	West Valley	300	1966–72

Table 1.1. Past and current civilian reprocessing plants.[28] All plants reprocessed light water reactor fuel except where indicated. Belgium, Germany, Italy, Japan, the Netherlands, Spain, Sweden, and Switzerland are former customers of France's reprocessing services and United Kingdom. Only the Netherlands has renewed. Armenia, Bulgaria, Czechoslovakia, East Germany, Finland, Hungary and Ukraine are former customers of the reprocessing services provided by Russian/Soviet facilities. Design capacity is also often expressed as tons of heavy metal per year (tHM/y). For natural or low-enriched uranium fuel, the heavy metal refers to the uranium in the original fuel. For MOX fuel, it refers to the plutonium and uranium originally in the fuel.

Of these twenty countries, fewer than half continue to do so to any significant extent. The six countries with currently operating reprocessing plants fall into three broad categories.

The first consists of India and Russia, whose governments continue to support both their reprocessing and breeder reactor R&D programs and are currently reserving their separated plutonium for future use in breeders. India is the only country that is actively expanding its reprocessing capacity, primarily rationalized by plans to construct a growing fleet of breeder reactors that are to be fueled by MOX initially and eventually metallic plutonium. Russia's plans suggest greater uncertainty since it is developing three different fast reactor types (sodium, lead and lead-bismuth cooled) and three different plutonium fuels (MOX and nitride fuel for fast-neutron reactors and MOX for light water reactors). In both countries, breeder reactor plans have been delayed by decades.

France and Japan are in a second category of countries. They continue to be rhetorically committed to large reprocessing programs but neither is currently constructing a breeder reactor or has plans to do so in the foreseeable future. France is using its separated plutonium in light water reactor MOX. Japan has tried to do the same since 2001, but with little success thus far and at enormous current and projected future cost.[29] The Japanese reprocessing program has been substantially delayed by technical problems.[30]

The United Kingdom is in a third category. It has decided to end its reprocessing program when its current reprocessing contracts have been fulfilled (currently estimated for about 2020) and is now focusing on how to dispose of its more than 100 tons of separated civilian plutonium as well as on cleaning up its Sellafield reprocessing site.[31] In 2011, it abandoned a MOX plant constructed at great expense after fabricating MOX fuel containing only about 1 ton of plutonium cumulatively during the previous ten years.[32] Subsequently, the United Kingdom offered for a suitable payment to take ownership of the approximately 20 tons of foreign (mostly Japanese) plutonium it is storing.[33]

And finally there is China, which, despite verbal expressions of interest, appears to be uncertain about reprocessing and breeder reactors. Although China has built a pilot reprocessing plant and an experimental breeder reactor, the first operated only briefly in late 2010 and the second briefly in 2011 and 2014.[34] China's government also has been hesitating since 2007 over a proposal from France's Areva to sell China a large reprocessing plant.

There has been an even greater reduction in the number of countries that exported their spent fuel to other countries for reprocessing.

- The Netherlands is the only West European reprocessing customer country to renew its contract with France for the reprocessing of the spent fuel from its single 500 MWe power reactor. The separated plutonium is to be returned to the Netherlands in MOX fuel for use in that reactor.

- The situation with regard to Russia's reprocessing customers is mixed. During Soviet times, foreign countries and non-Russian republics with first-generation (~400 MWe generating capacity) Soviet-supplied light water reactors shipped their spent fuel to the RT-1 pilot reprocessing plant in the Urals for reprocessing.[35] Countries with second-generation Soviet/Russian-designed light water reactors with approximately 1000 MWe generating capacity contracted to ship their spent fuel to the site of an incomplete reprocessing plant in Zheleznogorsk, Siberia for storage pending a future decision on building a new reprocessing plant at that site.[36]

After the breakup of the Soviet Union, most of Russia's client countries decided to store their spent fuel at home instead of shipping it to Russia. Ukraine made this decision in 2014.[37] China and India do not plan to send to Russia the spent fuel discharged by Russian-designed reactors in those countries. Iran has agreed to ship back to Russia the spent fuel from the Russian-built Bushehr reactor, however, in order to reduce Western concern about the plutonium in the fuel. The contracts for nuclear power plants that Russia is proposing to finance in some other countries also include provisions for spent fuel take-back.[38]

The Soviet Union took ownership of all the plutonium it separated from foreign spent fuel and Russia continues that practice. Russia's reprocessing of foreign spent fuel therefore has not increased the number of countries with access to separated plutonium.

Figure 1.5. Civilian nuclear reprocessing plants around the world. Only Europe and Asia currently have operating plants.

Only one new country has expressed an interest in reprocessing its spent fuel: South Korea. It argued, in the context of its negotiations with the United States on the renewal of their 1974 Agreement of Cooperation on the Civil Uses of Atomic Energy, that the United States should provide South Korea the same prior consent to reprocess spent fuel as Japan received in its 1988 agreement of cooperation with the United States.[39] South Korea's government makes he spent fuel accumulating at its nuclear power plants;[40] an additional erroneous argument offered is that ultimately it will be necessary to fission the plutonium and other transuranics in the spent fuel in order to reduce the area of a geological repository for South Korea's nuclear waste to an acceptable size.[41] The United States held firm, however, against including in the agreement prior consent for reprocessing in South Korea.

Institutional forces

The problems with reprocessing discussed above are not new. Over the decades, there has been increasing appreciation of the dubious nature of the arguments for reprocessing, and a steady decline in the number of countries that reprocess. All indications are that this trend is likely to continue. At the same time, the decline has not been as rapid as warranted by the poor economics and the nuclear-proliferation-related objections to reprocessing. The chapters in this report offer some insight into the institutional forces that have sustained national commitments to separating plutonium and, often, breeder reactors.

In all of the countries that continue with, or are exploring, reprocessing, the government-owned organizations in charge — China National Nuclear Corporation in China, Areva and the Commissariat à l'Energie Atomique in France, the Department of Atomic Energy in India, Japan's Atomic Energy Agency, the Korea Atomic Energy Research Institute, and Russia's Rosatom — exercise powerful influences on national policies. Getting independent voices into the domestic policy debates and obtaining a balanced assessment of the economic, environmental and security problems caused by reprocessing has been a challenge.

While India and Russia have active breeder programs that create a justification for reprocessing, the nuclear establishments in France and Japan still include influential factions that believe that breeder reactors will become economically competitive after 2050 — although with no objective basis apparent for this belief. Japan's "nuclear village" has been particularly obdurate in its insistence that Japan's commitment to reprocessing continue even in in the aftermath of the Fukushima accident, which considerably diminished the future of nuclear power in Japan.[42]

The persistence of civilian reprocessing in nuclear-weapon states reflects in part the strong institutional connections their reprocessing establishments formed within their governments when they were providing plutonium for weapons and the desire of those establishments to continue to have a mission after national requirements for weapons plutonium were fulfilled. The United States is the exception because it decided that reprocessing would be done under private ownership, which ended funding from the U.S. Treasury.[43] The persistence of reprocessing in Japan may also be due in part to interest within Japan's security establishment in maintaining a nuclear-weapon option at a time of rising concern about security threats from China and North Korea.[44] Yet, this overlap between military programs and civilian programs offers one of the most important arguments for the cessation of reprocessing.

In his 1999 book, *Nuclear Entrapment*, political scientist William Walker described the British government's decision to build and operate the costly and inefficient Thermal Oxide Reprocessing Plant at Sellafield despite a "radical change in the market for its products" and the increased realization that direct disposal of spent fuel was more economical.[45] A decade and a half later, the U.K. government has managed to decide to stop reprocessing and its attention has shifted to the disposal of its dangerous legacy of a vast stockpile of separated plutonium and huge cleanup costs. The United Kingdom's shift, although belated, suggests that the combination of economic, environmental, and security related arguments can, over time, overcome institutional resistance. Similar processes are at play in other countries as well. Indeed, as this report shows, the world is getting closer to the end of reprocessing of spent fuel and separating plutonium.

2. China

With ambitious plans for its nuclear energy program before and continuing after the Fukushima nuclear power plant accident in March of 2011, China has become the focus of the hopes of the international nuclear industry. Although China's nuclear industry is relatively young in comparison with other states with major nuclear power programs, nowhere else in the world today are so many nuclear power reactors being built. As of April 2015, China had 26 power reactors in operation with a total power generation capacity of 23 gigawatts (electric, or GWe) and with 22 units under construction (22 GWe).[46] China officially plans its total nuclear capacity to be 58 GWe by 2020,[47] and much more is under consideration for the coming decades.[48]

Officially, at least, China maintains a commitment to reprocessing and plutonium breeder reactors, a policy first announced in the 1980s. According to its proponents, the major benefits of this policy will be full utilization of the energy in China's uranium resources, a drastic reduction in the volume of radioactive waste requiring storage in a deep underground repository, and a path forward for the spent fuel accumulating in China's reactor pools.[49] It appears, however, that these claims are beginning to be challenged within China's nuclear establishment.

In practice, China has very limited experience with reprocessing spent fuel from civilian nuclear power plants. In December 2010, the China National Nuclear Corporation (CNNC) started operating a pilot scale reprocessing facility with a design capacity to process spent fuel containing 50 metric tons of "heavy metal" (uranium and plutonium) per year (50 tHM/year) but operated it for only ten days. Also, although CNNC has been negotiating with France's Areva over the purchase of a commercial reprocessing plant (800 tHM/year), it is not clear that this deal will be supported financially by the central government. In parallel, CNNC also has proposed to build a medium-scale demonstration commercial reprocessing plant (200 tHM/year). This proposal has not been approved by the government either.[50]

Although those involved in reprocessing research & development or associated with the pilot reprocessing plant or with China's former military reprocessing plants still advocate building commercial reprocessing plants as soon as possible, some Chinese nuclear experts have begun to argue that China should rethink its fuel cycle policy.[51] As of the end of 2014, therefore, it was not clear whether or not China would embark on a large-scale reprocessing program. As discussed below, spent fuel storage would be fairly straightforward and relatively low cost in China.[52]

Spent fuel storage

The on-site spent fuel pools at Chinese nuclear power plants built before 2005, were designed to accommodate ten years of spent fuel discharges. Newer plants are usually designed with twenty years of storage capacity. All these capacities can be increased by dense-racking the pools. Only China's second oldest nuclear power plant, at Daya Bay, whose two pressurized water reactors came on line in 1993 and 1994, has shipped spent fuel off-site, mostly since 2003, to the interim storage pool at China's pilot reprocessing plant. That pool currently can store up to 500 tons of spent fuel from nuclear power plants and 50 tons for fuel from other types of reactors. While this pool became full in about 2014, a second pool has been completed at the pilot reprocessing plant with a 760-ton capacity and is awaiting approval for operation. Studies and plans are underway for a still larger interim spent fuel storage facility that would increase the total storage capacity on the site to 3,000 tons. China also is considering dry-cask storage options.[53]

Table 2.1 shows the spent fuel stored at China's reactor sites as of the end of 2010. In total, China's nuclear power plants had generated 3011 (metric) tons of spent fuel of which 2477 tons were in on-site storage pools, while an additional 211 tons of spent fuel from two heavy water reactors (Qinshan III-1 and III-2) were in on-site dry-cask storage. The remaining light water reactor fuel has been transported to the pilot reprocessing plant.

Reactor	First grid connection	On-site spent fuel storage capacity (tons heavy metal)	In storage as of the end of 2010 (tons heavy metal)	Storage expected to reach capacity
Qinshan I-1	1991	344 (DP)	138	2025
Daya Bay 1	1993	319	233	2003
Daya Bay 2	1994	319	204	2004
Qinshan II-1	2002	317 (DP)	114	2022
Qinshan II-2	2004	317(DP)	98	2024
Lingao1	2002	554 (DP)	169	2022
Lingao2	2002	554 (DP)	180	2022
Qinshan III-1	2002	960 (incl. DS)	615	2042
Qinshan III-2	2003	960 (incl. DS)	596	2043
Tianwan 1	2006	325	65	2026
Tianwan 2	2007	325	65	2027
Qinshan II-3	2010	317	0	2030
Lingao 3	2010	554	0	2030
Lingao 4	2011	554	0	2031
Qinshan II-4	2011	317	0	2032
Total		**7,036**	**2,477**	

Table 2.1. Spent fuel stored at China's nuclear power plants, 2010. Note that DP stands for dense-packed and DS stands for dry storage. *Source: China's Second National Report under the Spent Fuel and Radioactive Waste Management Safety Convention (Chinese), 2011*

With the exception of Daya Bay, the pre-2005 light water reactor pools have been reracked (dense-packed) to increase the amount of spent fuel that they can hold. On-site dry storage has only been introduced at the Qinshan Phase III plant (two CANDU reactors) due to the fact that they discharge about seven times as much spent fuel per GWt-day heat energy output because the amount of energy released by each kilogram of natural uranium in these reactors is about one seventh that released by the low-enriched uranium fuel used by light water reactors. China has no plans to reprocess heavy water reactor spent fuel. The plan is to construct, within the nuclear power plant site, eighteen Macstor-400 concrete storage modules at a rate of two modules every 5 years (Figure 2.1).[54]

Figure 2.1. Macstor-400 Dry Cask Spent Fuel Storage at Qinshan III NPP. The black squares are vents for convective circulation of air. *Source: Beijing Starbecs Engineering Management Co.*

One major motivation for reprocessing is to provide an off-site destination for spent fuel accumulating at the reactor sites. As shown in Figure 2.2, with the 760-ton pool at the pilot reprocessing plant, China will not need additional spent fuel storage capacity until around 2027, and if an additional 3000 tons of storage capacity is built before 2027, it would not need additional spent fuel storage till about 2035.[55] There is plenty of space for additional spent fuel storage around the pilot reprocessing plant, which is located in a low-population area on the edge of the Gobi desert.

China also could mandate that new reactors have larger pools and add on-site, dry-cask storage when the pools are full. In practice, dry cask storage is the safest and most cost-effective approach.[56]

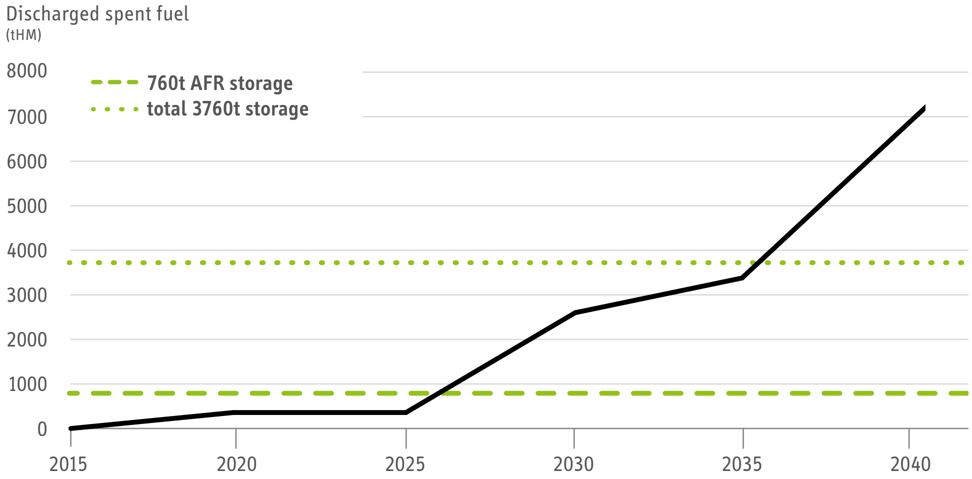

Figure 2.2. Cumulative additional demand for spent fuel storage in China till 2040. This estimate assumes that each reactor has in-plant storage for twenty years of operations, that from 2014 to 2020, PWRs discharge around 20 tons/GWe each year, that this discharge rate goes down to 15 tons/GWe thereafter because of the use of higher-burnup fuel, and that new PWRs are constructed with 20 years storage capacity.

Military reprocessing

Like the other nuclear-weapon states, China started reprocessing to acquire plutonium for nuclear weapons. Beijing decided in 1962 to build first a pilot-scale military reprocessing plant (also referred as the Small Plant or First Project) and a larger military reprocessing plant later (also referred as the Large Plant or Second Project) both at the Jiuquan nuclear complex (plant 404) in Gansu Province. At first, China used a design provided by the Soviet Union.[57] After the Soviet experts were withdrawn from China in 1964, China decided to switch to the PUREX method that had been developed in the United States and described in the open literature. Construction of the pilot reprocessing plant started in 1965 and it began operations in September 1968. The plant had a design capacity of 100 tons per year. When the larger plant began operating in 1970, the pilot plant was shut down. The large plant operated until the mid-1980s. Its capacity has not been publicly reported.

In 1969, Beijing decided to build a second military plutonium reprocessing plant (Plant 821) at Guangyuan in Sichuan province. The plant started operations in 1976 and was shut down around 1990.[58] China's military reprocessing program helped lay the foundation for a civilian spent fuel reprocessing program that was sited next to the large Jiuquan military reprocessing plant and uses some of its facilities (Figure 2.3).

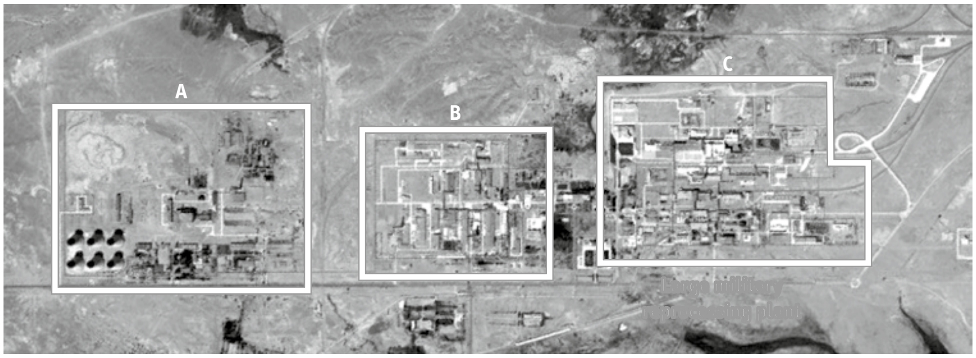

Figure 2.3. Jiuquan nuclear complex. Satellite image from 18 July 2011. Coordinates N 40° 13' 48", E 97° 21' 50". Box A envelopes the shutdown plutonium production reactors; Box B envelopes the small military reprocessing plant; and Box C envelopes the large military reprocessing plant and civilian pilot scale reprocessing plant. *Source: DigitalGlobe and Google Earth*.

Civilian pilot plant

China decided to develop a closed nuclear fuel cycle in the early 1980s. With an anticipated shortage of uranium supplies (in retrospect, because of limited uranium exploration activities), the plan was to extract the plutonium from power reactor spent fuel and use it to fabricate startup fuel for plutonium breeder reactors.[59]

In July 1986, China's State Council approved the construction in the Jiuquan nuclear complex of a pilot civilian reprocessing plant with an annual reprocessing capacity of 50 tons of light water reactor fuel. Research and development on the technology for the plant was carried out by the China Institute of Atomic Energy (CIAE), the Beijing Institute of Nuclear Engineering (BINE), and the staff of the Jiuquan military reprocessing plant. All these organizations are under CNNC. The pilot reprocessing plant was paid for by the government and constructed by CNNC. Its mission is to serve as an experimental base and training center and possibly a template for China's next indigenously designed reprocessing project — the medium scale plant with a capacity of 200 tons/year mentioned above.

The design of the civilian pilot plant was based primarily on experience derived from PUREX hot cell test facilities developed in the 1960s for the military plutonium production program.[60] After a long period of research and design work, construction of the pilot plant started at the Jiuquan plutonium production complex in July 1997. The plant did not incorporate advanced technology for fuel shearing and dissolution of the spent fuel, and plutonium processing. It also lacked automatic controls and remote-repair techniques for use within the radioactive environment inside the operations area.[61] Construction was completed in December 2005. On 21 December 2010, a hot test was conducted that revealed design and safety problems and the plant's reprocessing operations were stopped after 10 days. Further research and design changes are in process.[62] As of the end of February 2015, reprocessing operations had not resumed.[63]

The Jiuquan complex also is the home of a pilot MOX fuel fabrication facility (0.5 tons/year capacity) completed in 2014. Its purpose is to supply fuel for China's Experimental Fast Reactor (CEFR). The CEFR, which reached criticality in July 2010, has an initial core provided by Russia containing about 240 kg of highly enriched uranium (64.4 percent uranium-235).

Plans for commercial reprocessing and breeder reactors

In 2004, China's nuclear-energy policy was changed from "moderate" to "aggressive development" and, in 2008, in its Medium- and Long Term (2006 – 2020) Science and Technology Development Plan, the government listed reprocessing R&D as an important focus with funding of over 7 billion RMB (about $1 billion) for that 15-year period.

Initially, China planned to build a commercial-scale reprocessing plant with a capacity of 800 tons per year by 2020. In November 2007, CNNC signed an agreement with France's Areva for cooperation on spent fuel reprocessing and MOX fuel technologies. In April 2013, CNNC and Areva signed a letter of intent for the purchase of an 800-ton/year capacity reprocessing plant.[64] In October 2013, Areva's executives visited CNNC and discussed details of project siting, safety standards, etc.[65]

Areva's asking price of € 20 billion struck CNNC as too high, however — even with the government offering to pay 80 percent of the cost.[66] There also have been disagreements over other issues including France's requirement that China accept IAEA safeguards in the plant and China's interest in acquiring French military technologies as part of the package. China's planning for breeder reactors with a closed fuel cycle also is incomplete in that it does not include plans to build a facility to reprocess spent fuel discharged from plutonium breeder reactors.[67]

While CNNC was still negotiating with Areva on the commercial plant's purchase, it began to plan a medium-scale plant with a capacity of 200 tons/year for completion around 2020, based on a scale-up of the pilot plant.

Breeder reactors

China's development of plutonium breeder reactors too has fallen behind schedule (Table 2.2). China's fast-neutron-reactor experts proposed a three-stage development plan, starting with the 20 MWe experimental fast-neutron reactor (CEFR) project at the China Institute of Atomic Energy (CIEA) (Table 2.2). However, this proposed timetable (except for the CEFR) will be delayed. The CEFR, designed using technologies developed for Russia's BN-600 reactor, went critical in July 2010 and started supplying up to 40 percent of its full power to the electricity grid by July 2011. However, the reactor was online for only 26 hours during 2011 and produced the equivalent of one full power-hour; it was not connected again during 2012 and 2013.[68] After three years, the CEFR operated at full capacity for 72 hours during 15–18 December 2014.[69] The total elapsed time between approval in 1995 and achieving full capacity in 2014 was about 19 years.

Stage	Reactor type	Power range (MWe)	Commissioning	Fuel type
1	Experimental	20	2010	HEU (first load), MOX
2	Demonstration Commercial	600–900 800–900	2018–2020 2030	MOX Metal alloy
3	Demonstration Commercial	1000–1500 1000–1500	2028 2030–2031	Metal alloy

Table 2.2. China's proposed breeder reactor development schedule, 2010.[70]

The likely reason for the CEFR not operating is a shortage of funding. Funding the pre-operational phase was the responsibility of China's Ministry of Science and Technology. After operations began, however, funding was to be provided by CNNC, which evidently did not supply adequate funding.[71]

According to the pre-2013 plan, during the second stage of China's breeder development program, two demonstration fast reactors (CDFR) were to be built,. In October 2009, CNNC signed a high-level agreement with Russia's government-owned nuclear conglomerate, Rosatom, to jointly construct two copies of Russia's BN-800 fast-neutron reactor in China. The most recently proposed dates for initiating construction on these two reactors were 2013 and 2014.[72] China's government has not officially approved the plan, however. Here too, Chinese experts complain that the price Russia is demanding is too high. Also, CNNC wants the intellectual property rights to the technology, which Russia is unwilling to part with.[73] Currently, it is not clear when — or even if — the project will go forward.

While the negotiations on the purchase of the BN-800s were ongoing, CNNC decided in 2013 to focus on developing an indigenous 600 MWe breeder reactor, the CFR-600. It planned to finish the conceptual and primary process designs in February 2014 and

December 2015 respectively.[74] The CFR-600 is to start construction in 2017 and operate in 2023. However, it too has not yet received government approval.

Before commercializing fast-neutron reactors, China would need to construct the proposed commercial reprocessing plant and a commercial-scale breeder fuel fabrication plant. China is exploring potential partnerships with Areva to develop MOX fuel manufacturing capabilities.[75] According to CNNC nuclear experts, there is no active discussion of using MOX fuel in light water reactors.

Assessing the arguments for reprocessing and breeder reactors

China's reprocessing and fast breeder reactor advocates make many of the same arguments for that as have been made in other countries. Some of these arguments are dealt with in other chapters of this report. Those that involve country-specific information for China are discussed below.

The uranium constraint

One major argument for reprocessing and breeder reactors in China is that China should not become dependent on foreign uranium. This concern will only become serious, however, if China's energy system becomes much more dependent on nuclear energy. Also, China is finding that it has much more domestic uranium than it once thought. After 2004, when China decided to greatly expand its commitment to nuclear power, it increased domestic uranium exploration activities and used more advanced prospecting techniques. As a result, China's uranium reserves increased more than threefold during the following decade. Recent projections by several institutes in China estimate that the country has over 2 million tons of potentially economic uranium resources.[76]

China's annual uranium requirements have been increasing far faster than its domestic production capacity (Table 2.3). Instead of increasing its uranium production more rapidly, China took advantage of low international uranium prices. As Table 2.3 shows, during 2006–2013, China imported a total of 73,000 tons of uranium (73 ktU). This was more than three times the uranium required by its nuclear plants during this period, about 20 ktU. During the same period, domestic production totaled about 10 ktU. The total surplus acquired therefore was about 60 ktU.

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Annual requirement	1,024	1,355	1,130	1,680	1,860	1,860	1,860	2,766	3,067	3,025	4,375
Production	840	840	840	1,040	1,040	1,200	1,200	1,350	1,350	1,450	1,450
Imports				8,000				17,136	16,126	12,908	18,968

Table 2.3. China's annual uranium requirements, production, and imports (tons).[77]

Assuming that China's total nuclear capacity grows to 58 GWe by 2020, and that thereafter total capacity increases linearly to 130 GWe (for a low-growth case) and 400 GWe (high-growth case) in 2050, we estimate that China would require cumulatively 0.5 to 1 million tons of uranium from 2014 through 2050.[78] Even under the high-growth scenario and even if China used only its domestic uranium, however, only roughly half of its currently estimated minimum 2 million tons of uranium resource would be consumed by 2050.

In fact, China's uranium strategy appears to be one of combining domestic production, overseas mining, and imports. China's nuclear industry is purchasing overseas uranium and participating actively in overseas exploration and mining in all the major uranium-producing regions: Africa, Australia, Canada, and Kazakhstan.[79]

In addition, when China purchases foreign reactors, it often requires the foreign vendors to supply fuel. For example, Areva will supply fresh fuel for 15 years for the two EPRs at the Guangdong Taishan NPP,[80] and Westinghouse will supply the first loads for the four AP1000s it has sold to China.[81]

In short, uranium resources should not constrain China's development of nuclear energy for at least the next several decades.

To the extent that China is concerned about potential disruptions of its uranium supply, it could easily and inexpensively establish a strategic uranium stockpile — which is, in fact, under consideration as a national energy project in the 12th five year energy plan.[82] This would be a much less expensive strategy than one based on reprocessing and breeder reactors.

Environmental benefits

Like other countries, China plans to bury its high-level radioactive waste (vitrified HLW and some spent fuel) underground at a depth between 500 and 1000 meters.[83] Reprocessing and breeder reactor advocates in China argue that reprocessing can reduce the volume of high-level radioactive waste twentyfold because the uranium and plutonium that would be recovered and used as fuel constitute 95 percent of the mass of the spent fuel.[84] They advocate the repeated use of separated plutonium in fast breeders, claiming that this would reduce the long-term (10,000 to 100,000 years in the future) radiotoxicity by a factor of about one hundred.[85] They also emphasize that plutonium recycling in PWRs is not effective in accomplishing this goal because light water reactors do not effectively fission the even isotopes of plutonium or the minor transuranics.[86] These issues are discussed in detail in Chapter 10. Here, we briefly discuss the case for the specific site that is being considered by Chinese policy makers.

The Beishan area in Gansu province, near Jiuquan, which is underlain by granite, has been selected as the primary candidate site for the repository.[87] More than 11 deep boreholes have been drilled.[88] The design requirement is that the repository be large enough to store all high level wastes produced by China during the next one to two hundred years.

The Beishan geological repository would be in granite and have basically the same design as Sweden's and Finland's proposed spent fuel repositories. Spent fuel and/or high-level radioactive waste would be buried in copper canisters surrounded by bentonite clay in granite.[89] The area of the repository would be determined by the need to keep the temperature of the bentonite below 100 °C.[90] The thermal performance analysis for Okiluoto shows that, for 50-year spent fuel with average burn-up of 50 MWd/kgU, the maximum temperature at the canister-bentonite interface would occur about 15 years after emplacement.[91]

Reprocessing would increase the capacity of the repository by removing some transuranic elements. The transuranics account for roughly half of the radioactive heat generation from spent fuel at 50 years. Assuming all of the transuranics could be separated from the nuclear waste stream to be buried in the repository, the loading capacity of the repository would go up by approximately a factor of two. In practice, however, reprocessing of the kind carried out in most countries would only separate out plutonium, which means that the increase in loading capacity would be somewhat smaller.

The loading capacity also could be increased by waiting until the spent fuel is one hundred years old before burying it. By that time, 30-year-half-life strontium-90 and cesium-137, which dominate the fission-product heat output at 50 years would have largely decayed away.[92] China therefore could opt for relatively low-cost dry-cask storage for a hundred years instead of an expensive reprocessing plant. Interim dry-cask storage would in any case preserve the option for later reprocessing.

Cost

According to Chinese experts, the initial investment for the Jiuquan pilot civilian plant, which has a 50 ton/year capacity was 1.33 billion RMB, including 17 sub-projects.[93] The funding was provided by the government. In addition, the cost for startup testing has been estimated at 0.5-0.7 billion RMB.[94] Overall, therefore, the reprocessing plant was estimated to cost about 2 billion in 2005 RMB, which is about 2.9 billon in 2014 RMB ($0.68 billion in 2014 dollars using a PPP conversion rate).[95]

China has not provided an official estimate of the cost of a Chinese reprocessing plant with a capacity of 800 tons/year. However, a CNNC nuclear expert who has been working on costing reprocessing facilities used an exponential scaling method to estimate that an 800 tons/year reprocessing plant could cost a minimum of $7.2 billion in 2014.[96] That is dramatically lower than public reports of the price requested by France, reported to be in the range of €20 billion (approximately $20 billion). Some Chinese experts argue that one major reason for the lower price in China would be the low labor cost in China. In practice, experience with reprocessing in other countries and with China's own pilot reprocessing plant has shown that the final real cost could be much higher than the original estimate, due to a number of factors including delay of the project and unexpected and complicated engineering issues. The capital cost of China's pilot reprocessing plant, for example, was originally estimated as several hundred millions RMB. Its final cost in 2005 was about two billion RMB and much more has been invested since then to fix the design.[97]

If the proposed commercial plant used more advanced equipment and technology (either domestic or imported), the capital cost would be significant higher. Even $10 billion, 50 percent of Areva's asking price, would still be much more expensive than dry-cask interim storage. Assuming the proposed 800 tHM/year reprocessing plant has a capital cost of $10 billion and a lifetime of 30 years and using a discount rate of 4 percent and an annual operation and maintenance cost of 6 percent of the capital cost,[98] reprocessing would cost would be about $2000/kg HM excluding interest on the capital investment.[99] Interim dry cask storage of spent fuel for up to 100 years costs about $200/kg HM in the United States, Europe and Japan.[100] This means that building and operating a reprocessing plant with a capacity of 800 tHM/year would cost at least $40 billion more over its 30-year lifetime than simply storing the spent fuel. Given the plan to use the plutonium for breeders, the extra cost for the electricity produced would be still more because the capital cost of breeder reactors is typically more than that of light water reactors.

Nuclear policy-making

Making sense of the diverse developments described above requires a better understanding of the institutional structures involved in nuclear policy making in China. Due to the lack of a lead nuclear-energy development body, China's National Development and Reform Commission (NDRC) typically relies on organizations such as CNNC and Tsinghua University, based on their expertise and qualifications, to propose projects and to demonstrate their feasibility. For example, in the 1980s, the NDRC requested that CNNC propose strategic projects related to pressurized water reactors.[101] After CNNC submitted its proposal, the NDRC organized a panel of academic and industry experts to review it and relied heavily on the panel's findings for its nuclear energy policy proposals to the State Council and other policy makers.

The decision to start the military reprocessing project was based on national security policy. After the economic policy transformation during the 1980s, however, military industries were converted into state-owned and managed enterprises focused mainly on making commercial profits in accordance with the principles of a market-oriented economy.

Although China has a long-term commitment to reprocessing, China's nuclear industry does not have the motivation or financing to implement reprocessing without governmenl support. Reprocessing is technically complicated and requires a large amount of financial support. Currently, CNNC, as the lead for developing the back end of China's fuel cycle, is the major driver for a reprocessing program. CNNC hopes the government will provide most of the funding to build the reprocessing plant and hopes to profit by reprocessing other nuclear utilities' spent fuel as well as its own.

After China committed to large-scale nuclear energy development in 2004, the government realized that it had to plan for spent fuel management. Even though China has been negotiating with Areva on cooperation in spent fuel reprocessing and MOX fuel technologies, however, there has not been any formal decision-making process.[102] Some experts believe changes in national and global security trends or bilateral relationships might force China to move forward and make the decision on CNNC's reprocessing project. For example, China might want to promote its bilateral relationship with France or international developments might make reprocessing relevant to national security. These experts also believe, however, that such a push would only temporarily stimulate the reprocessing industry.

Conclusion

China should learn from the experiences of other countries that have prematurely launched large reprocessing programs in the expectation that the commercialization of breeder reactors would follow. The commercialization of breeders did not follow and the result has been hugely costly programs to clean up the reprocessing sites and to dispose of the separated plutonium.

There is no urgency to go down this risky road. The current generation of light water reactors that China is building can serve it well if the spent fuel is simply stored. The cost of uranium accounts for only a few percent of the cost of nuclear power and will not rise to levels that would justify the cost of reprocessing and breeder reactors anytime in the foreseeable future. China has mastered uranium enrichment and the other technologies required to fuel these reactors. China should focus on assuring that the reactors it is building operate safely and economically. In the meantime, spent fuel can be safely stored at low cost in dry casks while a deep geological repository is being established.

3. France

France is currently the only country in the world that operates a commercial-scale spent fuel reprocessing plant and uses plutonium thus recovered to fabricate plutonium-uranium mixed oxide (MOX) fuel that then is used in light water reactors (LWRs).[103] After close to 40 years of reprocessing of LWR spent fuel and over 25 years of MOX use, this enterprise is about to encounter significant strategic challenges. The reactors currently licensed to use MOX fuel are amongst the oldest in the country and President Hollande's commitment to reduce the nuclear share of France's power production from about three quarters to half by 2025, which passed the first reading in the French National Assembly in October 2014, puts the future of these reactors into question.[104] If all the reactors that are currently loaded or licensed to load MOX fuel were operated until age 40 and were to absorb the entire French plutonium stockpile prior to shutdown, additional plutonium separation should cease by 2018. If the foreign plutonium currently in France were to be used as well, reprocessing should stop by 2016. The potential use of plutonium fuel on a large scale in other types of reactors is decades away. It is urgent, therefore, for France's government to come up with a new spent fuel and plutonium management strategy.

France's current strategy dates from a previous era, when it was assumed that sodium-cooled fast breeder reactors would be commercialized, fueled initially with plutonium separated from LWR spent fuel. When commercialization of breeder reactors failed, the use of plutonium to fuel LWRs was adopted as an interim strategy. It was assumed that breeder reactors would eventually be commercialized and could be started up with the plutonium accumulated in the spent MOX fuel. The commercialization of breeder reactors continues to recede into an uncertain future, however, and plutonium use has not kept up with plutonium separation. With the MOX-fuel-using reactors facing retirement, France may be heading into a cul de sac.

France's plutonium industry — past and present

Reprocessing of power reactor spent fuel at La Hague began at the UP2 facility in 1966. Because it was dual purpose, the original plant was financed equally from the civilian and military budgets of the Atomic Energy Commission (CEA). During the first ten years only gas-graphite reactor fuels were reprocessed. LWR fuel reprocessing started in 1976. The rationale for the separation of civilian plutonium was the expected rapid introduction of plutonium breeder reactors to reduce the uranium requirements of France's growing nuclear energy sector.[105]

But world uranium requirements did not rise as anticipated and the real price of uranium actually declined substantially in subsequent years. Further, the costs of reprocessing and breeder reactors proved to be much higher than expected. Nevertheless, reprocessing remained central to France's spent fuel management. France's highly centralized nuclear decision-making process always guaranteed that democratic debates and parliamentary votes did not interfere with a strategy developed, carried out and supervised by elite technocrats.[106]

There has been discord between the two chief organizations involved in the generation and management of spent fuel, however, namely France's national electric utility, Électricité de France (EDF), and Areva, the operator of the reprocessing plants in La

Hague.[107] Both companies are majority government owned, but have conflicting commercial interests. While EDF, the client, attempts to lower costs, Areva, the service provider, is depending on EDF as the sole remaining major client for its reprocessing services. In December 2008, the two signed a "framework agreement for the recycling of used nuclear fuel from 2008 to 2040." [108] The agreement provided that EDF could increase the annual quantity of spent fuel reprocessed at La Hague from 850 to 1,050 tons per year.[109] It also allowed EDF to increase its MOX fuel purchases correspondingly from 100 to 120 tons per year. A framework agreement is not a binding contract, however, and in January 2010, in the absence of a contract, Areva stopped shipping spent fuel from EDF plants to La Hague. Finally, on 5 February 2010, the two companies released a joint press release announcing that they had "reached an agreement covering the transportation, treatment and recycling of used nuclear fuel, for which a contract will be signed before the end of the first quarter of 2010."[110] In a letter to the author dated 30 March 2011, EDF stated that an "Agreement on Processing-Recycling" had been signed on 12 July 2010. According to EDF, the agreement covered the period 1 January 2008 to the end of 2012, including reprocessing of 850 t/a and MOX fabrication of 100 t/a for 2008 – 2009 and reprocessing of 1,050 t/a and 120 t/a for 2010–2012. Additional contractual conditions allow for the adaptation, "if necessary" of the various quantities to the quantities "effectively recycled."[111] The agreement covered a period of only five years including two previous years covered retroactively.[112]

In January 2014, the conservative daily, *Le Figaro,* reported that, in 2013, Areva's La Hague reprocessing site was audited at the request of EDF, which wished to increase its influence over the management of the site.[113] On 7 May 2014, Luc Oursel, then Areva's CEO, confirmed in front of a National Assembly's Enquiry Committee that a detailed cost audit had been done,[114]

> "which allowed (EDF) to regain confidence [but] we have not yet succeeded to conclude the negotiations between EDF and Areva on the La Hague plant and MOX fabrication… What we will do is that the contract will probably cover a longer period than the preceding contracts in order to avoid to be confronted with deadlines that are too close. It is likely that the reprocessed volumes will be slightly higher. It is obvious that in exchange, EDF will ask for a price slightly lower."

On 1 August 2014, in the press release announcing its half-year results, Areva indicated an increase of its order backlog by €3.5 billion "thanks to the treatment-recycling agreement with EDF".[115] Areva stated that the agreement includes "the shipment and recycling of used fuel and the fabrication of MOX assemblies".[116] The announcement of that commercial agreement, which only extends to 2020, could not cover up the disastrous condition of Areva's overall finances with a €694 million loss for the year. The result was a historic one-day drop of over 20 percent of Areva's share value on the stock market. Areva's share was valued less than 20 percent of what it was at the end of 2007. On 20 November 2014, the credit-rating agency Standard & Poor's (S&P) downgraded Areva's rating to non-investment grade, i.e., "junk" territory, associated with a negative outlook.[117] Areva's 2014 annual results revealed the technical bankruptcy of the world's largest reprocessing company: a loss of €4.8bn ($5.2bn), unprecedented in the nuclear sector, cumulating to almost €8bn ($8.7bn) losses over four years, which is close to Areva's annual turnover of €8.3bn ($9bn). Areva's debt burden has increased to €5.8bn ($6.3bn). The announcement of asset sales and significant job cuts, including 500 at the La Hague facility, did not prevent Standard & Poor's from downgrading Areva another two notches, to BB-.[118]

The downgrade will likely have a significant effect on the costs of Areva's large debt. Lack of financial and economic stability of a company that deals with very large quantities of highly security-sensitive strategic nuclear materials raises serious questions about its long-term reliability.

In France, power reactor spent fuel is cooled in pools on the reactor sites for several years before being shipped by rail to the Valognes station where the 100-ton shipping casks are loaded onto heavy trucks that carry the fuel assemblies 30 km to the La Hague reprocessing plant. There are about 220 spent fuel shipments between the reactor sites and La Hague every year.

As of 2014, EDF did not dense-pack the spent fuel in the storage pools of its reactors. In 2010, however, EDF requested a license to more than double the spent-fuel-storage capacities of the pools of twenty-eight of its thirty-four 900 MWe units, from 382 to 800 fuel assemblies each.[119] EDF justified the request by citing the need of higher burnup and MOX fuels to have longer cooling periods prior to shipment. As of the end of 2014, the safety authorities had denied this request.[120]

After shipment to the reprocessing plant, the spent fuel is stored for an additional period of several years in the cooling ponds at La Hague before being reprocessed and separated into uranium, plutonium, and high level waste (HLW). The HLW contains most of the fission products and the minor transuranics (neptunium, americium and curium). In addition, reprocessing generates a whole range of low- and intermediate-level wastes. The spent fuel pools at La Hague have been dense-packed since a major re-racking was authorized by ASN, France's national nuclear safety authority.[121]

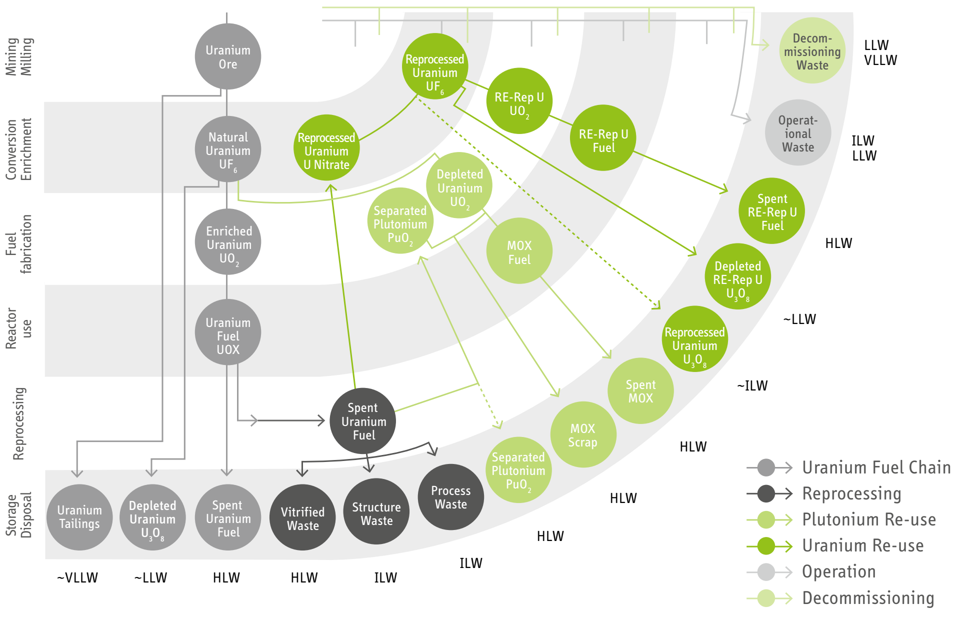

Figure 3.1. Radioactive waste streams generated by France's nuclear industry. *Source: Spent Nuclear Fuel Reprocessing in France (IPFM, 2008).*

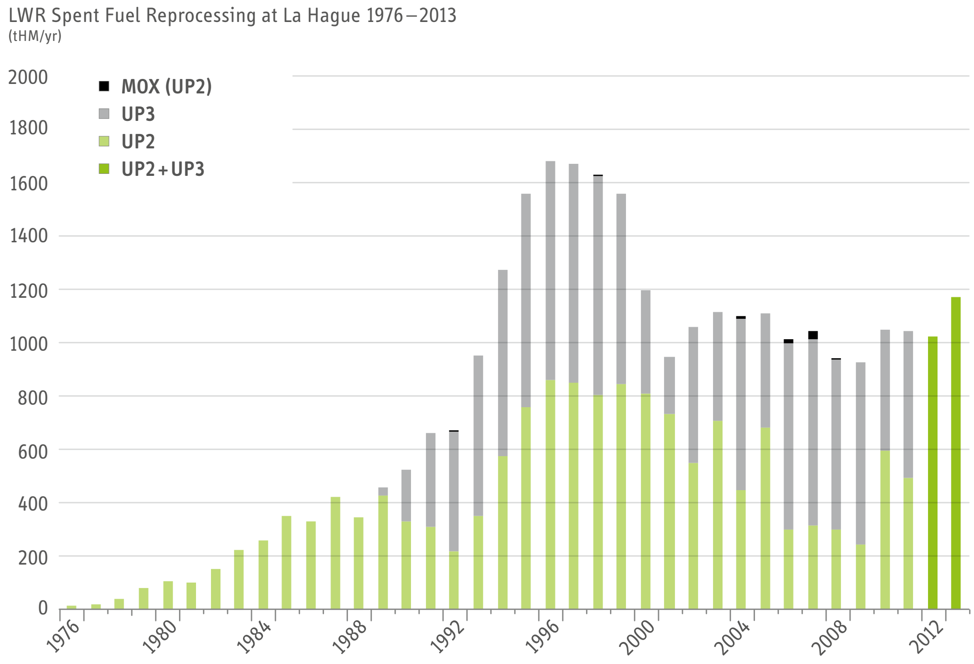
LWR Spent Fuel Reprocessing at La Hague 1976 – 2013
(tHM/yr)

Figure 3.2. LWR Reprocessing at La Hague, 1976 – 2013. UP3 was originally built to reprocess foreign spent fuel. Today, however, virtually all spent fuel being reprocessed is domestic. *Sources: COGEMA, Areva, ASN and others, compiled by Mycle Schneider Consulting.*

Management of Reprocessed Uranium

Most of the uranium recovered during reprocessing, about 1,000 tons per year, is shipped to Areva's Pierrelatte/Tricastin enrichment site in the Rhône valley for conversion from uranium nitrate into stable U_3O_8 for long-term storage. As of the end of 2012, France had almost 26,000 tons of reprocessed uranium stored mostly at Tricastin.[122] In the past, about 300 tons per year (average for 2007 to 2009) were re-enriched in Russia or by URENCO in the Netherlands. The re-enriched uranium was fabricated into approximately 37 tons of new fuel,[123] which was used in two 900 MWe reactors at the Cruas site starting in 1994. The shipments to Russia were halted in 2010 after a public controversy triggered by a 2009 French television documentary about France shipping its radioactive waste to Russia.[124] A new strategy was proposed according to which up to 650 tons of reprocessed uranium would be re-enriched annually and fabricated into approximately 75 tons of fuel to be used in all four Cruas reactors, which had all started running on this basis in 2009.[125] Areva proposed to EDF a long-term framework agreement to develop a conversion-enrichment-fuel-fabrication scheme starting in 2017.[126] That offer was declined by EDF, however, as it was considered "non-competitive" and, since Areva did not wish to make an agreement covering only the period 2013–2017, France's production of re-enriched reprocessed uranium fuel ceased in 2012 until a new arrangement is put in place. Georges Besse II (GB II) the new centrifuge-based plant at Tricastin, can enrich reprocessed uranium but is not expected to do so "for several years".[127] For the near term, therefore, all uranium recovered through reprocessing at La Hague will be stored.

Management of separated plutonium

After reprocessing, separated plutonium is converted to plutonium oxide and stored in a large dedicated onsite bunker at La Hague. On average, two trucks per week (about 100 shipments per year) carry about 100 kg or more of separated plutonium oxide each on a 1,000 kilometer road trip from La Hague in Normandy to Areva's MELOX mixed oxide (MOX) fuel fabrication facility at Marcoule in the South of France.[128] Twenty-four 900 MWe reactors at six nuclear power plants are licensed to be loaded with up to 30 percent MOX fuel in their cores.[129] In 2013, according to the Court of Accounts, just under 120 tons of MOX were loaded into 22 reactors and just over 100 tons of spent MOX were unloaded (see Table 3.1). There are about 50 shipments of fresh MOX per year between Marcoule and nuclear reactors,[130] each shipment containing about 200 kg of plutonium. All these road shipments of weapon-usable materials constitute a significant security challenge.[131]

Year	Low enriched uranium		Reprocessed re-enriched U		MOX	
	Loaded (tHM)	*Unloaded* (tHM)	*Loaded* (tHM)	*Unloaded* (tHM)	*Loaded* (tHM)	*Unloaded* (tHM)
2008	—	1,049	19	16	83	93
2009	1,005	995	52	21	93	80
2010	981	1,030	72	29	113	86
2011	1,022	1,033	70	48	103	90
2012	919	991	74	52	109	98
2013	1,022	954	11	61	120	101

Table 3.1. Fuel loaded and unloaded in French nuclear power plants, 2008 – 2013.
Source: Cour des Comptes, 2014[132]

After several years of cooling on-site, spent MOX fuel is shipped to the La Hague reprocessing plant and stored there. Spent MOX fuel must be cooled at least 24 months prior to shipment compared to 18 months for spent uranium fuel. In practice, it takes about ten years from the unloading of the fuel from the reactor till reprocessing. There is no incentive to use the plutonium from spent MOX fuel in LWRs because it contains a reduced fraction of fissile plutonium-239 and plutonium-241 compared to the plutonium in spent low-enriched uranium fuel. Spent MOX fuel is therefore stored in the pools at La Hague pending the construction of a hypothetical fleet of fast-neutron plutonium breeder reactors in the 2040s or later.

In preparation for that goal, Areva is studying the possibility of constructing a head-end unit for the UP2 line at La Hague that would be capable of dissolving 10-30 tons of MOX fuel per year.[133] According to the National Evaluation Commission of Research and Studies Relative to the Management of Radioactive Materials and Wastes, the UP2 design requires that it operate with a ratio of dissolved plutonium/uranium of less than 2.45 percent and can process spent MOX fuel only if it has a plutonium/uranium ratio of less than 5 percent. Spent MOX fuel therefore has to be dissolved together with uranium fuel.

Over the entire operational period of La Hague, from 1976 to 2013, Areva has reprocessed about 30,000 tons of LWR fuel, including 72.5 tons of MOX fuel (see Figure 3.2). During that same period, EDF has accumulated a backlog of more than 14,000 tons of spent fuel, of which roughly 70 percent (9,759 tons as of the end of 2013) is stored at La Hague. In recent years, the licensed spent fuel storage capacity of the four massive spent-fuel storage pools at La Hague has been increased from 13,600 to 17,600 tons. While comparison of the current stored amount of spent fuel with the nominal licensed capacity seems to indicate that considerable storage capacity remains to be used, the available space in the La Hague pools is severely limited by unused racks for Boiling Water Reactor (BWR) fuel once used for foreign spent fuel, MOX fabrication wastes in various forms, and possibly other unirradiated material, such as an unused core from the abandoned German SNR-300 fast breeder reactor project. The “operational” spent-fuel storage capacity at La Hague therefore could be exhausted within a few years.

The spent-fuel backlog is expected to increase significantly as long as the current generation reactors operate (see Table 3.2, where it is assumed that most of them operate at least until 2030). France's 2006 law on radioactive waste and nuclear materials requires the reprocessing of spent fuel to reuse the uranium and plutonium that it contains.[134] The current design of France's geological repository for long-lived high level wastes assumes that no spent fuel from the current reactors will be disposed of there. In 2005, however, the National Radioactive Waste Management Agency (ANDRA) concluded that direct disposal of spent fuel would be feasible.[135]

	Type of fuel	End of 2010 (tHM)	End of 2020 (tHM)	End of 2030 (tHM)
Fuel in reactor cores	Uranium oxide	4,477	4,340	3,650
	Reprocessed uranium	156	290	290
	MOX	299	490	380
	Subtotal	4,932	4,590	4,320
Spent fuel awaiting reprocessing	Uranium oxide	12,006	11,450	12,400
	Reprocessed uranium	318	1,050	1,750
	MOX	1, 287	2,400	3,800
	Fast Breeder Reactor	104	104	104
	Subtotal	13,715	15,004	18,054
	Total	**18,647**	**19,594**	**22,374**

Table 3.2. Projections of France's spent fuel inventories, 2020 & 2030. *Source: ANDRA, Inventaire National des matières et déchets radioactifs – Rapport de synthèse 2012.*

France has accumulated a large stockpile of unirradiated plutonium (60.2 tons as of the end of 2013) mainly as separated PuO_2 (See Figure 3.3).[136] The stockpile has increased continuously since France began introducing MOX into its LWRs starting in 1987 and it increased by another 1.8 tons in 2013. This increase is partially due to France taking responsibility over time for the disposition of various quantities of formerly foreign plutonium. But the main reason is a steady difference between the quantities of plutonium separated by reprocessing of French spent fuel and the quantities used in MOX fuel fabrication. This continuous increase in stockpiles is contrary to repeated declarations by the government and industry that they follow a policy of balanced production and consumption of plutonium.[137] Sylvain Granger, director of EDF's fuel division, stated in 2005 that "it is a management rule that we fix for ourselves and the inventory of currently separated plutonium is maintained in a stock that corresponds to three years of MOX fuel fabrication, that's all!"[138] Why three years of consumption would be the appropriate "management rule" has never been explained. In any case, the figures don't add up. MELOX now produces annually about 120 tons of MOX for EDF. At an average plutonium content of around 8.5 percent, three years of production would add up to about 30 tons of plutonium, half of the more than 60 tons of unirradiated plutonium in stock as of the end of 2013. The math only works, approximately, if the plutonium contained in unirradiated fuels and wastes is not taken into account.

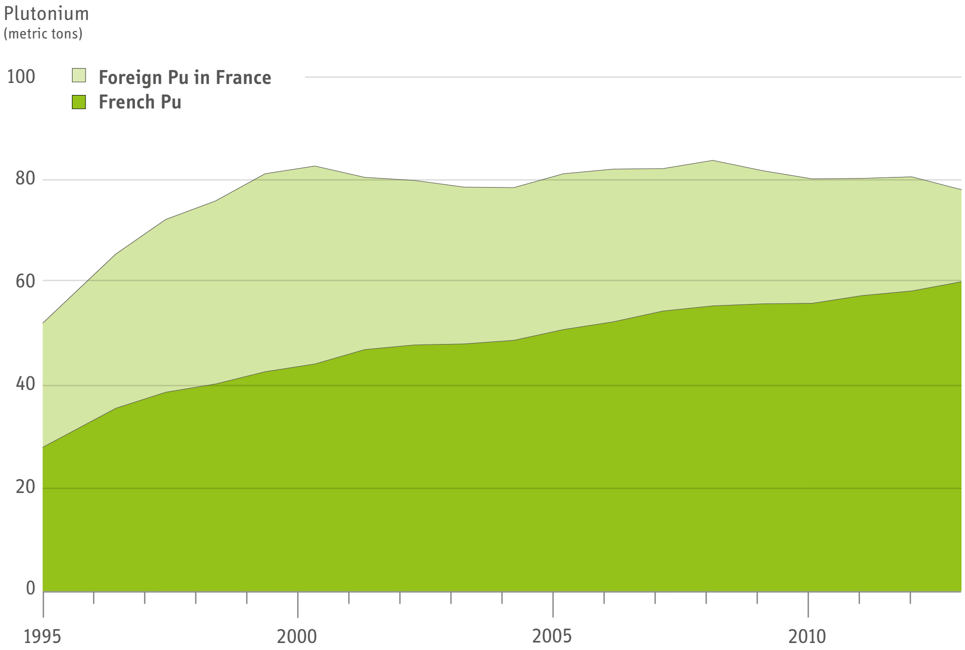

Figure 3.3. Stocks of unirradiated plutonium in France, 1996 – 2013. The foreign stocks have been declining because Belgium, Germany and Switzerland have ended their reprocessing contracts and have used most of their separated plutonium in MOX. Most of the remaining foreign stock belongs to Japan. France's own stockpile of unirradiated plutonium has increased steadily despite an apparently successful MOX program. *Source: IAEA, Communication Received from France Concerning its Policies Regarding the Management of Plutonium, INFCIRC/549/Add5/18, 2014 and previous annual reports.*

France's stock of unirradiated plutonium, as of the end of 2013, included about 39.5 tons at La Hague,[139] including an unknown amount but likely more than 10 tons contained in MOX fuel fabrication wastes,[140] either in powder form, pellets or as assemblies that are stored in the spent fuel pools at La Hague. This material includes:

- A core of unirradiated MOX fuel containing 1.6 tons of plutonium that was produced for Germany's never-operated SNR-300 breeder reactor.[141] It is now in storage at La Hague — probably in exchange for a payment to Areva and an equivalent amount of plutonium in MOX fuel for Germany's light water reactors.[142]
- An unknown amount of plutonium scrap processed into sub-spec MOX as a means of packaging it when Areva's Cadarache MOX fuel fabrication plant was cleaned out.[143]
- An unknown amount of sub-spec MOX from the decommissioning of Belgium's Dessel MOX Fuel Fabrication Plant.[144]
- An unknown amount of plutonium in 14 tons of sub-spec MOX from the decommissioning of Germany's Hanau MOX Fuel Fabrication plant.[145]
- Areva's large Melox MOX fuel fabrication plant also packages scrap MOX into sub-spec MOX fuel for shipment to La Hague. About 5 percent of the plutonium it processes ends up in MOX scrap, whose production has increased as the throughput of the plant has increased.

The updated national inventory of radioactive waste and nuclear materials that ANDRA, France's national agency for radioactive waste management, plans to publish in 2015, will for the first time include a scrap MOX fuel category. According to a preview as of mid-April 2015, ANDRA's estimate of the French scrap MOX fuel inventory as of the end of 2013 amounts to 230 tHM.[146] If this scrap MOX contains on average seven percent plutonium, it would contain about 16 tons of plutonium. France's remaining stock of unirradiated plutonium consisted of:[147]

- 13 tons in the form of fresh MOX at the MELOX plant or at the reactor sites or in the process of fabrication;
- Close to 6 tons in the form of fabricated breeder reactor fuel that was used in the unirradiated second Superphénix breeder-reactor core, which is stored on-site in the spent fuel pool of the shutdown reactor at Creys-Malville;[148]
- 0.6 tons in process at reprocessing plants and estimated amounts of separated plutonium held at research facilities (CEA or universities).

In addition to the 60.2 tons of French unirradiated plutonium, there are 17.9 tons of foreign unirradiated plutonium in France. In its annual INFCIRC/549 declarations to the IAEA, France indicates less than 50 kg of French plutonium as stored in other countries. The lack of comprehensive official data and the inconsistencies between categories found in various governmental and industry sources make a more accurate overview of the French plutonium inventory impossible.

An estimated 290 tons of plutonium has been separated from LWR spent fuel at La Hague between 1976 and the end of 2013.[149] This divides roughly into 190 tons of French plutonium and 100 tons of foreign plutonium. Thus, close to one third of France's separated plutonium and almost one fourth of the foreign plutonium separated in France have not been reused to date. It should also be noted that, as of the end of 2013, close to 270 tons of France's plutonium remains in spent fuel, roughly 190 tons in spent uranium fuel and 80 tons in spent MOX fuel.

Assessment

France's spent fuel management program has resulted in increasing stocks of plutonium in unirradiated form and in spent MOX fuel. The government's decision to reduce the share of nuclear power in the electricity mix from about three quarters to one half will have significant consequences for this program. The twenty-four 900 MWe reactors currently licensed to use plutonium fuels are amongst the oldest of the French fleet.[150] As of early 2015, they had operated for 33 years on average.[151] No other reactor option has been explored for the disposal of separated plutonium and no authorization request has been transmitted by EDF to the regulator for using MOX fuel in France's 1300 MWe reactors or in the 1600 MWe EPR that is under construction at the Flamanville site. It would take years to adapt and relicense 1300 MWe units for MOX use.[152]

France's Commissariat à l'Énergie Atomique (CEA) envisages the construction of a fleet of sodium-cooled reactors that could fission all plutonium isotopes more effectively, but these plans have been regularly postponed and are increasingly questioned. Commercial deployment is currently not foreseen, even by its proponents, significantly before the middle of the century. Under the influence of the CEA, France has decided to develop a new sodium cooled fast breeder reactor prototype called ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration). France's 2006 law on the management of nuclear materials and radioactive waste called for the reactor to start up by 2020 but the project is not on track to meet this deadline. According to the National Evaluation Commission of Research and Studies Relative to the Management of Radioactive Materials and Wastes (CNE), the decision to build ASTRID should be taken soon so that construction of the reactor can be started in 2019 in order to meet a schedule for loading fuel in 2025.[153] However, Areva's director of waste and nuclear material management, Jean-Michel Romary, told a parliamentary committee in January 2014 that the startup of ASTRID "will be rather 2030, and 2040 for the construction of a first of a series of reactors".[154]

CEA, the proposed license-holder, has filed a first document to the French nuclear safety authority (ASN) that gives an initial preview of the reactor's safety features. ASTRID is designated as a Generation IV reactor but ASN Commissioner Philippe Jamet has stated that, "ASN considers that this project [ASTRID], whose safety level does not exceed the one of third generation [light water] reactors, cannot constitute a prototype" of a fourth generation plant.[155] Talks are underway between the CEA and the regulator about possible technical upgrades of the design of ASTRID that would be required for to make it acceptable to ASN.

The connection between reprocessing and Gen IV reactors was highlighted in the National Assembly's 2014 Baupin Report, which states that the "consensus is that the rationale of reprocessing largely depends on the capacity to develop one day a fourth generation of reactors."[156] CEA's General Administrator, Bernard Bigot, told the National Assembly that "the first problem to tackle (…) is the plutonium one: if it is not multi-recycled, the problem remains unresolved."[157]

The Baupin Report states in its recommendations:[158]

> [The Enquiry Commission] "Notes that France does not today have any global in-depth cost-benefit assessment of the backend of the nuclear system (reprocessing, MOX fabrication). Considers that a report by the Court of Accounts on the question would make it possible to inform public authorities on the pertinence of the possible strategies, on the real economic potentials of reusable materials (or the consequences of their potential classification as waste) as well as the options opened up by the potential development of a '4th generation' of reactors."

The Court of Accounts does not rule out including such a study into its upcoming (unpublished) multi-annual program. This could significantly impact the strategy of reprocessing and Gen IV development.

Phasing out reprocessing

The cost of reprocessing of spent fuel and using the recovered plutonium and uranium in new fuels vastly exceeds the uranium cost savings. EDF consequently has allocated a zero book value to its plutonium and reprocessed uranium stocks since 1996 and 1997 respectively.[159] There also are no net environmental benefits from reprocessing. Reprocessing facilities release much more radioactivity to the air and water than light water power reactors and there is no overall net waste management benefit.[160] And, despite plutonium use in MOX fuel, the overall quantity of France's plutonium accumulating in unirradiated form and in spent uranium and MOX fuels, has increased by nine to ten tons per year – not much less than if the spent uranium fuel had simply been stored.

This does not mean that it will be easy to change France's spent-fuel management policy. The commitment to reprocessing in the UK has been described by William Walker as "nuclear entrapment."[161] The Director of EDF's Fuel Division has stated similarly: "Once an industrial policy has been decided, changing it becomes extremely costly."[162] Since there would be significant economic savings from abandoning reprocessing, the "costs" being referred to are primarily political and organizational.

The 2012 pre-electoral agreement between the Socialist Party and the Green Party called for: [163]

> "Reconversion at constant employment level of [France's] reprocessing and MOX fabrication industry as well as the means of storage of different types of waste, in particular the Bure laboratory, into centers of excellence for the processing of waste and decommissioning."

After intervention of the nuclear industry,[164] however, this commitment was watered down with an addendum,[165] which states:

> "It is foreseen in the agreement that the share of nuclear in electricity generation in France will decrease from 75% to 50% by 2025. As a consequence and concomitantly with this reduction, the quantity of fuel for the supply of [nuclear] plants operating on our territory as well as the reprocessing needs for those fuels will continue but will diminish."
>
> "This is why it is foreseen to accompany this progressive evolution by a plan of reconversion allowing to maintain the number of jobs by the implementation of centers of excellence in the processing of wastes and decommissioning."

The idea of converting France's reprocessing and MOX fuel fabrication complex was raised as early as 2001.[166] There are a number of reasons why the issue is more pressing today:

1. The Hollande government has initiated a policy in the new Energy Bill — still in the parliamentary process — of reducing the share of nuclear power in France's electricity generation to about 50 percent by 2025. At a constant level of electricity consumption, this would lead to the shutdown of a significant part of the reactor fleet currently using MOX fuel.
2. There is no guarantee at this point that the nuclear authorities will grant lifetime extensions for the reactors that currently use MOX fuel.[167]
3. There is no longer any operational scheme for the use of reprocessed uranium; and
4. Given that Japan's MOX use program barely moved forward before the 2011 Fukushima accident and has been frozen since, France may have to dispose of the 18 tons of foreign (mostly Japanese) plutonium it is holding in the country.

However, the industry and authorities still fail to take this changing reality into account. The reference scenario used by Areva, which serves as a basis for the projected inventory of nuclear materials elaborated by ANDRA, is still assuming that most of the Japanese plutonium will be sent back by 2020 as MOX fuel.[168]

There are other developments around the world that add to the urgency of finding a path forward to deal with the global stock of separated plutonium. The United Kingdom has accumulated over 120 tons of unirradiated plutonium, including 23 tons of foreign plutonium, as of the end of 2013, because of the failure of its initial strategy of converting foreign plutonium into MOX.[169]

Across the Atlantic, the Obama Administration decided in 2013 that it needs alternative plutonium disposition options to Areva's Savannah River MOX Fuel Fabrication Facility (MFFF). After having spent over $4 billion on building the facility, the U.S.Department of Energy cost estimate for the plant had skyrocketed from $1 billion to over $10 billion and for the total MOX program to over $20 billion.[170] The U.S. government intends to review alternative plutonium disposition options over the coming 12 to 18 months. This could create a powerful dynamic in France, Japan and the United Kingdom to consider possible immobilization and disposal options for their own plutonium.[171]

France's nuclear industry, with the extensive research capacities of the CEA and the industrial capacity of Areva, is well positioned to be a key player in the international effort to bring plutonium immobilization to industrial scale. The future of Areva's industrial capacity is threatened by its dire financial situation and a radical strategic reorientation is indispensable. Beyond plutonium immobilization, Areva's La Hague site and the Marcoule site of France's first reprocessing complex could be turned into centers of excellence for decommissioning and waste management. Both sites already are deeply involved in these areas of activity.

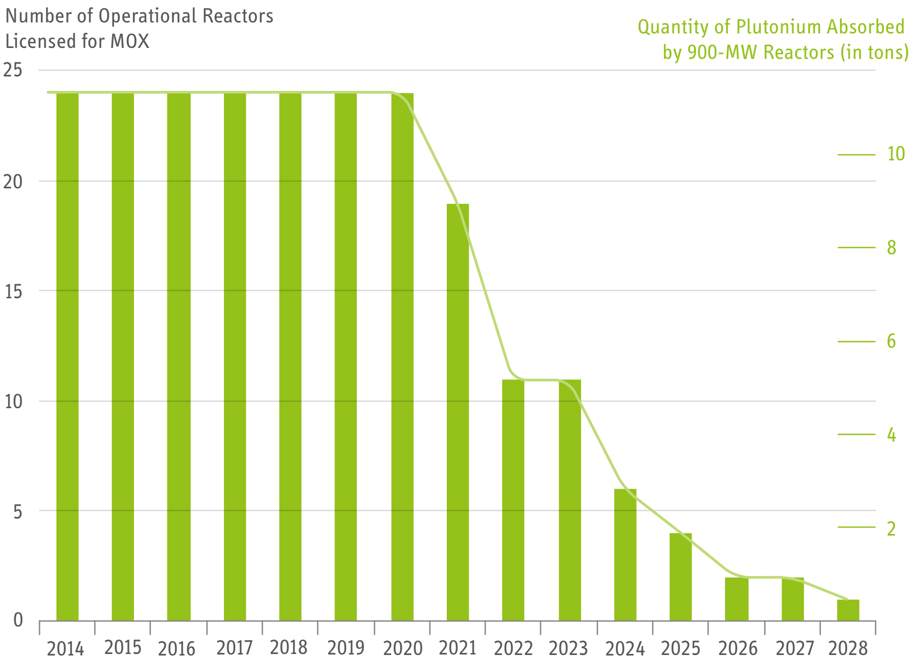

Figure 3.4. Scenario for France's plutonium disposal capacity. The figures represent the plutonium disposal capacity of the twenty-four 900 MWe reactors currently licensed to operate with MOX fuel if they don't receive license renewals beyond 40 years. Each reactor irradiates about 0.44 tons of plutonium in MOX per year.

Below we consider two scenarios for the disposal of the remaining separated plutonium if France's 900 MWe reactors were not to receive license extensions beyond 40 years (Figure 3.4). It should be noted, however, that the scenarios exclusively assess the reactor availability and do not take into account potential delays such as licensing procedures for reprocessing some of the plutonium waste forms (MOX scrap assemblies, unirradiated fast breeder reactor fuel, etc.). The first scenario would involve the disposal of France's unirradiated plutonium in MOX. The second would require France to dispose of foreign unirradiated plutonium in France (mostly belonging to Japan) as well.

Under scenario 1, reprocessing would have to cease by 2018, in order for all of France's plutonium to be irradiated in the existing licensed reactors. This result is consistent with an analysis by EDF cited by ANDRA and ASN: "It is possible to leave neither plutonium nor reprocessed uranium unused, under the condition of the anticipated stop of the [re]processing operations (the time horizon 2018–2019 guarantees the complete use of the separated plutonium)…"[172] Under scenario 2, if foreign plutonium were to disposed of as well, reprocessing would have to end in 2016.

Conclusion

France's plutonium industry is a legacy of the fast breeder reactor dream that was buried with the shutdown of Superphénix in 1996. The conjunction of a number of developments has created an urgent need, and, at the same time, an opportunity to fundamentally reassess the rationale for plutonium separation and use in France. The urgent need stems from the following factors:

- All the reactors that use MOX fuel in France will reach an operational lifetime of 40 years by 2027 (by 2022 on average).
- The government has decided to significantly reduce the nuclear share in the electricity mix from 75 percent to 50 percent by 2025. A draft energy bill has been introduced and is still in the parliamentary process.
- France's national utility, EDF, has serious financial problems; and
- The MOX programs in Japan, the United Kingdom and the United States all appear to have failed.

France's Nuclear Safety Authority and its Court of Accounts have both urged the government to rapidly take a decision on whether operating reactors should receive extensions and continue to be in service beyond 40 years of operation.

At the same time, the current situation provides two kinds of opportunities. First, there is the financial opportunity provided by converting France's nuclear energy sector from reprocessing to interim dry storage and direct disposal of spent fuel and immobilization of already separated plutonium. Because such a conversion would provide significant savings to EDF, Areva could treat this as a business opportunity since it is already one of the largest dry cask providers in the world as well as the top player in plutonium technologies but is facing a deep financial and economic crisis as a result of its current industrial strategy. Second, there is a non-proliferation opportunity provided through the phase-out of plutonium separation and the development of a no-plutonium-stockpiling policy. This is particular important today when Japan's plutonium stockpile — a large share of which is in France — is raising serious concerns in a number of its neighboring countries.

4. Germany

President Eisenhower's "Atoms for Peace" speech in 1953 was intended to shift the world's attention from the nuclear arms race to peaceful uses of atomic energy. It was followed by the first United Nations International Conference on the Peaceful Uses of Atomic Energy in 1955 in Geneva.

These efforts to promote atomic energy fell on fruitful soil in Europe. Among the early adopters was the Federal Republic of Germany (FRG),[173] which began its nuclear power program formally in 1955 by setting up the Federal Ministry for Atomic Issues.[174] A few years later, in 1959, the Atomic Energy Act was promulgated.

While the government could set up the framework of a nuclear-energy program, it had to rely on private electricity companies to build nuclear reactors for electric-power generation. The government had great difficulty in getting Germany's biggest utility, Rheinisch-Westfälisches Elektrizitätswerk (RWE) interested in nuclear energy.

The government, therefore, started four big federal and state owned research centers:

- A facility for testing candidate reactor and fuel materials using a 4 MWt research reactor (FRM) at Garching (close to Munich);
- A reactor development center at Karlsruhe that started with heavy water reactors (the 44 MWt FR2 and 58 MWt MZFR) before shifting its focus to sodium-cooled fast-neutron breeder reactors (the 20 MWe KNK reactor);
- A reactor development center at Jülich that concentrated on developing high temperature reactors for production of electric power and process heat with the 15 MWe AVR reactor operating on a high-enriched uranium-thorium fuel cycle;[175]
- A reactor-development center at Geesthacht that concentrated on developing ship-propulsion reactors and operated the only German nuclear-powered ship, the *Otto Hahn*, from 1968 to 1979, after which its nuclear propulsion reactor was replaced by diesel engines.

Leading German nuclear physicists, including Werner Heisenberg, Karl Wirtz, and Wolf Häfele, preferred heavy water reactors because they did not want to depend on imported enriched uranium fuel that, at that time, could only be obtained from the U.S. Atomic Energy Commission.[176] But Germany's utilities were interested in the high-power-density cores of U.S. light water power reactors. So an industry effort, subsidized by the government and in cooperation with the Dutch and the British led to the development of gas centrifuges and the multinational uranium-enrichment company, URENCO.[177]

After initial reluctance, RWE decided to learn more about the reliability of this new energy source and, in 1958, ordered a small 15 MWe light water reactor for its Kahl site from a joint venture of Allgemeine Elektricitäts-Gesellschaft Aktiengesellschaft (AEG) and General Electric (GE).[178] RWE refused any government subsidies but requested that the government take care of the radioactive waste.

Motivations for and origins of reprocessing

Uranium supply security was an issue from the beginning of Germany's interest in nuclear power. The FRG had only one small uranium mine at Menzenschwand in the Black Forest. The associated small uranium processing center at Ellweiler had a capacity to recover only 125 metric tons of uranium per year and had produced cumulatively only 700 tons of uranium by the time it was shut down in 1989.[179] This small capacity was perceived to be insufficient for the anticipated demand from the FRG's growing nuclear power program.

An indirect boost to the perception that uranium would be costly was provided by the decision by the Soviet Union in 1947 to open a large mine at Wismut in the adjoining German Democratic Republic (GDR). The FRG's planners reasoned that, if the Soviet Union, with its huge landmass, had to come to the GDR to obtain uranium for its needs, then uranium must indeed be scarce. It was therefore decided to maximize the efficiency of uranium utilization. This led to the decision to pursue reprocessing and fast breeders.

Nuclear planners in other countries in Western Europe came to similar conclusions. In 1957, therefore, twelve European countries decided to jointly finance the construction of the Eurochemic reprocessing facility at Mol, Belgium.[180] Prior to Eurochemic, reprocessing in Europe only took place in the plants at Marcoule in France and Windscale (later renamed Sellafield) in the United Kingdom.[181] Eurochemic, which operated from 1966 to 1974, had a design capacity of 30 tons heavy metal throughput per year and used the PUREX process, which had been developed in the U.S. military plutonium production program. Many members of the multinational technical group involved in this project later led reprocessing programs in their own countries.

In Germany, the WAK pilot reprocessing plant, which also used the PUREX process and had a design throughput of 35 tons of spent fuel per year, was built in Karlsruhe and operated from 1971 to 1990. In total it reprocessed 208 tons of spent fuel.[182] The high level radioactive waste produced by this plant was stored in liquid form on site and was vitrified only much later (see below).

The WAK plant was safeguarded both by the IAEA and Euratom, a part of the European Commission. Legally Euratom is the owner of all civil nuclear material within the Member States.[183]

In 1975, France, the United Kingdom and Germany created United Reprocessors, a cartel authorized by the European Commission to construct large reprocessing plants, first in France and England and then Germany. The purpose of these reprocessing facilities was to deal with the spent fuel from the many reactors that were proposed for construction.

As in the United States, West Germany's commitment to private enterprise, coupled with the high capital costs for nuclear facilities, meant that the government could not start the nuclear program on its own and essential decisions had to be taken by the utilities. This proved difficult in the area of reprocessing. Initial cost estimates for reprocessing were based on offers of the military reprocessing agencies such as the U.K. Atomic Energy Authority and led to overly optimistic views on reprocessing economics. The prices quoted for reprocessing each unit of spent fuel grew rapidly, from about 15 dollars per kgHM ($74 in 2014$) in 1969 to nearly 700 $/kgHM in 1980 ($1700 in 2014$).[184] (See Figure 1.3 in Chapter 1.)

First steps towards a radioactive waste disposal facility

In the early years of the nuclear program, the government did little to deal with nuclear waste problems, and did not take any steps towards creating a disposal facility.[185] This was a major mistake that later allowed nuclear power critics to accuse the industry and government of having launched an airplane without creating a landing strip. In 1963, the government procured a worked-out former salt mine, Asse II, for testing and demonstration of disposal of low-active wastes. From the beginning of the project, however, the responsible government officials knew that, due to the very extensive excavations associated with the salt mine, water was leaking into some chambers, which could one day lead to an unstable situation. In 1976, the State of Lower Saxony, where the facility was located, decided to stop all waste disposal at this site by 1979.[186]

1974 – 1989, The big reprocessing projects, Gorleben and Wackersdorf

In 1974, the Federal Government started promoting the idea of placing all future fuel cycle facilities on top of a "virgin" salt dome suitable for later disposal activities. Although the site had not yet been selected when this idea was advanced, Lower Saxony declared its willingness to make such a site available. To cover the needs of Germany's future nuclear capacity, which was projected to be 45 GWe by 1990, the government pressed the utilities to get directly involved in reprocessing on the large scale of 1500 tons of heavy metal per year (tHM/yr). The proposal was that the utilities would start by taking over the operation of the small 35 tHM/a WAK Facility in Karlsruhe and then prepare a non-site-specific Preliminary Safety Report for a "nuclear park" where all their fuel cycle activities would be concentrated.

In 1976, the government threatened that no nuclear power plants under construction (some were almost finished) would receive an operating license in the absence of concrete plans for a reprocessing plant. This forced the utilities to overcome their hesitation about building a domestic reprocessing plant. They established a Projektgesellschaft für die Wiederaufarbeitung von Kernbrennstoffen (PWK) [Project Company for the reprocessing of nuclear fuel] in Essen. All of Germany's fuel cycle facilities, including enrichment, reprocessing, mixed-oxide (MOX) uranium-plutonium fuel fabrication and disposal, were to be co-located. A 3000 tHM (metric tons heavy metal, i.e., uranium plus plutonium) spent-fuel pool was to be the intake facility for the reprocessing plant with an initial design capacity of 1500 tHM/a.[187] In parallel, the utilities undertook to construct at Ahaus an away-from-reactor storage facility with a capacity of 1500 tHM.

On 22 February 1977, after extensive consideration of several alternative sites with salt domes, Lower Saxony offered Gorleben, a town close to the border of the GDR, as a potential site for the proposed nuclear park. PWK was renamed DWK (Deutsche Gesellschaft für Wiederaufarbeitung von Kernbrennstoffen) [German Company for Reprocessing Nuclear Fuel] with the necessary financing guarantees from the utilities and moved to Hannover, the capital of Lower Saxony. The Preliminary Safety Report was made site-specific and submitted to the local authority. Heavy opposition to the site quickly developed, however, from the Greens, farmers and many local people.[188]

In the meantime, the government tightened the Atomic Law to require proof from the utilities that they had concrete plans for managing their spent fuel six years in advance. At that time, reprocessing was considered the only acceptable form of management. In 1978, therefore, DWK entered into interim reprocessing contracts on behalf of the utilities with COGEMA, the French fuel services company, and British Nuclear Fuels Limited (BNFL). Due to the government's requirement that they reprocess, they had almost no negotiating power over the price.

In 1979, the State of Lower Saxony held an international hearing on the Gorleben project. Among the concerns voiced by the international experts was the possibility of a release of liquid high level waste into the atmosphere if cooling of the tanks was lost. Prime Minister, Ernst Albrecht, a Christian Democrat, declared the reprocessing project "technically feasible but politically unenforceable."[189] Exploration of the salt dome for a radioactive waste repository was declared acceptable, however. This allowed the federal government to continue to argue that it was indeed working to solve the disposal issue.

The door also was left open for an interim storage facility for solidified high level reprocessing waste and spent fuel at Gorleben, but only under the condition that it would be passively cooled. This requirement had just become technically feasible because a dry storage cask (CASTOR) had recently been developed by the engineering company GNS under a contract with PWK/DWK. The design requirements for the cask were dry storage in helium for spent fuel with a burnup of 35 gigawatt-days per ton of heavy metal (GWd/tHM) for a period of up to 20 years after only one to two years of cooling in a spent-fuel storage pool. This resulted in small casks that could contain 4 pressurized water reactor (PWR) or 16 boiling water reactor (BWR) fuel assemblies that had been cooled for a year or 9 PWR fuel assemblies if they had been cooled for 2 years.

As a result of these developments, by 1979, DWK had switched its two central spent-fuel storage project sites, Gorleben and Ahaus, from wet to dry storage. These dry storage facilities had a design capacity of 1500 tHM each.

In 1983, Franz Josef Strauss became the Prime Minister of Bavaria. He had been Federal Minister of Atomic Affairs from 1955 to 1956 and Minister of Defense from 1956 to 1962, during which time he had signed a short-lived agreement for joint nuclear-weapons development with France and Italy.[190] He was a promoter of nuclear energy and, soon after taking office, announced that he was willing to accept a reprocessing facility in his state. A site near the town of Wackersdorf was selected.

DWK's aspirations with regard to the plant's capacity had become more moderate. Its 1983 Safety Analysis Report assumed a nominal throughput of 350 tHM/yr and a maximum throughput of 500 tHM/yr.[191] An important cause for this recalibration was the accident at the U.S. Three Mile Island nuclear power plant in 1979. After that accident, only three more power reactors were ordered in Germany.

The decision to build the Wackersdorf facility caused protests at levels that surpassed imagination, causing long and costly delays. Design changes added further delays and cost overruns, so that the initial cost estimate of 4 billion German Marks (DM, $2.5 billion in 2014$) for the reprocessing plant had increased to 10.5 billion DM by 1989. It also was clear that the trend to higher fuel burnups that started in the early 80s would soon again make necessary license revisions, which would result in further delays.

The other relevant development around this time was the delay in the construction of Germany's demonstration breeder reactor, the SNR-300 near the Dutch border. The reactor's construction had started in 1973 and, by the mid-1980s it was approaching completion. However, because of the Chernobyl accident and the possibility of a Bethe-Tait excursion, a safety concern specific to fast-neutron reactors,[192] the state government refused to license fuel loading and operation. The abandonment of the $6 billion (2014$) project resulted in the disappearance of a potentially major user for the plutonium that was to be separated at Wackersdorf.[193] The site of the SNR-300 reactor has been converted into an amusement park (Figure 4.1).[194]

Figure 4.1. Amusement park at Germany's abandoned SNR-300 breeder reactor. Shown here are rides inside its cooling tower. *Source: Kalle Koponen.*

From domestic to foreign reprocessing

Then something unanticipated happened. In 1988, Hermann Krämer, Chairman of the supervisory board of DWK and also CEO of the important utility, Preussen Elektra, had begun secret negotiations with France's reprocessing services company, COGEMA. Krämer's ambition was to be the exclusive agent in Germany for reprocessing contracts with France's COGEMA UP3 reprocessing plant beyond the existing 7000 tons of "base-load" contracts that had paid for the construction of the plant. In March 1989, Bennigsen-Foerder, the CEO of VEBA, the owner of Preussen Elektra, met secretly with Chancellor Helmut Kohl and his chief of staff to inform them of these negotiations and that Preussen Elektra intended to end its support for reprocessing in Germany. Both the Chancellor and his chief of staff forgot this presentation because they were deeply engaged in issues related to the upcoming reunification of the two Germanys.

When reports of these meetings leaked out several weeks later, however, it became a great scandal. Various German utilities threatened to go to court against Preussen Elektra. Some of them called in British Nuclear Fuel Limited (BNFL), which made even lower offers for reprocessing services to the other utilities. Eventually, COGEMA had to meet BNFL's price.

The net result of all these parallel developments: the signing of contracts with COGEMA, the cancellation of the fast breeder reactor, and the cost overruns in the construction at Wackersdorf was that construction of the German reprocessing plant was halted in 1989. The associated MOX fuel fabrication project at Hanau near Frankfurt was abandoned a few years later. The utilities decided to shut down DWK immediately and transferred to GNS its remaining activities: the spent-fuel storage facilities at Gorleben and Ahaus, return of vitrified high-level waste from the reprocessing of German spent fuel in France and the United Kingdom and the licensing and construction of a Pilot Conditioning Facility (PKA) at the Gorleben final disposal site for extracting rods from spent fuel assemblies: and the development of the POLLUX final disposal cask to hold the rods in the repository. GNS also took over DWK's 25 percent share in DBE, the German Company for Construction and Operation of Final Disposal Facilities.

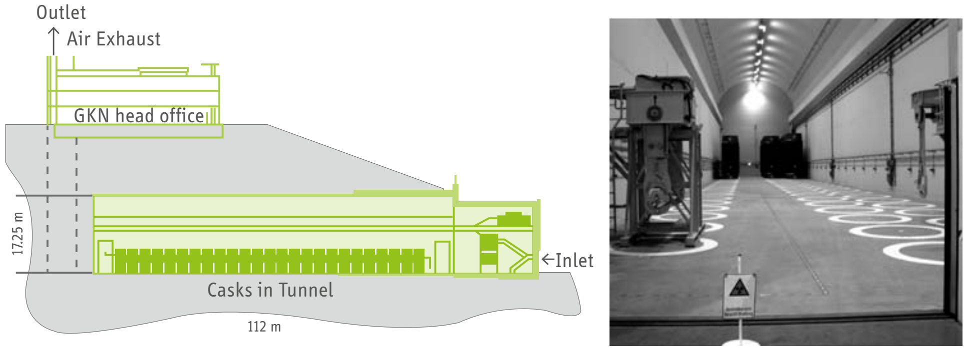

Figure 4.2. Dry-cask spent fuel storage at Neckarwestheim nuclear plant. On the left is the cross-section of one of the two parallel tunnels. On the right is the inside of one of the tunnels with the first dry casks. Each of the tunnels has a capacity for 151 Castor V casks, each of which can hold 19 PWR fuel assemblies, about 10 tons of spent fuel. *Source: Wolfgang Heni, former managing director, GKN.*

This was not yet the complete end of reprocessing in Germany, however, as the federal government continued to require that the nuclear utilities arrange their spent fuel management six years in advance, which most utilities interpreted as requiring them to continue to enter into contracts for reprocessing abroad. Wolfgang Heni, manager of the utility GKN, dealt with this requirement by giving GNS a development contract for big CASTOR V storage casks with a capacity of ten tons of spent fuel each for Gorleben.[195] As a result of this capacity increase the theoretical capacity associated with the 420 cask storage positions in the Gorleben facility capacity went up to more than 4000 tons, although a certain number of positions were reserved for casks containing vitrified high-level reprocessing waste.

The other utilities went along with the government's requirement by signing additional reprocessing contracts with France and the United Kingdom. This did not last long, however. With the SNR 300, the MOX facility at Hanau,WAK, and Wackersdorf all abandoned, the closed fuel cycle in Germany had been exposed as an "Emperor without Clothes." In 1994, the Atomic Law was changed to allow direct disposal as an alternative to reprocessing of spent fuel.

Decommissioning WAK

Decommissioning WAK has been a costly affair. When the shut-down decision was made in 1990, WAK had no decommissioning plan nor did it have a facility in which to solidify its High Level Liquid Waste (HLLW). The initial idea was to ship the HLLW to the Pamela vitrification (glassification) facility in Belgium. Public protests blocked shipment of the liquid waste and it was decided to build an on-site vitrification facility (VEK) for the approximately 80 cubic meters of HLLW.

Designing, building, licensing and testing the vitrification facility took quite some time. WAK's host state, Baden-Württemberg, which had not joined the Federal Government and the utilities in funding the project, was criticized for not running its licensing process efficiently.

By 2010, however, the HLLW was vitrified and several months later shipped to the federal radioactive waste storage facility at Greifswald next to the shutdown East German nuclear power plant on the Baltic Sea. By 2006 the cost of decommissioning WAK was estimated at €2.5 billion, about 83 times its initial construction cost estimate of € 30 million (not corrected for inflation).[196]

The cleanup project was still not complete, however, because, cleaning all the pipes and tanks of the vitrification facility produced an additional 10^{16} Bq (270,000 Curies) of radioactive waste that required treatment for disposal. Completion of decommissioning operations at WAK and VEK is scheduled for 2020 but 2023 would be more realistic. Finally, if there is still no radioactive waste repository in operation by that time, an intermediate storage facility will have to be constructed for the associated waste.

Nuclear phase-out

In 1998, the government changed again, from Christian Democrats/Liberals to Social Democrats/Greens, and the new coalition partners started to prepare the ground for a phase-out of nuclear power. As part of this process an agreement was reached between the utilities and the government to end transport of spent fuel to the French and British reprocessing plants in 2005 and to limit the lifetimes of Germany's nuclear power plants to the Gigawatt-hour equivalent of 32 years of normal operation. This timeframe appeared to allow for the use in MOX fuel of all of Germany's separated plutonium within the remaining lifetime of the reactor fleet.

It was further agreed that all reactors would apply for on-site dry-cask spent-fuel storage facilities with capacities sufficient for their residual life-time unloadings. As the GKN reactors are built in a former quarry with very little extra space, the operator built tunnels under the head office to hold the casks (Figure 4.2).

In 2010 the utilities obtained some adjustments of these phase-out conditions allowing them to shift their limited electricity production allowances between their different nuclear power plants.

The Fukushima accident changed the situation once again, however. Eight reactors were shut down immediately in 2011 while the remaining nine are to be shut down between 2016 and 2022. This decision was made by Chancellor Merkel and was based on the recommendation of an ethics commission.

Germany's utilities were able to accelerate fabrication of their separated plutonium into MOX fuel in France by using capacity that Japan's utilities could not use while their reactors were shut down. It therefore is expected that, despite the reduced number of reactors available, all of Germany's separated plutonium from reprocessing will have been irradiated by the time the nuclear phaseout is completed.

In 2013, the government again delayed making any decisions on siting a geological repository for high-level waste and spent fuel. Also, it established a very high tax on nuclear fuel. As a result, unless they are able to obtain government compensation through court action for their losses due to the accelerated shutdown schedule, the nuclear utilities will not be able to put enough money aside for nuclear power plant decommissioning or high-level waste disposal during the remaining lifetimes of their nuclear power plants.

5. India

India has been reprocessing irradiated uranium and separating plutonium since 1964. The Department of Atomic Energy (DAE), which is in charge of India's nuclear program, offers the following rationales:

- Plutonium is required for the initial cores of the fast breeder reactors that, for 60 years, have been at the center of the DAE's ambitious plans for a vast nuclear power program.
- Plutonium also can be used to construct nuclear weapons and the DAE deliberately kept open the weapon option, even in the early decades when India's nuclear program was ostensibly peaceful.[197]
- Reprocessing is a way to deal with nuclear waste.[198]

History

India started on the path to reprocessing during the 1950s. In 1954, the DAE put out the first of its many ambitious projections for the growth of nuclear power in the country, based on a three-stage plan that was aimed at utilizing the country's limited reserves of relatively high-grade uranium ore to pave the way for exploiting India's much larger resources of thorium.

1. Heavy water reactors fueled by natural uranium would produce chain-reacting plutonium, which then would be separated out of the spent fuel.
2. The resulting plutonium stockpile would be used to provide the startup fuel for fast breeder reactors. The cores of these reactors could be surrounded by a blanket of uranium to produce more plutonium while building up the fleet of breeder reactors and by blankets of thorium later, to produce chain-reacting uranium-233.
3. Breeder reactors using uranium-233 in their cores and thorium in their blankets would be phased in.

Reprocessing of spent fuel and blanket assemblies to recover the plutonium and uranium-233 for fabrication into new fuel clearly was central to this scheme.

The DAE's quest for technical information about reprocessing was aided by the fact the United States made public extensive details as part of its Atoms for Peace program and at the 1955 Geneva Conference.[199] At the Geneva Conference, the first four nuclear-weapon states, the United States, Soviet Union, United Kingdom and France, showed off their expertise in various nuclear technologies and vied with one another to supply these technologies to other countries.[200] Later on, DAE leaders, such as the physicist Homi Bhabha, discussed the design of India's first reprocessing plant in Trombay with U.S. scientists and engineers, and technical personnel working on the plant were sent to the United States for training.[201] The American company Vitro International was involved in its design and construction.[202]

Reprocessing heavy water reactor fuel

India has built reprocessing plants at three locations: Trombay, Tarapur, and Kalpakkam (See Figure 5.1).

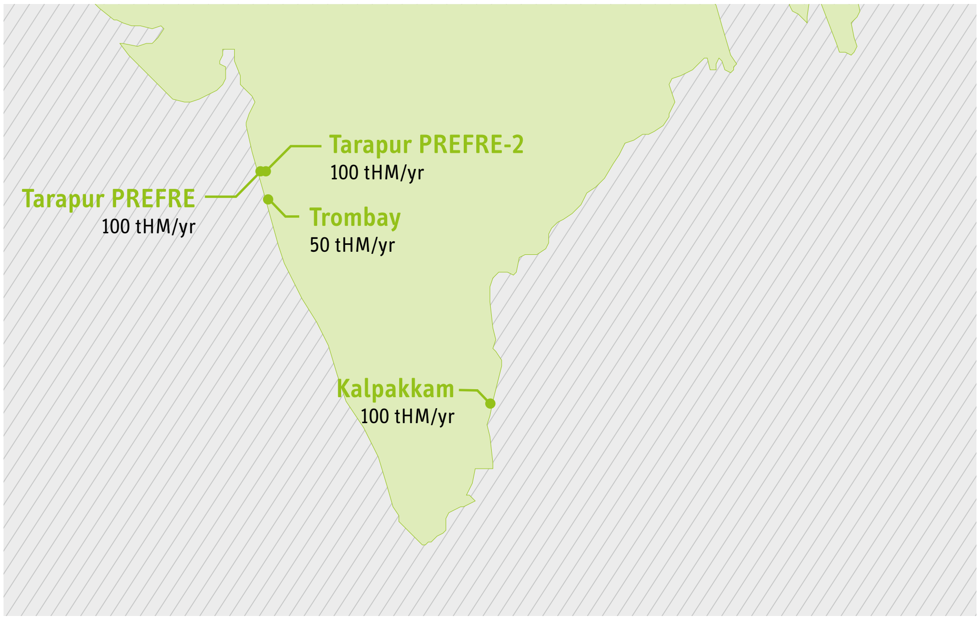

Figure 5.1. Locations of India's reprocessing plants. The Trombay reprocessing plant is used for producing plutonium for the military stockpile.

The first, in Trombay, has been used to reprocess the irradiated fuel from the CIRUS and Dhruva research reactors. Because of the relatively short irradiation time of this fuel, the ratio of the higher isotopes, plutonium-240, plutonium-241, and plutonium-242 in the plutonium to plutonium-239 is low. Such relatively pure plutonium-239 is preferred by weapons designers and described as "weapon-grade". It is generally assumed that India has used this plutonium primarily for manufacturing nuclear weapons. Early on in India's nuclear program, some was used to fuel research reactors as well.

The PREFRE and Kalpakkam reprocessing plants are currently used to reprocess spent fuel from power plants of the Pressurized Heavy Water Reactor (PHWR) type. The plutonium produced at PREFRE and Kalpakkam is almost all reactor-grade, i.e., not weapon-grade, although weapon-useable. The plutonium in the spent fuel first discharged when any PHWR starts operating, however, would likely be weapon-grade.[203]

Trombay

The Trombay reprocessing plant, located in the Bhabba Atomic Research Center near Mumbai, started operating in 1964 and the first samples of plutonium oxide and plutonium metal produced there became available later that year or early the following year.[204] The Trombay plant was designed initially to reprocess spent fuel containing 30 tons of heavy metal per year (30 t/y) but this was increased to 50 t/y later on. Reportedly, the plant had major operational problems in the initial years,[205] but it produced enough plutonium to fuel a small pulsed fast reactor called PURNIMA that was commissioned in 1972 and used in neutronics studies of the design of India's first nuclear explosive, which was tested in 1974.[206] By that time, however, Trombay's plant equipment and piping had been seriously corroded, and the plant had to be shut down for about a decade for decontamination and partial decommissioning before it could be rebuilt.[207]

All of the plutonium used in India's 1974 nuclear weapon test,[208] and in its 1998, nuclear weapons tests probably was produced at Trombay.[209] At least 50 kilograms of weapon-grade plutonium from Trombay, however, was used for the initial core of the Fast Breeder Test Reactor (FBTR).[210]

The Trombay reprocessing plant uses the PUREX process.[211] The fuel of the CIRUS and Dhruva reactors was uranium metal sheathed in aluminum.[212] Because metal fuel swells and gets distorted under neutron irradiation, the fuel has to be replaced when the fractional burnup of its uranium-235 is relatively low.[213] This means that the concentrations of fission products, i.e., the level of radioactivity in the spent fuel rods, would have been low and, as already noted, the plutonium would be weapon-grade.

Tarapur

India's second reprocessing plant, the Power Reactor Fuel Reprocessing (PREFRE) facility, was located in Tarapur, north of Mumbai. Construction started in the early 1970s and the plant was commissioned in 1977.[214] The first batch of spent fuel rods was reprocessed in April 1978.[215] PREFRE has a capacity of 100 metric tons of heavy metal per year (t/y).

For the first few years, PREFRE reprocessed only spent fuel rods from CIRUS.[216] In 1982, the plant began to reprocess PHWR spent fuel from the Rajasthan Atomic Power Station (RAPS) whose fuel is subject to IAEA safeguards.[217] Therefore, while reprocessing Rajasthan spent fuel, PREFRE also came under IAEA safeguards.[218] These campaigns reportedly "provided valuable experience in material accounting practices".[219] After PREFRE "completed the third campaign... [of reprocessing] spent fuel bundles" from RAPS in 1986, however, it was shut down for "an extended maintenance outage".[220] Since then it appears to have reprocessed only spent fuel from unsafeguarded PHWRs.[221] The DAE evidently did not want IAEA safeguards to follow the separated plutonium into its breeder program.

Since 1986, the spent fuel of the safeguarded RAPS and TAPS (Tarapur Atomic Power Station) reactors has not been reprocessed.[222] Instead, separate "away-from-reactor" facilities for extra spent-fuel storage were constructed within both the RAPS and TAPS sites.[223] RAPS fuel is stored in both pool and dry storage. The BWR spent fuel from TAPS is sent only to a pool storage facility.[224] The storage facilities are under IAEA safeguards.[225]

The PREFRE plant appears to have performed quite poorly in its first two decades. In the 1990s, it was reportedly running "substantially" below its design capacity, with an average throughput of 25 percent.[226] Similar reports of poor performance have continued.[227]

Operations at a new reprocessing plant (Power Reactor Fuel Reprocessing Plant-2 or PREFRE-2) were inaugurated at Tarapur in January 2011 by then Prime Minister Manmohan Singh.[228] The new plant has a capacity of 100 tons of spent fuel per year and is said to be operating succesfully.[229] The older PREFRE-1 is reportedly used to "carry out aged Pu purification work,"[230] which presumably means that it is being used to separate out americium-241, which builds up in plutonium due to the decay of 14-year-halflife plutonium-241.[231]

Kalpakkam

A third reprocessing plant, the Kalpakkam Atomic Reprocessing Plant (KARP), was built in southern India. Like PREFRE and PREFRE-2, it has a capacity of 100 tons/year.[232] Plans for the plant were first announced in the Indian parliament in 1978,[233] and government expenditures for building it started in 1983.[234] Operation of the plant was originally planned for 1991,[235] but, due to quality-control problems in piping and other equipment, it was delayed.[236] The plant was finally commissioned in 1998 after 16 years of construction.[237] In 2010, KARP was reported as having been "recommissioned with improved features,"[238] but its outage period was not revealed.[239] The reprocessing capacity at Kalpakkam is in the process of being doubled,[240] although there is no information on when this project will be completed. Kalpakkam also has a smaller facility for reprocessing spent fuel from the fast breeder test reactor (FBTR).

In October 2014, the Director of the Bhabha Atomic Research Centre (BARC) announced that BARC had "been able to produce all the pins necessary for criticality of PFBR (Prototype Fast Breeder Reactor)".[241] The PFBR has been long delayed and it has been suggested unofficially that this delay was due to a lack of plutonium. The BARC Director's announcement offers some official corroboration. If this is true and the necessary amount of plutonium needed to produce the first core of plutonium was only available around 2013 or 2014, then both the Tarapur and Kalpakkam reprocessing plants must have operated quite poorly, with a combined average capacity factor of around 15 percent.

Future plans

As with other aspects of India's nuclear-power program, the DAE's plans for expanding its reprocessing capacity have been significantly delayed. In 1987, P.K.Iyengar, who headed the DAE in the early 1990s, wrote, that "a plant with 400 t capacity is planned to become operational by mid 1990s to receive spent fuel from Narora and Kakrapar reactors. It is envisaged that another 400t capacity plant would have to be suitably located for reactors beyond Kakrapar to bring the total reprocessing capacity to 1000t by 2000".[242] In 2003, the DAE was projecting a total reprocessing capacity of 550t by the year 2010 and 850 t by 2014.[243] As of May 2015, not including the Trombay military reprocessing facility, India's reprocessing capacity was 200 tons per year.

Apparently, the DAE finally is constructing a larger reprocessing plant. But there is little clarity on the capacity of this plant, with figures varying between 400 tons and 600 tons per year.[244] Current plans are to set up three "Integrated Nuclear Recycle Plants" that would carry out both reprocessing of spent fuel and management of the associated waste (presumably in the case of high-level waste by vitrification).[245] According to a 2011 answer to a question in India's parliament, the first such plant will be constructed at Tarapur.[246]

Since the 2006 US-India nuclear deal and the 2008 special waiver for India of the Nuclear Suppliers Group's (NSG's) ban on providing nuclear technologies and materials to countries that are not members of the Nonproliferation Treaty, the DAE has sought to import reprocessing plants as well as nuclear power plants and uranium. It is not clear that any country in the NSG is willing to export a reprocessing plant to India, however, and, as of May 2015, no agreements had been reported.

As part of the nuclear deal with the United States, however, the Indian government agreed that, if it were to reprocess foreign nuclear material, it would establish one or more new national reprocessing facilities that, unlike its other reprocessing plants, would be under IAEA safeguards. In 2010, the United States granted India prior consent to reprocess spent fuel from any U.S. origin nuclear reactor.[247] Currently, India only has two such reactors, the twin 150 MWe boiling water reactors at Tarapur, which were completed in 1969 before India's 1974 test. U.S. nuclear vendors are eager to sell India new power reactors but do not want to accept any liability for the consequences of any accidents that might occur at the reactors.[248] As a result, as of May 2015, India had not signed any reactor orders with the United States. Nor were there any serious plans to construct reprocessing plants to deal with safeguarded spent fuel from either indigenous heavy water reactors using imported uranium or imported light water reactors.

Vitrification and waste management

In addition to plutonium and uranium, reprocessing also produces three types of waste, classified on the basis of the concentration of their contained radioactivity as high-, intermediate- and low-level wastes (HLW, ILW, LLW).[249] The largest waste stream by volume (more than 80 percent of the total) is LLW, but it contains only about 0.1 per cent of the total activity from the spent fuel. ILW accounts for over 10 per cent of the volume and contains about 1 per cent of the radioactivity, and HLW constitutes about 2 per cent of the volume but contains nearly 99 per cent of the total radioactivity.[250]

HLW is concentrated by evaporation and through the removal of nitric acid from the solution.[251] According to the DAE, as a result of these procedures "the high level waste volume could be restricted to 600 liters/ton" of spent fuel reprocessed.[252] After concentration, the HLW is stored in stainless steel tanks. These storage tanks require cooling and continuous surveillance.[253] The hazards associated with such storage are discussed in Chapter 12.

High-level liquid waste is converted into a disposal form by "vitrification," that is by mixing into molten glass at high temperatures, which is poured into canisters and cooled. The DAE, like France, Japan and the United Kingdom, uses borosilicate glass for vitrification. It consists mainly of silica and boron oxide along with small percentages of other oxides.[254]

The DAE is vitrifying HLW at waste immobilization plants at all its reprocessing plants: Trombay, Tarapur, and Kalpakkam. At Tarapur, the first vitrification plant has been decommissioned and a new one went into operation in August 2012.[255] The glass blocks containing vitrified HLW are kept in the interim Solid Storage Surveillance Facility (S3F) at Tarapur. They are eventually to be disposed of in a geological repository.[256]

Reprocessing fast reactor spent fuel

India also is in the process of constructing plants to reprocess spent fuel from fast reactors. The first is the CORAL pilot plant commissioned in 2003. It has a capacity of only 12 kilograms per year (kg/y).[257] The next one, currently under construction, is the Demonstration Plant (DFRP), which is designed to initially process 100 kg/y of Fast Breeder Test Reactor (FBTR) fuel, and eventually 500 kg/y of Prototype Fast Breeder reactor (PFBR) fuel.[258] Finally, there is the prototype Fast reactor fuel Reprocessing Plant (FRP) that is being designed to process annually about 14 tons of spent fuel from the core and radial blanket of the PFBR.[259] The FRP will be part of a larger Fast Reactor Fuel Cycle Facility (FRFCF) that is to be constructed in Kalpakkam.[260]

Plutonium stockpile estimate

Between 1987 and 2014, India's three reprocessing plants separated somewhere between 2.5 and 4.9 tons of reactor-grade plutonium, of which about 0.4 tons are under IAEA safeguards.[261] This estimate assumes that 3.75 kg of plutonium is separated for every ton of PHWR spent fuel reprocessed. There probably has not been sufficient operating capacity to reprocess all the accumulated spent fuel. Of the spent fuel that has not been reprocessed so far, there are about 110 tons from the Tarapur LWRs and 4100 to 5200 tons of spent fuel from various PHWRs. Of the latter, about 2500 to 3600 tons is not safeguarded and is eventually to be reprocessed; this will yield an additional 11 to 13.5 tons of separated plutonium.

Plutonium use

There are two chief uses to which India's separated reactor-grade plutonium has been put. The first has been to fuel the Fast Breeder Test Reactor (FBTR) after its first core of weapon-grade plutonium. The second has been for the first core of the Prototype Fast Breeder Reactor (PFBR), which is expected to be commissioned late in 2015. The FBTR was initially designed to produce 40 MWt of heat, but it never achieved this power. The cumulative total plutonium use in FBTR fuel is about 130 kg.[262] The 500 MWe PFBR design requires 1.9 tons of plutonium in its initial core.[263] As mentioned above, this much separated reactor-grade plutonium is likely to have become available only in 2013 or 2014. Once the reactor begins operating, the first two or three fuel reloads also will require plutonium from the reactor-grade stockpile before it becomes possible to use plutonium extracted from the PFBR's own spent fuel arisings.

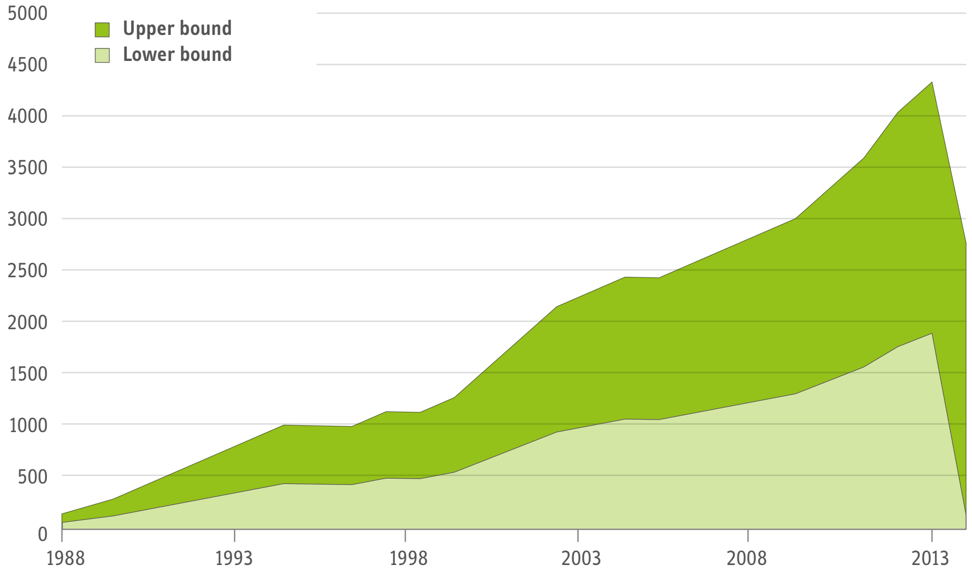

Figure 5.2. India's stockpile of separated reactor-grade plutonium, 1988 – 2014. The lower estimate corresponds to the PREFRE, PREFRE-II and KARP reprocessing facilities operating at the minimal capacity needed to produce all the plutonium used for FBTR refuelings since 1988 and the initial core for the PFBR by 2013. The higher estimate corresponds to PREFRE, PREFRE-II and KARP all operating at average capacity factors of 40 percent during the years they were not shut down for refurbishing.

A third relatively small requirement for reactor-grade plutonium is for tests of MOX-containing assemblies in the boiling water reactors at Tarapur and various heavy water reactors in the country.[264] There is no public information about how many such fuel assemblies have been loaded or how much plutonium each assembly contained;[265] so a quantitative estimate of the associated plutonium use is not possible. Since this is only an experimental program, however, the amounts should be relatively small.

After accounting for all these withdrawals, India's remaining stockpile of separated reactor-grade plutonium as of the end of 2014 would be between 0.1 and 2.8 tons (Figure 5.2).

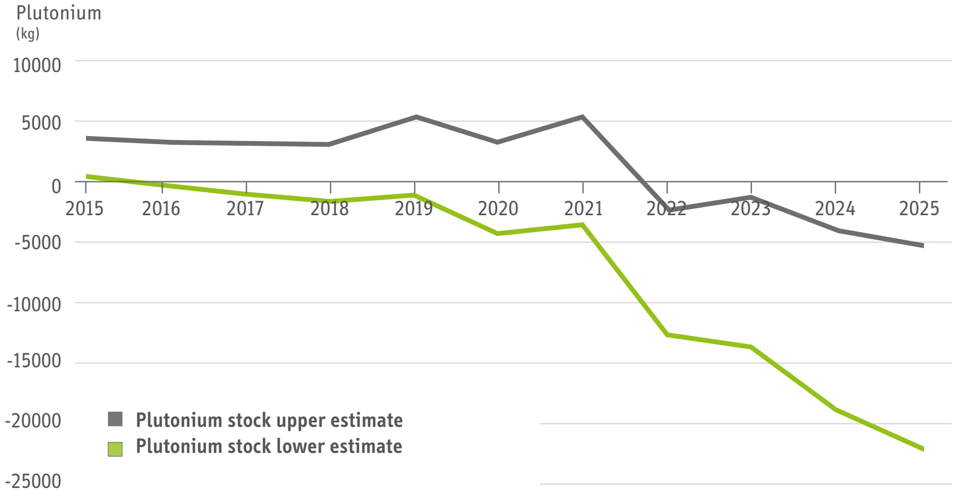

Figure 5.3. Scenario for India's plutonium stock with six FBRs, 2015 – 2025. The lower estimate in the figure on the left corresponds to a PHWR average capacity factor of 65 percent and a reprocessing plant efficiency of 20 percent; the upper estimate corresponds to a PHWR average capacity factor of 85 percent and a reprocessing plant efficiency of 60 percent. The decline in the plutonium stock in 2015 – 2018 is due to withdrawals for fuelling the PFBR for the first three years of operations before it becomes self-sustaining; the further declines in 2019 and 2021 are due to the requirements for first cores of the six follow-on breeder reactors. From 2016 onwards, the lower estimate of the plutonium stockpile is negative and from 2022 onwards, even the upper estimate is negative.

Scenarios for the future of India's plutonium stockpile

India has four 700 MWe (gross capacity) heavy water reactors under construction since 2010 and 2011 that are not under safeguards.[266] Their combined capacity is more than that of the six currently operating 220 MWe (gross capacity) and two 540 MWe unsafeguarded heavy water reactors that are currently operating.[267] The government plans to construct many more such PHWRs.[268] In our scenarios below, we assume that four more PHWRs, with a combined capacity of 2800 MWe, will start construction and be operating by 2025 for a total unsafeguarded capacity of about 8,000 MWe.

We assume that all of these PHWRs will be unsafeguarded. There is a long history of the DAE being opposed to putting indigenously designed or constructed reactors — heavy water or fast breeder reactors — under safeguards.[269] It also is likely that the DAE would oppose safeguards at any indigenously designed or constructed reprocessing plant, especially one that reprocesses spent fuel from unsafeguarded PHWRs. There are only two circumstances under which India might accept safeguards on a reprocessing plant:

1. India imports a reprocessing plant or is allowed to reprocess spent fuel from an imported light water reactor (LWR).[270]
2. A Fissile Material (Cutoff) Treaty is negotiated and enters into force.

Neither of these possibilities is likely to obtain within the next decade. Accordingly, the scenarios considered below do not consider the possibility that India will reprocess the spent fuel from any reactor, heavy water or light water, that is under safeguards.

As described above, the DAE proposes to expand India's reprocessing capacity to 900 tons/year by 2018. Even this capacity will be insufficient, however, to deal with all the spent fuel produced by all of India's operating and proposed unsafeguarded heavy water reactors. Based on announced plans for the construction of heavy water reactors, reprocessing plants, and fast breeder reactors, we have drawn up two scenarios. Both include lower and upper estimates of the plutonium stockpile, corresponding respectively to PHWR average capacity factors of 65 and 85 percent and average reprocessing plant capacity factors of 20 percent (the same as the lower estimate in the calculations of the plutonium stockpile above) and 60 percent (higher than the 40 percent assumed earlier).

The first scenario is based on DAE projections of six 500 MWe breeder reactors (three twin units) by 2023 in addition to the PFBR.[271] Under this scenario, even for the upper estimate of the plutonium stockpile, by 2022, there would be insufficient separated plutonium available for fabricating the initial cores and reloads of all the breeder reactors (See Figure 5.3, lower curve).[272] In other words, there will not be enough plutonium to fuel six fast breeder reactors.

The second scenario involves the construction of four more 500 MWe fast breeder reactors after the PFBR, two fewer than the six-FBR scenario described above.[273] Two are assumed to come online in 2023, and the plutonium for their initial cores is assumed to be withdrawn in 2021. The second pair is assumed to come online in 2025, and plutonium for their initial cores is withdrawn in 2023. Under this scenario, for the upper estimate of the plutonium stock, there would be sufficient separated plutonium available for fabricating the initial cores and first reloads of the fast breeder reactors, but not in the case of the lower estimate of the stock. In other words, the construction of four FBRs is possible if the reprocessing plants and heavy water reactors perform reasonably well.

As argued elsewhere, this problem of inadequate plutonium stocks makes impossible the DAE's projection of a large-scale and rapid expansion of India's fast breeder reactor capacity.[274] This would be a problem even if one did not allow for the DAE's history of long delays and operational problems (including those having to do with the use of sodium coolant) that have plagued India's breeder program.[275] Failure to meet projections and technological problems of various kinds have afflicted other countries' "demonstration" fast breeder reactor programs as well.[276]

Given this reality, one might expect India's policy makers to re-examine their commitment to reprocess all of India's unsafeguarded spent fuel. But for various institutional and other reasons, this is unlikely. First, any official decisionmaking bodies that set policies impinging on nuclear matters seem always to include current or former senior members of the nuclear establishment. For example, DAE officials serve on the energy-related committees of the national Planning Commission, the Central

Electric Authority and the Confederation of Indian Industry. In the case of India's most recent proposed energy plan, the 2006 report by the Expert Committee on Integrated Energy Policy of the Planning Commission, the drafting committee included Anil Kakodkar, then the head of the DAE. Not surprisingly, the report concluded, inter alia, that:[277]

> "Nuclear energy theoretically offers India the most potent means to long-term energy security… Continuing support to the three-stage development of India's nuclear potential is essential."

Likewise, just about every head of the DAE and the government has extolled the importance of the three-stage program and the eventual use of thorium to breed uranium-233 for India's nuclear power plants.[278] This unchallenged vision is the ossified legacy of Homi Bhabha, the founder of India's nuclear program. Even in the wake of the NSG decision allowing exports of light water power reactors and their fuel to India, such transfers are discussed within India's nuclear establishment in terms of how they could help or hurt the three-stage program.

As worldwide experience over the past few decades has shown, however, breeder reactors are expensive and unreliable. For the foreseeable future, India's breeder-reactor capacity will remain a small — perhaps even miniscule — part of India's overall electricity generation capacity.

It also appears, however, that, for the foreseeable future, India's government will not be willing to confront its nuclear establishment with the increasing irrelevance of the three-stage program and will continue to provide the DAE with the funding it needs to slowly expand its reprocessing capacity.

6. Japan

In 2005, Japan's Atomic Energy Commission (JAEC) justified maintaining its commitment to spent fuel reprocessing with the argument that, in the absence of a destination to which spent fuel could be shipped, Japan's reactors would have to shut down when their spent fuel pools were full.[279] Expanding on-site storage by adding dry casks, as has been done in the United States and many other countries, was deemed politically impossible. Constructing off-site storage also was deemed politically impossible. The JAEC concluded that the Rokkasho Reprocessing Plant was the only politically feasible off-site destination.

The French and UK reprocessing plants had provided off-site destinations for Japan's spent fuel through the 1990s but France and the United Kingdom required that Japan take back the reprocessing waste.[280] This meant that the problem of finding an off-site storage site for the spent fuel — now in the form of separated plutonium, uranium, and glassified radioactive waste — had been solved only temporarily. The Rokkasho Reprocessing Plant site, which hosts as a package a reprocessing plant, a high level waste storage facility, a low level waste storage facility, an uranium enrichment plant, and a MOX (mixed plutonium uranium oxide) fuel production plant (under construction) has offered a temporary solution to that problem by providing interim storage for the reprocessing waste being returned from Europe.

Separated plutonium is a directly nuclear-weapon-useable material, however, and, as a result of its reprocessing programs, Japan had accumulated enough in country (10.8 tons) as of the end of 2013, including that in fresh MOX fuel, to make more than a thousand nuclear warheads. In this sense, Japan is a "latent" nuclear weapon state. Currently, it is the only non-nuclear-weapon state that reprocesses domestically. If South Korea, or any other country for that matter, succeeds in leveraging Japan's example into justifying becoming the second non-weapon state that reprocesses, it could destabilize the nonproliferation regime. The 36.3 tons of plutonium separated from Japanese spent fuel remaining in Europe contribute further to the global stockpile of excess plutonium.

Separated plutonium also is a potential terrorist target that could be used for either a nuclear explosive or a radiological weapon. The United States has expressed concerns to the Government of Japan about the security of its separated plutonium.[281]

Below, we review the current state of Japan's spent fuel management policies and then the feasibility in Japan of on-site interim dry-cask spent fuel storage, the alternative to reprocessing that has been adopted in most other countries with nuclear power plants.

Reprocessing policy

In Japan, as in other leading industrialized countries, the original purpose of reprocessing of power-reactor fuel was to provide startup plutonium for the liquid-sodium-cooled plutonium breeder reactors that, according to the Japan Atomic Energy Commission's 1967 long term plan, were to be deployed commercially starting in the latter half of the 1980s.[282] Between 1974 and 2011, Japan spent $17 billion on breeder reactor research, development and demonstration (RD&D, 2012$).[283]

Despite spending so much money, Japan, like other countries with breeder programs, has not managed to develop a commercially viable breeder reactor. Indeed, Japan's experience with its 250 MWe *Monju* Prototype Breeder Reactor is an extreme example of the problems that have beset other sodium cooled reactor demonstration projects. So much so that, in 2005, Japan's Atomic Energy Commission pushed back its projected date for *possible* commercialization of breeder reactors beyond 2050.[284] Because of a sodium fire, a refueling accident and other safety issues, Monju has operated for only a few months since it was first connected to the grid on 29 August 1995.[285] As of the end of 2012, the reactor had cost over ¥1 trillion (~$10 billion) to build and maintain.[286]

Japan's government continues to be committed to Monju, but the emphasis has shifted from breeding to burning plutonium and other transuranic elements in order to reduce the volume and toxicity of Japan's nuclear waste. Japan's Basic (or Strategic) Energy Plan, adopted by the cabinet on 11 April 2014, does not even mention the word breeder. Instead, it states that the Japanese government "will position Monju as an international research center for technological development, such as reducing the amount and toxic level of radioactive waste and technologies related to nuclear nonproliferation".[287]

Japan's government has maintained solidarity with France's Atomic Energy Commission (CEA) on this issue. In April 2014, France and Japan signed an agreement to use Monju to test fuel for a proposed new French sodium-cooled reactor, ASTRID, whose construction the CEA is justifying with a waste-minimization objective.[288] (See Chapter 10 on transmutation.)

This does not mean, however, that Japan's government has given up completely the idea of breeding. According to the September 2013 "Monju Research Plan", drafted by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Monju is to be operated for six years to demonstrate the feasibility and reliability of "fast breeder reactors", reduction of volume and toxicity of radioactive waste and "fast breeder reactor/fast reactor" safety.[289] If this program can be completed, Monju will continue operating thereafter to prove its long-term reliability.

By the 1990s, Japan's stockpile of separated plutonium had grown considerably because of continued reprocessing of the spent fuel from its light water reactors despite the postponement of its breeder reactor program. This raised questions in the United States and among Japan's neighbors. In 1997, therefore, following France's lead, Japan announced, that, as an interim measure, it would use its excess separated plutonium in MOX fuel for light water reactors.[290] Initially, France and the United Kingdom would manufacture MOX fuel from Japanese plutonium that had been separated in those countries. MOX fuel fabrication would begin in Japan after it completed construction of its own industrial scale reprocessing and MOX fuel fabrication plants at Rokkasho.

Japan's Federation of Electric Power Companies released a plutonium use plan that called for using MOX fuel in four reactors by 2000, ramping up to 16 to 18 reactors by 2010.[291] These 16–18 reactors would irradiate annually about 5–8 tons of fissile plutonium (7-11 tons of total plutonium).[292] Due to public resistance, exacerbated by scandals, including MOX fuel quality control data fabrication in the United Kingdom, however, the first loading of MOX fuel in a Japanese light water reactor occurred only in 2009. By the end of 2012, of the 3.5 tons of separated plutonium in the form of MOX fuel shipped from France to Japan, only 1.9 tons had been irradiated in four light water reactors (including Fukushima Daiichi unit #3, which subsequently melted down following the 11 March 2011 earthquake and tsunami). In 2013, France shipped MOX fuel containing another 0.9 tons of plutonium to the Takahama Nuclear Power Plant bringing to about 4.4 tons the total amount plutonium shipped in MOX fuel from France to Japan (Table 6.1).

Year	Received in Japan (Nuclear Power Plant)	Plutonium (kg, assemblies)	Used (reactor, kg)	Stored (kg, end of year)
1999	Fukushima I (FI) Takahama	210 (32 BWR) 255 (8 PWR)		465
2001	Kashiwazaki Kariwa (KK)	205 (28 BWR)		670
2002	Takahama fuel returned to UK	-255		415
2009	Hamaoka Genkai Ikata	213 (28 BWR) 677 (16 PWR) 831 (21 PWR)	Genkai #3 677	1,458
2010	Genkai Takahama	801 (20 PWR) 552 (12 PWR)	F I #3 210 Ikata #3 633 Takahama #3 368	1,600
2013	Takahama	901 (20 PWR)		
Totals	**Six NPPs**	**4,390 kg** (not including shipment returned to the United Kingdom)	**1,888 kg** in 4 reactors, one of which (FI #3) melted down in 2011	**2,501 kg** at 6 reactors Genkai #3[293] 801 Ikata #3 198 Takahama #3 901 Takahama #4 184 Hamaoka #4 213 KK #3 205

Table 6.1. Plutonium in MOX fuel shipments from Europe to Japan.[294] Totals may not add up exactly due to rounding.

Thus, Japan's MOX-use policy has not significantly reduced its stockpile of separated plutonium, which will grow rapidly again if Japan brings the Rokkasho Reprocessing Plant into operation as planned (Figure 6.1).

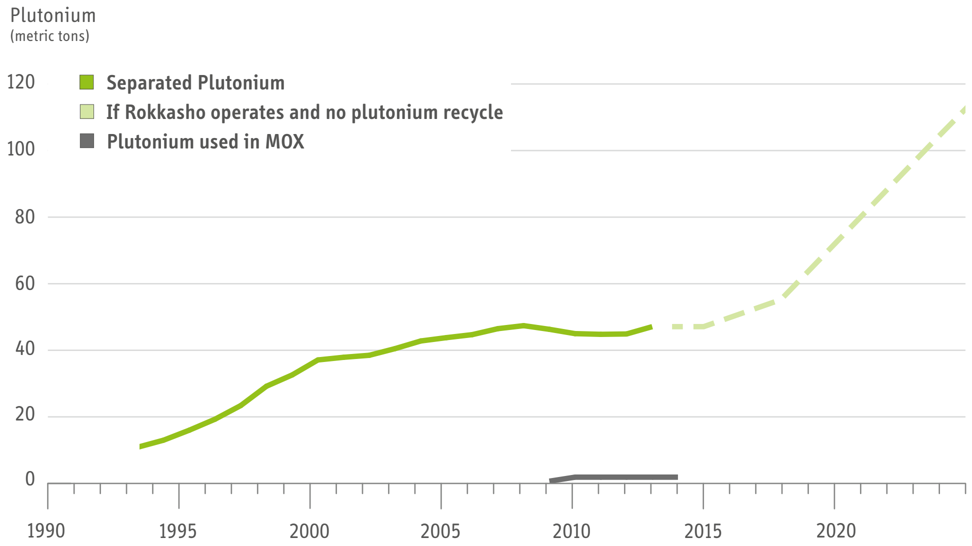

Figure 6.1. Japan's stockpile of separated plutonium, 1993 – 2025. The dashed line shows its projected growth if the Rokkasho Reprocessing Plant operates, beginning in the spring of 2016, at one-third capacity for three years and thereafter at design capacity (8 tons per year) and Japan's plutonium use in MOX continues to be delayed. Bottom line, Japan's cumulative use of plutonium in mixed oxide fuel for light water power reactors.[295]

Japan's reprocessing policy has been hugely costly. In 2011, the JAEC estimated that the cost of building the Rokkassho Reprocessing Plant (Figure 6.2) and operating it for 40 years would be ¥11.5 trillion (~$120 billion) — more than ten times the cost of interim storage of the spent fuel.[296]

Nevertheless, Japan's government has been unwilling to change its policy. Its April 2014 Basic Energy Plan states:[297]

> "GOJ [the Government of Japan] will promote plutonium use in LWRs [light water reactors] and proceed with such measures as completion of the Rokkasho reprocessing plant [and] construction of a MOX fuel processing plant."

Why does Japan continue to pour so much money into reprocessing? As already mentioned, in its 2005 report, Framework for Nuclear Energy Policy, the JAEC argued that reprocessing is necessary for the survival of nuclear power in Japan because, in the absence of central interim spent fuel storage facilities not associated with a reprocessing plant, reprocessing provides the only option for shipping spent fuel off the sites of Japan's nuclear power plants.

The JAEC asserted that:[298]

> "If we make a policy change from reprocessing to direct disposal [since it takes time for communities hosting nuclear power plants to] understand the new policy of direct disposal and accept the interim storage of spent fuel…it is likely that the nuclear power plants that are currently in operation will be forced to suspend operations, one after another, during this period due to the delay of the removal of spent fuel."

An analysis prepared for the JAEC in the process of developing the *Framework for Nuclear Energy Policy* had concluded that, if the cost for fossil fired plants necessary to replace shutdown nuclear power plants was included, the direct disposal option would be more expensive than the reprocessing option.[299]

For its part, Aomori Prefecture has accepted the burden of acting as Japan's interim radioactive waste storage site in exchange for the economic benefits of having the enrichment, reprocessing, and MOX plants. Local reprocessing supporters also maintain that plutonium separation and use are contributing positively to the country. Aomori Prefecture worries that, if the nation's nuclear fuel policy is changed even slightly, there will be a drastic reduction of economic benefits and the spent fuel and radioactive waste will stay there indefinitely (Aomori Prefecture has one nuclear power unit and two under construction, one of which is designed to have a full MOX core). Thus, the Prefecture firmly demands that the government stick to its original policy and operate the reprocessing plant.

Together these motives of the nation's promoters of reprocessing and the leaders of the Aomori Prefecture have combined to produce the one success of Japan's reprocessing policy thus far: an off-site destination for the spent fuel produced by the country's nuclear power plants and interim storage for the radioactive waste resulting from the reprocessing of this fuel and from the reprocessing of Japan's spent fuel in France and the United Kingdom. As of December 2014:

- The 3000-ton-capacity intake pool of the Rokkasho Reprocessing Plant was almost filled with 2,957 tons of spent fuel.[300]
- A dry-cask storage facility with a capacity for an additional 3,000 tons of spent fuel had been built by a joint corporation established by Tokyo Electric Power Company and Japan Atomic Power Company nearby in Mutsu, Aomori Prefecture, with a second building planned that would hold an additional 2,000 tons.
- Aomori Prefecture had agreed to store the radioactive waste from the reprocessing of 7,138 tons of Japanese spent fuel in France and the United Kingdom on the same site as the Rokkasho Reprocessing Plant.[301]
- Finally, the prefecture is storing the plutonium, uranium and high-level waste from the reprocessing of 425 tons of spent fuel during a test run of the reprocessing plant in 2006-8.

Figure 6.2. Japan's Rokkasho reprocessing plant, 2013.

As of the end of 2013, therefore, the total amount of spent fuel and radioactive waste that Aomori Prefecture had taken and committed to take — even before regular operation of the reprocessing plant had begun — was equivalent to 15,563 tons of spent fuel, more than the current amount of the spent fuel stored at all of Japan's nuclear power plants: 14,340 tons.[302] If and when reprocessing starts at Rokkasho, it will result in the accumulation of more waste in the prefecture. Clearly, what Aomori Prefecture needs is a sound national waste disposal policy and assurance of economic and employment support. Reprocessing produces local economic benefits but at enormous cost with no national benefit.

Plutonium management policy

As of the end of 2013, Japan had a stockpile of 47 tons of separated plutonium — 11 tons in Japan and 36 tons at the French and UK reprocessing plants.[303] Using the IAEA's assumption that 8 kg would be sufficient for a first-generation (Nagasaki-type) nuclear weapon, this would be enough for almost 6,000 first-generation nuclear weapons.

Japan's huge stockpile of separated civilian plutonium reflects the failure of its plutonium use program.[304] On 5 December 1997, in its "Plutonium Utilization Plan" submitted to IAEA, Japan committed to "the principle that plutonium beyond the amount required to implement the program is not to be held, i.e., the principle of no surplus plutonium".[305]

On 24 March 2014, in a joint statement with the United States at the 2014 Nuclear Security Summit at The Hague, Japan reaffirmed that "our mutual goal of minimizing stocks of HEU and separated plutonium worldwide, which will help prevent unauthorized actors, criminals, or terrorists from acquiring such materials."[306]

Their statement went on to say that Japan and the United States "encourage others to consider what they can do to further HEU and plutonium minimization."

In Japan's National Progress Report, submitted at the same Nuclear Security Summit, however, the goal of "not possessing excess plutonium" was defined as:[307]

> "not possessing reserves of plutonium *for which the purpose of utilization is undetermined*" [emphasis added]."

The progress report explained how the government determines whether this commitment is being met: "electric power companies and other operators publicly release their plutonium utilization plans. The appropriateness of the plans has been assessed by the Japan Atomic Energy Commission."

Thus Japan has reinterpreted its commitment not to have excess stocks of plutonium into a commitment to have "plans" to deal with its stocks of plutonium even though these plans have been delayed by more than a decade. To implement this policy, power companies and other operators have been required to announce how they intend to consume the plutonium expected to be separated from their spent fuel at Rokkasho in that fiscal year. These announcements are not very specific, however, and only say that the plutonium to be separated at Rokkasho will be consumed as MOX fuel after the MOX fabrication plant (J-MOX) under construction next to the Rokkasho reprocessing plant starts operation.[308] The plans do not mention the schedule for the consumption of the plutonium stored in Europe.

As of the end of 2014, the J-MOX plan was expected to start operating in October 2017.[309] Based on the fact that the safety standard compliance review process by the Nuclear Regulation Authority (NRA) is still going on and past experience with such facilities in other countries, J-MOX may be further delayed and face operational problems even after commissioning.[310]

Soon after the 2014 Nuclear Security Summit, Japan confirmed in its Basic Energy Plan that it would begin to operate the Rokkasho Reprocessing Plant as soon as it received safety clearance to do so. In October 2014, Japan Nuclear Fuel Limited (JNFL), the plant's operator, announced the 21st delay in the plant's completion date since the 1989 application to build it — till March 2016.[311] The delay was due to the Nuclear Regulation Authority's review process. The planned startup date is still well before the expected availability of the J-MOX plant to use the plutonium separated by the reprocessing plant. In any case, there are already 6.3 tons of separated plutonium oxide and nitrate in Japan that could be used for the startup operations of the J-MOX plant.[312] It therefore appears that Japan's "no surplus plutonium" policy has little meaning.

Spent fuel storage

The driving rationale for starting up the Rokkasho Reprocessing Plant as soon as possible is to create space in its spent fuel receiving pool for spent fuel from reactor pools that are filling up. Aomori Prefecture also requires that the plant go into operation before it will give TEPCO and JAPC permission to begin shipping spent fuel to the Mutsu interim spent fuel storage facility.

Utility	Plant	Capacity (GWe)	Discharge (tons U/yr)	Fuel stored (tons U)	Total capacity (tons U)	Years till full
Hokkaido	Tomari 1–3	1.97	27 (38)	400	1,020	23 (17)
Tohoku	Onagawa 1–3	2.09	33 (45)	420	790	11 (8)
	Higashidori 1	1.07	16 (23)	100	440	21 (15)
TEPCO	Kashiwazaki-Kariwa 1–7	7.97	126 (173)	2,370	2,910	4 (3)
Chubu	Hamaoka 3–5	3.47	55 (75)	1,140	1,740	11 (8)
Hokuriku	Shika 1,2	1.61	27 (38)	150	690	19 (14)
KEPCO	Mihama 1–3	1.57	27 (38)	390	670	11 (8)
	Takahama 1–4	3.22	55 (75)	1,160	1,730	10 (8)
	Ohi 1–4 PWR	4.49	60 (83)	1,420	2,020	10 (7)
Chugoku	Shimane 1,2	1.22	22 (30)	390	600	10 (7)
Shikoku	Ikata 1–3	1.92	27 (38)	610	940	12 (9)
Kyushu	Genkai 1–4	3.31	49 (68)	870	1,070	4 (3)
	Sendai 1, 2	1.69	27 (38)	890	1,290	15 (11)
JAPC	Tsuruga 1, 2	1.45	22 (30)	580	860	13 (9)
	Tokai Daini 2	1.06	16 (23)	370	440	4 (3)
Totals		**38.11**	**591 (810)**	**11,260**	**17,210**	**10 (7)**

Table 6.2. Spent fuel stored and total available storage capacity at Japan's nuclear power plants as reported by Japan's Ministry of Economy, Trade and Industry (METI) as of the end of September 2014.[313]
The average spent fuel "burnup" assumed by METI is 36.5 MWt-days/kg.[314] The annual discharge and years-till-full columns in Table 2 have been recalculated assuming a more typical burnup of 50 MWt-days/kg. The METI numbers for annual discharges and their implications for years till full are shown in parentheses. Figures are rounded and therefore may not add up to the total shown.

In fact, as shown in Table 6.2, only three of Japan's fifteen remaining nuclear power plants have significantly less than ten years of remaining storage in their pools: TEPCO's Kashiwazaki-Kariwa, JAPC's Tokai Daini, and Kyushu's Genkai. The first two may not restart because of seismic concerns and, in the case of Kashiwazaki-Kariwa, loss of confidence in TEPCO by the prefecture's governor.[315] In the case of Genkai, a plan has been submitted to the Nuclear Regulation Authority to increase the capacity of the plant's storage pools by 1034 PWR fuel assemblies (about 465 tons or 9.5 years of discharges)[316] and Kyushu Electric Power Company decided to give up on restarting Genkai #1, which will be 40 years old in 2015. Given the fact that even these three plants have about four years of storage left, there is no urgent need to start reprocessing because of spent fuel pools filling up.

If the Rokkasho Reprocessing Plant were abandoned, however, additional interim spent fuel storage eventually would have to be provided for any nuclear power plants that are restarted. But is interim dry-cask storage of spent fuel in Japan outside Aomori Prefecture actually politically impossible? In fact, interim dry cask storage has been installed at two nuclear power plants in Japan: the now closed Fukushima Daiichi Nuclear Power Plant and Tokai Daini (No.2) Nuclear Power Plant.

Fukushima Daiichi

In 1993, the governor of Fukushima Prefecture agreed to additional interim spent fuel storage at the now closed Fukushima Daiichi (No. 1) nuclear power plant in exchange for a commitment from the central government that the spent fuel stored there would be shipped to a planned second reprocessing plant when it went into operation in 2010. Since that time, given that there is no foreseeable need, discussion of a second reprocessing plant, to reprocess additional LWR spent fuel, MOX spent fuel and FBR spent fuel, has been dropped.[317] Given the reduced number of nuclear power reactors that are likely to operate in Japan, the Rokkasho Reprocessing Plant, if it operates at capacity (800 tons/year), could, if desired, process both their fuel and the eventually the stored fuel at the shutdown reactors (see Table 6.2). The problem will be how to dispose of spent MOX fuel since the Rokkasho reprocessing plant is not designed to handle spent MOX fuel.

In any case, in 1997, a central common-use spent-fuel storage pool was completed at Fukushima Daiichi. This pool contained about 1100 tons of relatively old spent fuel at the time the accident occurred in 2011.[318] In addition, a facility at the plant that had been built for temporary storage of spent-fuel transport casks was repurposed in 1994 to hold 20 storage casks.[319] At the time of the accident, nine casks containing 408 BWR spent fuel assemblies, or about 70 tons of spent fuel, were in this facility.[320] Although the building was damaged by the tsunami, the casks and the fuel within them were not.

The approximately 500 tons of spent fuel (3,100 fuel assemblies including fresh fuel) that were in the pools of the damaged Fukushima Daiichi reactors are now being unloaded into the common pool. To accommodate them, about half of the older spent fuel in that pool is being unloaded into dry casks that are to be placed in a temporary storage area on the site, sheltered in temporary structures, each containing one cask. The nine casks that were in the damaged dry-cask storage building also have been moved into the temporary storage area.[321]

Tokai

A dry cask storage facility licensed to hold 24 casks with a total capacity for 250 tons of spent fuel was established at the Tokai Nuclear Power Plant in 2001.[322] As of the end of 2010, seventeen casks had been installed of which two had not yet been filled.[323] Local communities are now demanding for safety reasons the speedy transfer of spent fuel in the pool to dry cask storage. They would accept a second building for additional casks.

The pre-Fukushima-accident record of local acceptance of interim storage in Japan is not all positive, however. In 2004, the mayors of the towns that host Kansai Electric Power Company's three nuclear power plants in Fukui Prefecture expressed a willingness to consider hosting an off-site interim spent fuel storage facility but the governor vetoed the idea.[324]

Developments since the Fukushima accident

Following the 11 March 2011 accident, dry-cask storage has become part of the nuclear safety debate. On 19 September 2012, in his first press conference as chairman of the Nuclear Regulation Authority (NRA), Shunichi Tanaka urged that:[325]

> "Spent fuel not requiring active cooling should be put into dry casks… for five years or so cooling by water is necessary… I would like to ask utilities to go along those lines as soon as possible."

Subsequently, there have been the following developments:

- In 2013, the Governor of Shizuoka Prefecture stressed the need for on-site dry-cask interim storage, saying that it would be a safety prerequisite for restarting the three nuclear power reactors at the Hamaoka nuclear power plant.[326]
- In a 29 October 2014 NRA meeting, Chairman Tanaka and Commissioner Toyoshi Fuketa urged Michiaki Uryu, president of Kyushu Electric Power Company, to introduce dry-cask storage.[327] Tanaka said that he would like President Uryu to voluntarily introduce dry-cask storage for safety and security reasons based on the lessons learned from the Fukushima accident. Uryu replied that the company was considering doing so while at the same time reminding NRA about Kyushu's applications to re-rack the pool of unit #3 and share pool capacity among the reactors at the Genkai site.[328] In fact, before the Fukushima accident, the company had been negotiating with the town of Genkai about constructing an interim storage facility next to the power plant with an initial capacity of about 1,000 tons possibly increasing eventually to 3,000 tons.[329] On 12 December 2014, Kyushu Electric announced a plan to purchase a 10-hectare area adjacent to the 90-hectare site of the Genkai nuclear power plant to solve the problem of "shortage of space at the plant due to the introduction of nuclear accidents response equipment."[330]

Japan's April 2014 Basic Energy Plan states that the government will promote construction and use of dry cask storage both on site and off site.[331] Japan's Ministry of Economy, Trade and Industry is reportedly planning to use special grants to encourage local governments to authorize dry cask storage.[332] Similar recommendations were made by Japan's Atomic Energy Commission in 1987 and 2005,[333] but 21 years after the start of the construction the Rokkasho Reprocessing Plant, with its future operation still uncertain, the government may be feeling a sharper sense of urgency.

Conclusion

The futures of reprocessing and of its alternative, interim dry-cask storage, are uncertain in Japan. The Abe Administration, like its predecessors, seems unwilling to deal with the challenges of decisively ending Japan's reprocessing policy. The arguments for continuation of the present policy, however, are weak.

The choice between reprocessing and shutting down Japan's reactors offered by Japan's Atomic Energy Commission in 2005 was a false one. If local and prefectural governments approve the restart of nuclear power plants that they host, it will be because they have decided that the economic benefits outweigh the safety risks. Given the safety advantages of dry cask storage, it would be irrational for them to later force the reactors to shutdown when the pools fill up if there is no off-site destination to which spent fuel can be shipped.

The example of the priority being given to move the spent fuel in the pools of the four damaged reactors at Fukushima to dry casks may help the public understand the safety advantages of dry cask storage. The calls for swift transfer of spent fuel in pools to dry cask storage coming from the communities hosting the Tokai Daini and Hamaoka Nuclear Power Plants could be a harbinger of change. Experts and the media still have a lot to do, however, to inform the public about the safety benefits of dry casks. METI's decision to encourage dry cask storage may help in this regard. If the central government moves forward more convincingly in the process of siting a spent fuel repository, that also could help reassure local governments hosting nuclear power plants that eventually the spent fuel will leave.

The newest argument for reprocessing, that fissioning plutonium and other transuranics in spent fuel is essential to waste management, was challenged in May 2014 by the chairman of METI's technical working group on radioactive waste disposal, "If our aim isn't to utilize resources [with breeder reactors], then it would be better to dispose of the waste directly without reprocessing it."[334]

Some proponents maintain that, unless the Rokkasho Reprocessing Plant is started soon, the United States might try to withdraw its prior approval for spent fuel reprocessing in Japan in the negotiation of the U.S.-Japan Nuclear Cooperation Agreement, which is up for renewal in 2018. The message from the United States and other concerned countries should be that operations at the plant should be suspended until Japan fulfills its 1997 commitment of "no excess plutonium."

Foreign criticism of the size of Japan's plutonium stockpile could play a significant role in persuading its government to rethink its policy. There already is speculation that, because of foreign pressure, Japan may operate the reprocessing plant at only a fraction of its design capacity. One must be careful not to be overoptimistic, however, because the plan in any case is to reprocess only 240 tons, i.e., at 30 percent of design capacity during the startup year of the of the plant. Operation at any level will be used by Japan's reprocessing advocates to establish it as a fact that this unnecessary and dangerous plant has begun operating and will continue to do so.

7. South Korea

South Korea does not reprocess spent fuel today but has been demanding in its negotiations with the United States over a new Agreement on Nuclear Cooperation that the United States give "prior consent" to future South Korea reprocessing of spent fuel. Under their current agreement, South Korea has to obtain U.S. consent before reprocessing any fuel that was enriched in the United States or was irradiated in a U.S. designed reactor — in effect, this means the spent fuel discharged by all but two of South Korea's light water reactors (LWRs).[335] The Reagan Administration gave Japan such prior consent in 1988.

The argument for reprocessing being made by the Korea Atomic Energy Research Institute (KAERI) is the same one that Japan's Atomic Energy Commission used to justify Japan's reprocessing in 2005:[336] unless an off-site destination can be found to which spent fuel can be shipped, the reactors will have to be shut down when their spent fuel pools fill up a decade hence (Table 7.1).

Site	Reactor type	Reactors (+ under construction)	Spent fuel inventory, end 2013 (tHM)	Pool capacity (incl. reracking) (tHM)	Projected year when full
Kori	LWR	6 (+2)	2,291	7,244	2031
Hanul (Ulchin)	LWR	6 (+2)	1,938	5,525	2028
Hanbit (Yonggwang)	LWR	6	2,285	3,802	2023
Shin-Wolsong	LWR	2	28	1,093	2034
LWR subtotals		**20 (+4)**	**6,541**	**17,664**	
Wolsong	HWR	4	7,258	3,257 (pools) + 9,562 (casks)	2027

Table 7.1. Spent fuel inventories and storage capacities at South Korea's nuclear plants, 2013.[337]

It appears that the new Agreement for Cooperation announced in 2015 will not include U.S. prior consent for spent-fuel reprocessing in South Korea but the agreement will be open for the amendment and the discussion will continue.

South Korea's spent-fuel problem

In total, as of the end of 2013, South Korea had 6,541 tons of spent LWR fuel and 7,258 tons of spent heavy water reactor (HWR) fuel stored at four nuclear power plants (NPPs).

For years, Korea Hydro and Nuclear Power (KHNP), South Korea's nuclear utility has been warning that the pools at its three light water reactor (LWR) nuclear power plants were within a few years of being full and that a spent-fuel storage crisis was imminent. Some of these warnings were premature because they did not take fully into account the possibilities of dense-racking the pools,[338] and transfers of spent fuel between pools on the same site.[339] Table 7.1 shows, for the LWR pools, when the possibilities of re-racking and transfers between pools on the same site are taken into account, they will be full in different years ranging from 2023 to 2034.

The pools of the four heavy water reactors (HWRs) at Wolsong are already full. These reactors are fueled by natural uranium that is discharged at a much lower "burnup" (fission energy release per kilogram of uranium) than the fuel made with enriched uranium that is used in the LWRs. For the same power output, they therefore discharge spent fuel at about seven times the rate of LWRs. Cumulatively, they have discharged more spent fuel than South Korea's 19 LWRS and their spent fuel storage pools filled up in the 1990s. Since then, space has been created in the pools for newly discharged spent fuel at Wolsong by unloading older cooled spent fuel into air-cooled dry casks (Figure 7.1). Although this situation has attracted much less national attention than the anticipated filling up of the spent-fuel storage pools at the LWR sites, it undercuts KAERI's argument that on-site dry cask storage is politically impossible at the LWR sites.

Figure 7.1. Dry spent fuel storage at South Korea's Wolsong Nuclear Plant, 2014. Coordinates 35° 42'28"N, 129°28'38"E. The area in the lower left shows some of the spent fuel stored in individual casks and some in canisters embedded in reinforced concrete monoliths (see Figure 2.1 for a close-up of similar monoliths in China). This dry store currently has a capacity for as much tonnage of fuel as is in all of the pools of South Korea's nineteen pressurized water reactors but covers an area no bigger than that covered by one of the heavy water reactors and its associated structures at the top of the image. *Source: Digital Globe/Google Earth, 20 March 2010.*

Early efforts to site a central interim spent-fuel storage facility

South Korea has been attempting to find a host community for an off-site interim spent fuel storage facility since December 1988, when the Korea Atomic Energy Commission announced its intention to construct an away-from-reactor storage pool with a capacity for 3,000 tons of spent fuel. KAERI proposed three sites as technically suitable but all three communities rejected the facility and this initial effort was abandoned. In 1991, KAERI proposed a site on Anmyeon Island, but that proposal too was rejected by the local government. In 1993, the government offered additional incentives but was again rejected at two sites.

Finally, in 2003, the government offered a large financial incentive, 300 billion Korean won (about $300 million) and to move the headquarters of South Korea's nuclear utility, Korea Hydro and Nuclear Energy Company, to a community willing to host either a spent fuel storage site or a repository for low and intermediate waste. The mayor of Buan County volunteered to host the interim spent fuel storage facility but this led to the "Buan Uprising" of 2003, a referendum, and the withdrawal of the offer.[340]

In 2004, the Atomic Energy Commission decided to temporarily suspend the search for an interim spent fuel storage site and to focus instead on siting a shallow repository for short-lived low and intermediate-level wastes. A key change in its approach was the establishment of a competition between potential host communities for the repository and the associated economic incentives and the requirement of a referendum to measure the level of public support in candidate localities. The greatest political support was found in Geongju, which already hosts the Wolsong Nuclear Power Plant. In 2005, therefore, Korea's waste repository for low and intermediate-level waste was sited adjacent to the Wolsong Nuclear Power Plant.[341] Construction of the first six underground "silos" to hold the radioactive waste was completed in 2014.[342]

Pyroprocessing

In the meantime, in the United States, Congress's 1987 decision to site the national spent fuel repository under Yucca Mountain, Nevada was encountering increasing local political resistance. In 2001, Dr. Yoon Il Chang, Associate Laboratory Director for Engineering Research at Argonne National Laboratory, persuaded Vice President Cheney's National Energy Policy Development Group that pyroprocessing, a form of reprocessing in which the spent fuel is turned into a metal and dissolved in molten salt, might be able to solve the U.S. spent fuel problem. Unlike PUREX [Plutonium-Uranium Extraction], the standard reprocessing technology that had originally been developed in the United States to separate pure plutonium for weapons, the plutonium separated by pyroprocessing would be mixed with some uranium, the minor transuranic elements (neptunium, americium and curium) and lanthanide fission products.[343] The proposal was to use this mix as fuel for the liquid-sodium-cooled reactors that Argonne had been developing.

Dr. Chang also convinced Vice President Cheney's group that, because it does not separate pure plutonium, pyroprocessing is "proliferation resistant" and could be shared with other countries.[344] The Department of Energy gave Argonne permission to collaborate with KAERI on pyroprocessing research.

It was only at the end of the Bush-Cheney Administration that a systematic proliferation assessment of pyroprocessing by six U.S. national laboratories, including Argonne, was launched.[345] In 2009, a summary report was published that assessed pyroprocessing and two other proposed reprocessing technologies that do not produce pure separated plutonium. It found "only a modest improvement in reducing proliferation risk over existing PUREX technologies and these modest improvements apply primarily for nonstate actors."[346]

Nevertheless, both KAERI and Chang — now an advisor to KAERI — still insist that pyroprocessing is proliferation resistant.[347] KAERI has become a strident public advocate for pyroprocessing and managed to turn the issue of South Korea's right to reprocess into an issue of national pride ("nuclear sovereignty") and a central obstacle in the negotiations with the United States over the renewal of the two countries' Agreement of Nuclear Cooperation. The Obama Administration's unwillingness to follow the example of the Reagan Administration, which agreed in 1988 to give Japan "prior consent" for reprocessing of spent fuel, has been a particularly inflammatory issue in South Korea.[348]

U.S. State Department officials have argued that South Korea is a special case because of its 1992 agreement with North Korea that neither country would introduce either reprocessing or enrichment into the Peninsula. This argument has been undermined, however, by the fact that North Korea has blatantly violated the agreement.

In view of the difficulty of the negotiations, the United States and South Korea agreed to extend the expiring Agreement on Cooperation for two years to 2016. A ten-year-long US-ROK joint study on spent fuel management, including on the technical and economic "feasibility" of pyroprocessing, was launched in 2011.

In late 2014, it appeared that a compromise on a new Agreement on Cooperation may have been achieved in which KAERI would be allowed to carry out research on the preparation of light water reactor spent fuel for pyroprocessing, i.e., the conversion of the uranium, transuranic and fission-product oxides into molten metal.[349] The Agreement could be amended at a later date if, as a result of the joint research effort, both sides agreed that pyroprocessing of U.S. controlled spent fuel was necessary and could be carried out without undue proliferation risk. The United States also agreed that Argonne National Laboratory can collaborate with KAERI on the development of a sodium-cooled fast reactor if that reactor is fueled with low-enriched uranium, i.e., uranium enriched to less than 20 percent uranium-235.[350]

KAERI insists that direct disposal of spent fuel is both physically and politically impossible in South Korea. It argues that, if the plutonium and other long-lived transuranic elements were separated, sodium-cooled fast-neutron reactors could be used to fission them, thereby reducing the area of a repository to a manageable size.[351] Much of the reduction would be accomplished, however, by storing the fission products on the surface for two to three hundred years until they had largely decayed into stable non-heat-producing isotopes. This decay has nothing to do with reprocessing. Storage of un-reprocessed spent fuel on the surface would have the same result.

KAERI's advocacy of pyroprocessing has been supported by the Ministry of Science, ICT [Information and Communication Technology] and Future Planning (previously the Ministry of Education, Science and Technology), which funds KAERI's research on pyroprocessing and sodium-cooled reactor research and development.[352] The nuclear utility, Korea Hydro and Nuclear Power, and the Ministry of Trade, Industry and Energy, which oversees it, have not embraced pyroprocessing, however, because of concerns about its cost.

When pressed, KAERI experts acknowledge that it would take South Korea until mid-century to deploy both pyroprocessing and sodium-cooled reactors on the scale required to keep up with the rate of discharge of spent fuel by South Korea's power reactors. They also acknowledge that South Korea might — as other countries have — find liquid- sodium-cooled reactors too costly and unreliable to deploy on a commercial scale. They argue, however, that the prospect of the jobs associated with building and operating a pyroprocessing facility would help persuade a local government to host an interim spent fuel storage facility designated as the future site of a pyroprocessing facility.[353]

Figure 7.2. Surface facilities at Finland's planned Onkalo Repository, 2010. Coordinates N 61° 14' 10", E 21° 28' 50 The repository facilities occupy an area of about 0.25 km² (the small white rectangle on the right), one sixteenth that of the reactor site which hosts two operating reactors and one under construction (the white rectangle on the left). *Source: Satellite image by Digital Globe/Google Earth, 31 May 2010.*

Could an underground spent-fuel repository fit in South Korea?

A key argument KAERI makes for reprocessing is that the area of an underground spent-fuel repository would be too large for South Korea:[354]

> "By the end of the century (assuming the new planned reactors come on line), the cumulative amount of spent fuel produced by South Korean reactors is expected to exceed 110,000 tons. To dispose of such a large amount of spent fuel at a single site, an underground repository (and an exclusion zone surrounding the site) would need to cover as much as 80 square kilometers, an area considerably larger than Manhattan. Finding that much free space in South Korea would be enormously difficult. The country is approximately the size of Virginia and is home to about six times as many people."

The claim that a repository would require an area of 80 square kilometers builds on another KAERI paper that lays out a reference scenario in which nuclear power based on unchanged pressurized water reactors (PWRs) would double its share of a growing South Korean electricity supply from 27.5 percent in 2013 to 59 percent in 2030 and thereafter maintain that share for another 70 years until the end of the century. (South Korea's four HWRs are assumed to have a 50-year lifetime, after which they would be replaced with PWRs.) For that scenario, 92,000 tons of PWR and 18,000 tons of heavy water reactor spent fuel would accumulate by 2100. On the basis of Sweden's repository design, it was estimated that the area over which a South Korean repository would be spread if the rock were fault-free would be 15–20 km^2. If the site were intersected with faults, the area might increase to 22–46 km^2. [355]

Such a repository could be accommodated within a square 5 to 7 km on a side. For comparison, South Korea's nuclear power reactors occupy about 0.5 km of ocean front each. For the 69 GWe of nuclear capacity in KAERI's reference scenario for 2100 (assuming large 1.4 GWe reactors) 25 km of shoreline would be required. This is a relevant comparison, because the acceptance of the low-and-intermediate-level waste storage site adjacent to South Korea's Wolsong nuclear power plant and the siting of Sweden's and Finland's planned spent fuel repositories next to nuclear power plants suggest that communities that already host nuclear power plants are the most likely to be willing to host underground spent fuel repositories. Also, in most areas of South Korea where there is a low enough population density along the coast to accommodate a nuclear power plant, the area of low populations density extends inland.[356]

To get from an area of 22–46 square kilometers for a repository to 80 square kilometers KAERI adds "an exclusion zone surrounding the site".[357] The unwary reader could interpret the term as referring to an area where residential and business activities would be excluded. In fact, only deep drilling and mining need be excluded. One of the basic criteria for a spent-fuel repository site is that there be no deep underground resources that could attract such activities.[358] As Figure 7.2 shows for the case of Finland's Olkiluoto Nuclear Power Plant and the planned Onkalo underground repository adjacent to it, the surface installations associated with the repository have a much smaller area than that of the nuclear power plant.

On-site interim spent fuel storage

As has already been noted, South Korea has installed at the Wolsong Nuclear Power Plant more than 6,000 tons of dry cask storage capacity. This was done by the nuclear utility, KHNP, without consultation with the local government. KHNP could do the same on its other nuclear power plants but local public support obviously would be preferable.

In October 2013, South Korea's Minister of Trade, Industry and Energy (MTIE) established a Public Engagement Commission on Spent Fuel Management (PECOS) that is charged to consult widely and come up with a proposed policy for spent fuel management in South Korea. The thirteen members of PECOS are from academia, the regions that host South Korea's nuclear power plants, and non-governmental organizations.

The Commission is to provide recommendations to the South Korean government on spent fuel management by June 2015.[359]

It is expected that the Commission will describe reprocessing or deep burial of spent fuel as long-term options and will focus on options for interim dry-cask storage. The political struggle is over whether that storage will be on or off the nuclear power plant sites. In October 2014, South Korea's Nuclear Society issued a report urging storage at a central location.[360] Opponents of reprocessing believe that the thinking behind this recommendation is that the site would naturally develop into a center for pyroreprocessing, transuranic fuel fabrication and fast-neutron reactors to use that transuranic fuel.

With regard to on-site dry cask storage, consultations by a non-governmental group with local citizens at three out of four of the existing sites suggest that the local communities could be persuaded to accept dry cask storage, in part because of its safety advantages relative to spent-fuel pool storage.[361] Some financial compensation for acceptance of long-term interim spent-fuel storage would be expected, but this financial compensation would be negligible in comparison to the cost of pyroprocessing or off-site storage.

Conclusion

The future of spent fuel management is uncertain in South Korea. KAERI is lobbying for support of research and development on pyroprocessing and fast-neutron reactors, arguing that they are essential for spent fuel management in South Korea. Research and development on the scale proposed would, however, separate enough plutonium for a substantial nuclear-weapon program.[362]

In the meantime, the spent-fuel-storage pools at South Korea's older nuclear power plants are filling up and interim storage must be built whether or not pyroprocessing is pursued. KAERI would like off-site storage at a single site. Experience has shown that it is difficult to site central storage facility.

Committing to build pyroprocessing and fuel fabrication facilities and perhaps even fast reactors on a central storage site could be attractive to possible host communities because of the large number of jobs that would be created. Korea Hydro and Nuclear Power and the Ministry of Trade, Industry and Energy are reluctant to make such a commitment, however, because the use of pyroprocessing and transuranic fuel would make nuclear power in South Korea more expensive.

It is possible that KAERI's domination of South Korea's public debate over reprocessing may be broken by the report of the Public Engagement Commission on Spent Fuel Management (PECOS). The Commission's primary task is to map a path forward on interim storage of South Korea's spent fuel. If that could be done onsite at the reactors without committing to a hugely expensive reprocessing facility as the price of accepting storage, then the pressure for committing to pyroprocessing would be dramatically reduced.

8. Russia

Russia has the world's fourth largest nuclear generating capacity, 25 GWe as of the end of 2014, and is an important nuclear exporter. In the near term, light water reactors (VVERs) will dominate. In the longer term, Russia's national nuclear company (Rosatom) has accepted the view of its nuclear-energy establishment that limited uranium supplies and increasing stocks of spent fuel require the development of a closed fuel cycle based on fast-neutron plutonium-breeder reactors. Rosatom therefore has initiated several federal target programs aimed at the development of breeder reactors and plutonium recycle technologies.[363] The most recent, Program 2010, focuses on the development and demonstration of a variety of prototype fast-neutron breeder reactors fueled with plutonium.

Rosatom's strategy for spent nuclear fuel management, as laid out in its "Program of creation of infrastructure and spent fuel management for 2011–2020 and until 2030" has two stages.[364] During the first stage, Rosatom will:

- Complete construction of a national long-term dry storage facility for spent nuclear fuel at the Mining and Chemical Combine (MCC) at Zheleznogorsk near Kraznoyarsk, Siberia; and
- Develop innovative spent nuclear fuel reprocessing and plutonium-fuel fabrication technologies.

The second stage, presumably starting in 2021, would include the design and construction of a long-delayed large-scale spent fuel reprocessing plant and a plant to fabricate the recovered plutonium into mixed-oxide (MOX, uranium-plutonium) fuel for fast breeder and light water reactors. According to the plan, these plants are to be operating by 2030 and a deep geological repository is to be in place for disposal of the associated long-lived and highly radioactive wastes.

Despite this reconfirmation of a long-delayed plan that goes back to the 1960s, however, the current focus on research and development on different technologies for reprocessing and on different types of breeder reactors indicates uncertainty within Rosatom about the economics of the current reprocessing plant and breeder reactor designs.

Central long-term dry storage

The Federal Target Program (FTP) "Nuclear and Radiation Safety for year 2008 until 2015", approved by the government on 13 July 2007, proposed, among other things, the construction of additional central spent-fuel storage capacity at MCC and infrastructure for transport of spent fuel from Russia's nuclear power plants to that site. Ninety percent of the 145.3 billion rubles (approximately $5 billion) for funding the program comes from the federal budget.[365] The program's priorities include: [366]

- Refurbishment of the existing storage pools at the MCC in Zheleznogorsk for VVER-1000 light water reactor spent nuclear fuel;[367] and
- Construction of a new dry-cask spent-fuel storage facility at MCC.

MCC currently has two storage pools. The original design capacity of the first was about 6,000 tons (13,416 VVER-1000 fuel assemblies). Due to the installation of higher-density storage racks and the completion of an additional pool in November of 2011, the total pool storage capacity has been increased to 8,600 metric tons.[368] It is expected, however, that the facility will be completely full by the end of 2015. Starting in 2016, therefore, spent fuel that has been stored in the pools for more than ten years is to be transferred to dry-cask storage.[369]

A huge central dry-cask spent fuel storage facility is under construction at MCC with a planned capacity of 37,785 metric tons: 11,275 tons of VVER-1000 spent fuel and 26,510 tons for spent fuel from Russia's graphite-moderated RBMK-1000 power reactors. A first module, with a capacity for 1000 casks (8,129 metric tons) of RBMK-1000 fuel, was put into operation at the end of 2011.[370] As of the end of 2013, the first 427 tons (3744 spent fuel assemblies) of RBMK spent fuel had arrived from the Leningradskaya and Kurskaya Nuclear Power Plants (NPPs).[371] As of mid-2014, a second module was under construction with a design capacity of 11,275 tons of VVER-1000 spent fuel. It was to be put into operation by the end of 2015.[372]

Quantities of spent fuel and pilot reprocessing

Russia currently has over 23,000 tons of spent power-reactor fuel in storage (Table 8.1) and a pilot reprocessing plant, the RT-1 facility at Mayak in the Urals. Until recently, the only civilian power-reactor spent fuel reprocessed at Mayak has been from first-generation pressurized water (VVER-440) reactors and the sodium cooled BN-600 demonstration breeder reactor. Starting in 2013, however, RT-1 also began reprocessing an estimated 650 tons of damaged RBMK-1000 spent fuel assemblies currently stored in storage pools. RT-1 reprocessed more than 22 tons of this fuel during 2013 and the plan was to reprocess 50 tons annually starting in 2014.[373] RBMK spent fuel has lower burnup and therefore contains a lower percentage of plutonium than light water reactor fuel. Except for defective spent fuel assemblies, which constitute about 5 percent of the total RBMK-1000 spent fuel, there are no plans to reprocess it.[374]

The RT-1 reprocessing plant, which came into operation in 1977, was designed for a throughput of up to 400 metric tons of spent fuel per year but in recent years has not reprocessed more than 130 metric tons per year.[375] The plant also reprocesses naval and research reactor spent fuel. The recovered uranium is blended to an enrichment of 2.6 percent for fabrication into fuel assemblies for RBMK reactors. The high-level reprocessing waste is vitrified (embedded in glass) and placed in an on-site storage facility.

Based on the approximately 50 tons of separated civilian plutonium stored at Mayak as of the end of 2013, and assuming that VVER-440 spent fuel contains about 1 percent plutonium, RT-1 has cumulatively reprocessed about 5000 tons of VVER-440 spent fuel.[376]

	Number units & reactor type	Net generating capacity (MWe)	Start of commercial operation	Stored spent fuel (metric tons as of 1 Jan. 2014)
At VVER Sites				
Balakovo	4 VVER-1000	3,800	1985 – 1993	420
Kalinin	4 VVER-1000	3,800	1984 – 2011	278
Kola	4 VVER-440	1,644	1973 – 1984	97
Novovoronezh	2 VVER-440 2 VVER-440 1 VVER-1000	1,720	shutdown 1972 – 1973 1981	76 200
Rostov (Volgodonsk)	3 VVER-1000	2,911	2001 – 2014	150
At RBMK Sites				
Kursk	4 RBMK-1000	3,700	1976 – 1985	5,374
Smolensk	3 RBMK-1000	2,775	1983 – 1990	2,986
Sosnovy Bor (Leningrad)	4 RBMK-1000	3,700	1973 – 1981	4,962
At Other Sites				
Beloyarskt	2 AMB 1 BN-600	248 560	Shutdown 1980	191 30
Bilibino	4 EGP-6	44	1974 – 1976	160
In Central Storage				
Mayak (VVER-440)				320
MCC (VVER-1000) (RBMK-1000)				7,380 427
Total	**34**	**24,654**		**23,051**

Table 8.1. Estimated stocks of spent power-reactor fuel in Russia, 2013.[377] VVER - pressurized-water reactor; RBMK, AMB, EGP - graphite-moderated, water-cooled reactors; BN - sodium-cooled reactor.

Russia's eleven RBMK-1000 reactors discharge 400–450 tons of spent fuel annually.[378] The original combined design capacity of their spent-fuel storage pools was about 6,000 tons but has been more than doubled by the installation of higher density storage racks. Cumulatively, as of the end of 2013, Russia's RBMKs had discharged about 13,750 tons of spent fuel of which about 13,320 tons were still stored in pools adjacent to the reactors and in separate central storage pools on the same sites. Given that these pools were close to capacity, as already noted, Rosatom has begun shipping spent fuel to the new dry-cask spent fuel storage facility at the Mining and Chemical Combine (MCC) in Zheleznogorsk.

Russia's twelve VVER-1000 reactors produce together 270–300 tons of spent fuel annually. As of the end of 2013, about 1,000 tons were stored at the nuclear power plant sites. After three to five years in the cooling pools, the spent fuel is shipped to the centralized pool storage facility at MCC in Zheleznogorsk. As of the end of 2013, about 7380 tons of VVER-1000 spent fuel was stored at this facility. This quantity includes some spent fuel shipped from Ukrainian and Bulgarian nuclear power plants. Currently, the VVER-1000 spent fuel is not reprocessed, but the plan is to reprocess it at Zheleznogorsk.

Six older VVER-440 units discharge a total of about 55.5 tons of spent fuel annually.[379] The VVER-440 spent-fuel assemblies are relatively small, containing only 115 kilograms of uranium each, as compared to 390 kg in a VVER-1000 fuel assembly. After cooling in the reactor storage pools for three to five years, this fuel is shipped for reprocessing in the RT-1 plant.

The BN-600 discharges annually 3.7 tons of spent fuel and 2.5 tons of blanket containing together about 0.36 tons of plutonium. The spent fuel is cooled at the reactor site for three years before being sent to RT-1 for reprocessing.

About 160 tons of spent fuel have been discharged over the lifetimes of the four 11 MWe graphite-moderated, water-cooled EGP-6 reactors, which went into operation in the mid-1970s at Bilibino on Russia's Artic coast. All this fuel is stored on site.

Breeder reactor development

Russia's nuclear-energy community has long agreed that the future development of nuclear power in the country should be based on fast-neutron sodium-cooled plutonium breeder reactors operating on a "closed" fuel cycle with plutonium and uranium recycle. The schedule for breeder commercialization continues to slip, however, and thus far, very little plutonium has been used as fuel (see Table 8.2). Since it began operating in 1980, Russia's only operating fast-neutron reactor, the BN-600, has been fueled with highly enriched uranium. The current plan, however, is to fuel it with MOX made from excess weapons plutonium starting in 2018.[380] The BN-800, which became critical in 2014, had MOX as well as HEU fuel in its initial core and the plan was to switch to a full core of MOX about two years later.[381]

Experimental reactors	
BR-1 critical facility	1955 – 2010
BR-2	1956
BR-5/10	1959 – 2002
BOR-60	1968 – in operation
Demonstration reactors	
BN-350	1972 – 1999
BN-600	1980 – in operation
BN-800	start of commercial operation scheduled for 2015
SVBR-100	start of operation scheduled for 2017
BREST-300	start of operation scheduled for 2020
Commercial reactors	
Plan to construct five BN-800 adopted (was not realized)	1980
Program planning the commercialization of fast breeder reactors by 2025–2030 adopted	2010

Table 8.2. Timeline of Soviet/Russian fast breeder reactor program.[382]

Rather than replicating the BN-800, Rosatom's current strategy is to focus on the development and construction of different types of breeder reactors while, in parallel, conducting research and development on improved spent fuel reprocessing technologies.

In January 2010, the government adopted Federal Program 2010 with a total budget 170.6 billion rubles (≈$5 billion) of which 64 percent will come from the federal budget.[383] Its primary focus is the development of new types of fast neutron reactors. Accordingly, in November 2011, Rosatom's Director General approved a program to develop new experimental fast neutron power reactors, technologies for fabrication of mixed oxide (MOX) and dense nitride uranium-plutonium fuels, and advanced spent fuel reprocessing technologies.[384]

New experimental fast-neutron power reactors.

Historically, the focus of Soviet/Russian breeder-reactor development efforts has been on sodium-cooled reactors (Figure 8.1). The high radioactivity induced by neutron absorption in the sodium coolant and the possibility of a sodium fire in an accident are obstacles to making a convincing safety case for sodium fast reactors, however. Rosatom therefore has decided to fund another cycle of research on fast-neutron reactors with alternative coolants.

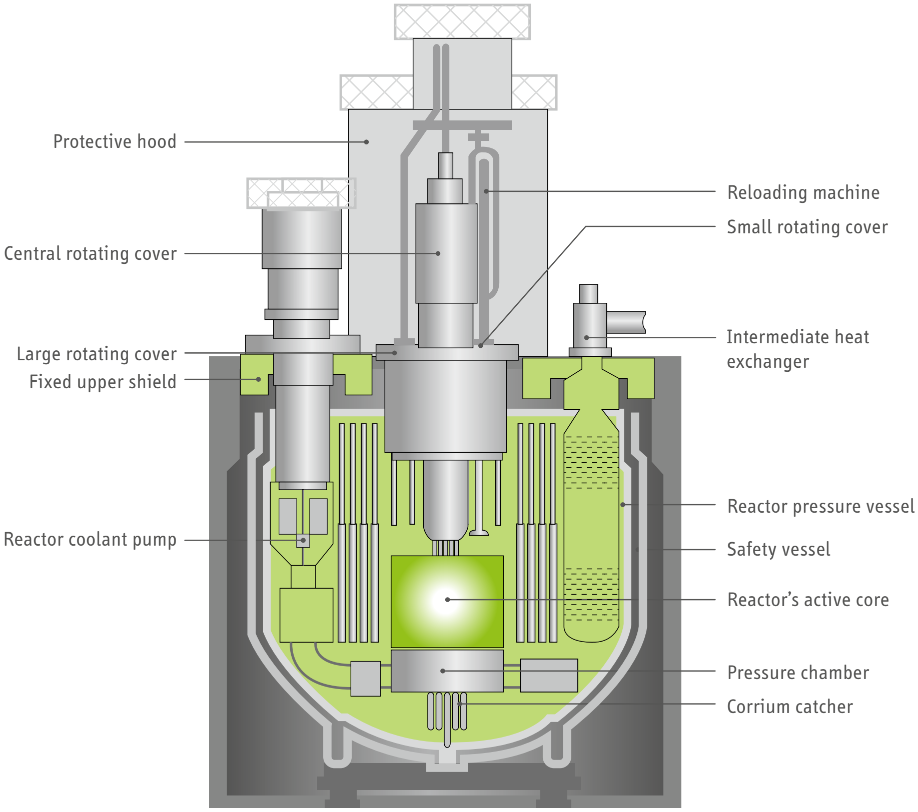

Figure 8.1. Cross-section of the BN-800 fast neutron reactor. Secondary sodium flows through three intermediate heat exchangers immersed in the primary sodium. The secondary sodium then carries the heat to steam generators.[385] *Source: Institute of Physics and Power Engineering.*

Lead is non-flammable and does not become highly radioactive when used as a coolant in a reactor. Also, neutrons lose little energy in collisions with heavy lead nuclei, which allows for larger spacing between fuel rods and more natural convective circulation of its coolant. Designers of lead-cooled reactors also propose the use of high-density, high heat-conductivity nitride fuel and compact electrochemical reprocessing technologies that would allow co-extraction and recycle of uranium, plutonium, and the minor transuranic elements.

Of the federal funds, 25.3 billion rubles (≈$0.8 billion) have been allocated for the design and construction of BREST-300, a pilot fast-neutron lead cooled reactor with a power of 300 MWe. It will be located in the Siberian Chemical Combine near Tomsk and is to be completed in 2020. The Moscow-based nuclear institute NIKIET is responsible for the design.[386] A large liquid metal test facility, SPRUT, has been established at the Institute of Physics and Power Engineering (IPPE) in Obninsk outside Moscow for experimental testing of the steam-generator design.[387]

Lead is extremely corrosive at high temperatures, however, and some Russian experts believe that the data on its reactions with reactor materials is inadequate for the development of a lead-cooled reactor.[388] Program 2010 therefore is also funding the development of a lead-bismuth cooled reactor and continued development of large sodium-cooled reactors.

Rosatom and Irkutskenergo, a private company, have established a joint venture, AKME-Engineering, for the construction of an experimental lead-bismuth-cooled fast-neutron reactor, SVBR-100, with a generating capacity of 100 MWe at the Research Institute of Atomic Reactors (NIIAR) in Dimitrovgrad.[389] A construction license was issued on 27 November 2013,[390] and completion is planned for 2017.[391] Funding originally committed was 13.2 billion rubles with 9.5 billion rubles coming from Irkutsenergo. Recently, however, the estimated project cost has more than doubled.[392]

Finally, Program 2010 allocated 5.1 billion rubles for the design of the BN-1200, a fast neutron sodium cooled reactor that is seen as the next step toward the commercialization of sodium-cooled reactors after the BN-800.[393] A key goal is to bring the cost of down to a level comparable to the cost of building a light water reactor with the same generating capacity. OKBM plans to complete the scientific research and design work by 2016.[394] In July 2014, Rosenergoatom, the division of Rosatom that operates Russia's nuclear power plants, announced plans to build three BN-1200s with construction to start by 2030. The first BN-1200 is to be located at the Beloyarskaya nuclear power plant, which already hosts the BN-600 and BN-800 reactors.[395] The final decision to build the BN-1200, however, awaits the assessment of the operation of the BN-800, which went critical on 27 June 2014.[396]

Mixed uranium-plutonium fuel production

Activities related to the production of fuel for fast-neutron reactors are taking place at four different sites in Rosatom's huge nuclear complex (Table 8.3):

- At the Mining and Chemical Combine (MCC) site in Zheleznogorsk, a plant has been built in the underground complex where separation of weapon-grade plutonium from uranium irradiated in the Zheleznogorsk production reactors previously took place. Pellet-type MOX fuel will be produced from both reactor- and excess weapon-grade plutonium for the BN-800 fast reactor.[397] The plant has a design capacity of 12.5 tons (400 fuel assemblies) per year with an estimated cost of 11.7 billion rubles.[398]

- The Research Institute of Atomic Reactors in Dimitrovgrad has produced 162 MOX fuel assemblies for the BN-800 initial core using vibro-packing technology.[399]
- At the Russian Federal Nuclear Center (VNIITF) in Snezinsk, a laboratory complex is being reconstructed and re-equipped with a chain of hot cells with an inert atmosphere for R&D and pilot production of mixed nitride fuel.[400]
- At the Siberian Chemical Combine (SCC) in Seversk, a first batch of experimental nitride fuel assemblies for the BREST and BN-1200 reactors was produced in March 2013. Test irradiation of these fuel assemblies in the BOR-60 and BN-600 fast-neutron reactors were to be initiated by September of 2013.[401]

In total, the federal Program 2010 allocated 18 billion rubles for the development of technologies for the production of dense nitride fuel for fast reactors.[402]

Technology	Design throughput (tons heavy metal/year)	Location
Pellet MOX for BN-800	12.5	MCC, Zheleznogorsk
Vibro-packed MOX for BN-800	1.9	NIIAR, Dimitrovgrad
Nitride Fuel	For fuel tests	SCC, Seversk
Nitride Fuel	Production R&D	VNIITF, Snezinsk

Table 8.3. Rosatom's projects for the fabrication of plutonium fuels.

Advanced spent fuel reprocessing technologies

Advanced fuel reprocessing technologies are being developed and deployed at the same four sites (Table 8.4):

- At MCC, a nuclear fuel reprocessing demonstration center is being constructed.[403] It will focus on the development of innovative technologies for the reprocessing of light water reactor spent fuel. One objective is to reduce the volume of high-level waste from reprocessing from the current level of about one to 0.075 cubic meter per ton of spent fuel. Another is the joint extraction of uranium, plutonium and minor transuranics for use in mixed oxide (MOX) fuel for fast reactors.[404] The originally planned capacity of the pilot plant was 100 tons of spent fuel per year and the construction cost was estimated at 8.4 billion rubles. Later, the design capacity was increased to 250 tons per year and the estimated cost to 20.7 billion rubles ($0.7 billion).[405] The hope is to use the plant as a pilot for the planned full-scale RT-2 reprocessing plant at the same site.[406] The plan is to have by 2015 an operating capacity for reprocessing 5 – 10 tons of VVER-1000 spent fuel annually and to expand the capacity with a second stage by 2018.[407]
- At NIIAR, a radiochemical research complex is being established to develop spent fuel reprocessing technologies for fast-reactor fuels. About 4.7 billion rubles (~$147 million) have been allocated from the federal budget.[408] Under this program, a hot-cell facility

(K-16) has been set up for pyrochemical reprocessing of spent MOX fuel from the BOR-60 and BN-600 reactors with a capacity of 100 – 150 kg of spent fuel per year.

- In Snezhinsk, laboratory facilities are being prepared to develop, test and demonstrate pyro-chemical technologies for reprocessing spent nitride fuel. Pyroprocessing facilities can be so compact that it might be possible for each fast-neutron reactor site to have its own combined spent fuel reprocessing and fuel fabrication facility.[409] It is argued that the presence of transuranics and some fission products mixed with the plutonium in the recylced fuel and confinement of the nuclear materials on-site, would reduce the risk of theft by subnational groups.[410]
- At the Siberian Chemical Combine (SCC) site in Seversk, Program 2010 provided 2.4 billion rubles for a prototype on-site fuel cycle to be created by 2020, including production of fresh nitride fuel and its refabrication after irradiation.[411]

Technology	Design throughput (tons heavy metal/year)	Location
Aqueous	VVER fuel (250 tHM/yr)	MCC, Zheleznogorsk
Pyroprocessing	MOX fast-reactor fuel (0.1-0.15 tHM/yr)	NIIAR, Dimitrovgrad
Pyroprocessing	Laboratory-scale nitride fuel	VNIITPh, Snezinsk
Pyroprocessing	Pilot-scale nitride fuel	SCC, Seversk

Table 8.4. Rosatom's reprocessing projects.

Use of light water reactors for nuclear fuel cycle closure

Until recently, Russia's strategy of nuclear power development has not envisaged the use of MOX fuel in light water reactors. This is why, in the absence of 100-percent foreign funding, Russia decided not to implement the original (2000) Russia-U.S. Plutonium Management and Disposition Agreement to dispose of its surplus weapon-grade plutonium in LWR MOX. In 2010, the parties signed a Protocol to the Agreement under which Russia would use its BN-600 and BN-800 fast-neutron reactors to irradiate the 34 tons of surplus Russian weapon-grade plutonium covered by the agreement.

In early 2012, however, there were reports of a proposal from Rosenergoatom to use MOX fuel in the new VVER-TOI.[412] The VVER-TOI is to be a 1,255 MWe light water reactor whose design was completed at the end of 2012.[413] The first VVER-TOI unit is to be built at the Nizhny Novgorod Nuclear Power Plant.

Rosenergoatom proposes to use 35 percent MOX fuel in the core of the VVER-TOI.[414] It proposes to construct VVER-TOI reactors with total capacity 27 GWe as well as six units of the BN-1200 and to build by 2020 MOX-fuel production capacities for these two reactor types of 150 tons and 50 tons of fuel respectively. Initially, Russia's accumulated separated reactor-grade and excess weapons-grade plutonium would be fed into these plants. As of the end of 2013, Russia had 51.9 tons of separated civilian plutonium and 34 tons of weapon-grade plutonium that had been declared excess. Single BN-1200 and VVER-TOI reactors would require respectively fuel containing 2.1 and 0.6 tons of plutonium per year. If Rosenergoatom's plans for a large fleet of VVER-TOI and BN-1200 reactors were realized, the amount of plutonium irradiated annually would be over 25 tons.

Such a large-scale expansion of Russia's MOX use seems unlikely in the forseeable future, however. Instead, Rosenergoatom's proposal of MOX use in LWRs may be a sign of a growing understanding within Rosatom that it is very unlikely that Russia's fast reactor capacity will expand rapidly enough to absorb the plutonium from large-scale reprocessing of VVER fuel.[415]

Siting a radioactive waste repository

Preparations are underway for deep-underground disposal of the high-level vitrified and other long-lived radioactive wastes from reprocessing of spent nuclear fuel. As a first step, it is planned to create an underground laboratory at a depth of 500 meters in the Nizhnekamskiy granitic massif at the Yeniseiskiy site in the Krasnoyarsk region, not far from Zheleznogorsk. The laboratory will investigate the suitability of the geology for a period of nine years before it is decided on whether or not to build a full-scale final disposal facility.[416] Local residents expressed support for the project during a public hearing in late July 2012.[417]

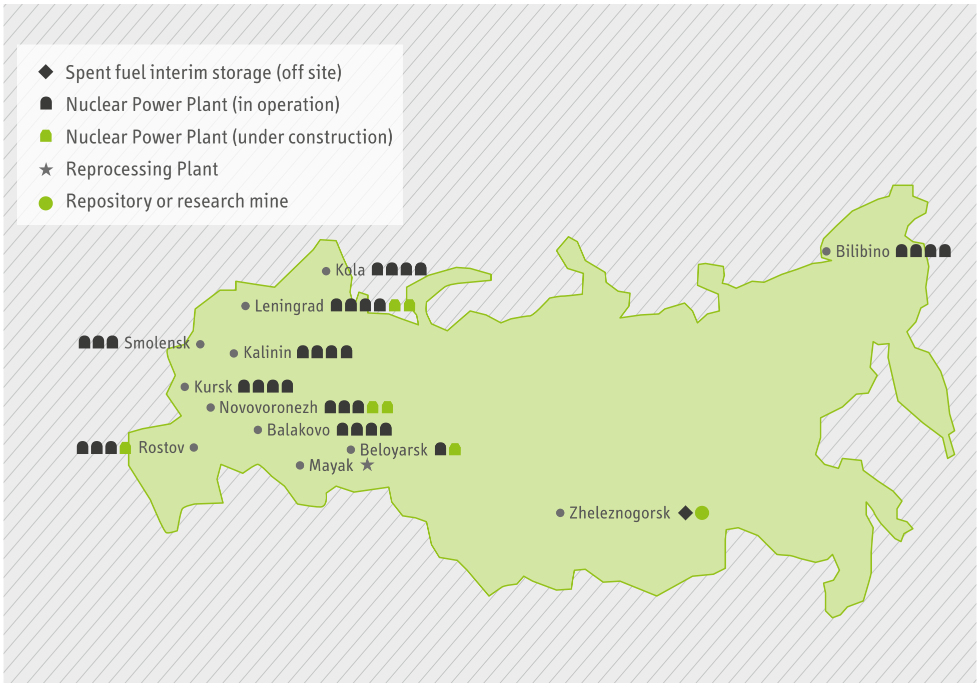

Figure 8.2. **Locations of Russia's nuclear power reactors, spent-fuel storage, and reprocessing facilities.**

Conclusion

Sustainable development of nuclear power requires dealing with spent fuel. It is completely justified for Russia to make a major effort to develop its own solution. It is difficult to understand, however, how Russia's multiple government programs fit together. Programs funded by more that 100 billion rubles (≈ $3 billion) from the state budget have been launched without public discussion or input from the scientific community. The focus of Russia's federal Program 2010 on the parallel development of three different fast reactor types (sodium, lead and lead-bismuth cooled) and three different fuel cycles (MOX and nitride fuel for fast-neutron reactors, and MOX for VVERs) suggests uncertainty about the prospects for success of a closed fuel cycle based on fast-neutron reactors.

9. United Kingdom

The United Kingdom has a fifty-year-long history of reprocessing spent fuel for civilian purposes. This is now coming to an end with official announcements that both of the United Kingdom's currently operating reprocessing plants will close. This chapter explains the history and motivations for United Kingdom reprocessing and also discusses briefly the main policy issue now being faced by Government — how to dispose of the very large quantities of civilian plutonium that have been separated during the course of reprocessing.

A brief history of UK reprocessing

The United Kingdom began military reprocessing soon after the end of the Second World War. Pursuing nuclear weapons and unable (like France) to access uranium enrichment technology under the U.S.McMahon Act of 1946, the United Kingdom chose plutonium production as its route. At Windscale in the north-west of England (a site later re-named Sellafield) it built two graphite-moderated plutonium production reactors — the Windscale "piles," which started operating in 1950.[418] A serious fire at one of the piles in 1957 caused their permanent shutdown. Meanwhile, the first reprocessing plant, B204, operated from 1952 to extract plutonium for the weapons program from the irradiated natural uranium fuel.[419]

In the early 1950s, the United Kingdom also embarked on a civilian nuclear power program based initially on Magnox reactors. These too were moderated by graphite and had fuel made of natural uranium in metallic form. The first two sets, with 4 reactors each, Calder Hall at Sellafield, and Chapelcross in southwest Scotland, were designed with the dual purpose of providing military plutonium as well as electricity.

In 1964, while additional Magnox nuclear power reactors (eventually 18) were being built across the United Kingdom for electricity production, B204 was augmented by the construction of a larger reprocessing plant, B205, with a design throughput of 1500 tons/year. The United Kingdom had no need for weapons plutonium from the additional power reactors.[420] The motivation for reprocessing their fuel was now the belief that plutonium breeder reactors would before long become the dominant source of nuclear power, and that they would need large quantities of plutonium as start-up fuel. Further, spent Magnox fuel was stored in pools and cooled by water. Fuel in metallic form corrodes quickly if left in water and reprocessing therefore seemed to be required in any case. This second justification for reprocessing Magnox fuel persisted for decades after the United Kingdom abandoned its breeder reactor program and has continued until the present time.[421] While long-term dry storage of spent Magnox fuel is technically possible, and would make it possible to avoid costly reprocessing, there was never a significant effort to make this possibility a reality.

In 1965, the United Kingdom began to build a second generation of reactors (Advanced Gas Cooled Reactors or AGRs) that were fueled with low-enriched uranium oxide fuel. Oxide fuel is stable in storage but the commitment to reprocess spent fuel for plutonium use in fast reactors was still strong in that period and there was a large fast reactor R&D program at Dounreay, a remote location on the north coast of Scotland.[422] The "head-end intake" portion of B204 was re-designed to reprocess oxide fuels and it was re-opened for that purpose but a serious accident in 1973 caused its permanent closure.[423]

At this point a decision was taken to investigate the prospects for building an entirely new oxide reprocessing plant, which eventually became the Thermal Oxide Reprocessing Plant (THORP) at Sellafield. Added impetus to plans for this plant was given by the interest shown by Japan to send its fuel to be reprocessed abroad. A public inquiry into the proposal for THORP led to a Government decision in favor of its construction in 1978,[424] by which time a number of foreign contracts had been signed, primarily with Japan but also with Germany, Switzerland, Italy, Spain, Sweden and the Netherlands. After significant delays, THORP started operating in 1994.

THORP was designed with an annual capacity to reprocess spent oxide fuel containing 1200 metric tons of uranium and it had an initial order book (the "base-load" contracts) of 7000 tons, which were to be completed by 2003. Because of the plant's poor performance, however, it only completed reprocessing this amount of fuel in December 2012.[425] There were limited post-base-load orders, totaling 2512 tons for the UK's AGR fuel and, initially, 1500 tons from Germany—a quantity that rapidly fell to 787 tons and then 100 tons, after a change in German law freed the utilities from the requirement to reprocess their spent fuel.[426] The post-base-load AGR contracts specified that BNFL would have the option to reprocess the fuel, or engage in the less costly option of storage. These contracts were made at a much lower (but undisclosed) price than for the base-load contracts.[427] THORP did not obtain any further contracts.

The terms negotiated for the base-load contracts were favorable to British Nuclear Fuels Limited (BNFL), the state-owned company created in 1971 to manage "commercial" fuel cycle activities in the United Kingdom. Overseas customers effectively paid for the construction of THORP and were also liable to pay for reprocessing operations, in both cases on a "cost-plus" basis. They were responsible for the effects of inflation as well as the costs of storage and shipping plutonium and wastes back to their home countries. BNFL anticipated that it would make a profit of £500 million ($800 million) on the base-load contracts.[428]

It is clear that very large sums would have been saved had the contracting utilities, in overseas countries as well as in the United Kingdom, been able to convert their THORP reprocessing contracts to storage.[429] Even considering the construction of the plant as a sunk cost, the operating costs of THORP were substantially higher than the full costs of storage would have been.

THORP's operating performance has been uneven and often poor. Its throughput has never reached 1000 tons and it was forced to close in 2005 after a major accident in which 22 tons of fuel dissolved in nitric acid leaked into a building, undetected over a nine-month period.[430] The plant re-opened at low capacity in 2008 but there was a further shutdown in 2009. This was due to reductions in capacity of the high-level liquid waste evaporators, shared between THORP and B205. The evaporators are used to concentrate the high-level liquid waste for storage.[431] As a result of these problems, as of early 2014, some 300 tons of overseas-owned spent fuel was still awaiting reprocessing.[432]

The UK breeder reactor program

As part of its program to develop fast-neutron breeder reactors, the United Kingdom built two liquid-sodium-cooled reactors at Dounreay: the small 14 MWe Dounreay Fast Reactor (DFR) in the 1960s and a 250 MWe Prototype Fast Reactor (PFR) in the 1970s.[433] By the 1980s, it was already becoming clear that there were no commercial prospects for fast reactors because of three factors: uranium remained cheap; fast reactor capital costs were always going to be greater than for thermal reactors;[434] and the reliability of the fast reactors that were being built, including DFR, was poor.[435] There were additional concerns about safety and the nuclear-weapon-proliferation implications of the "plutonium economy" that would result if fast reactors were widely adopted.[436] Only if uranium prices rose to exceptionally high levels over sustained periods would the economics of fast reactors potentially make any sense. During the 1980s, it became clear that this was very unlikely in the foreseeable future.[437] Expenditures on the UK fast reactor program continued at around a level of £100 million per year until 1988, when they were cut back drastically to £10 million per year and it was announced that funding for operating the PFR would end in 1994.[438] PFR therefore was shut down in the same year that THORP came on line.

Though the domestic requirements for civilian plutonium had now clearly evaporated, reprocessing continued — both in B205, using the argument that reprocessing was needed to avoid corrosion of wet-stored Magnox fuel, and at THORP because there were profitable and enforceable contracts for both domestic and overseas spent fuel.

A secondary argument for continuing to reprocess domestic fuel was that it would make the problem of spent fuel management easier to resolve. As explained in Chapter 10 this argument was specious.[439]

The MOX enterprise

While plutonium was no longer needed for fast reactors, it was possible to envisage its use in light water reactors (LWRs) in the form of uranium-plutonium mixed oxide fuel (MOX). The fabrication cost alone of MOX is substantially higher than the full cost of uranium-oxide fuel, however. Use of MOX also requires reactor relicensing, and spent MOX fuel is more difficult and expensive to manage because of its extended period of high heat output.[440] This means that, even if the plutonium is a free good — and on economic grounds, stocks of existing separated plutonium meet this criterion — MOX is a more expensive option than uranium-oxide fuel. Finally, the need to transport plutonium-based fuels from fabrication facilities to reactors raises issues of security and public opposition.

As a result of these factors, utilities would never choose to use MOX on economic grounds. Nevertheless some European utilities — sometimes under pressure from legislation, as in Germany, or under direct pressure from the state as in France — have used MOX in some of their LWRs from the 1980s onwards. Overseas customer utilities for THORP also were required to take back their separated plutonium. Where preferences were expressed, notably by Japan, these utilities decided to take back their plutonium in the form of MOX.

BNFL therefore developed a strategy to manufacture MOX as the means of sending back plutonium to its overseas customers. This would in principle allow virtually all overseas plutonium to be returned to its owners. The quantity of overseas plutonium was much smaller (approximately 30 tons) than the domestic plutonium arising from B205's reprocessing of Magnox fuel and THORP's reprocessing of AGR fuel (a combined total of about 100 tons as of the end of 2013).[441] There was no prospect of making UK-owned plutonium into MOX because there was only one UK reactor that was deemed suitable to use MOX (the light water reactor at Sizewell B).[442] Furthermore, its owner, Électricité de France (EDF) made it clear that it would not use MOX.[443]

BNFL's initial MOX strategy was to build a small demonstration plant at Sellafield, which opened in 1994. This delivered small quantities of MOX to Switzerland, Germany and Japan, but a scandal caused its closure in 1999, when it was discovered that there had been systematic falsification of quality assurance data in shipments to Japan.[444] Meanwhile BNFL was constructing the Sellafield MOX Plant (SMP), a commercial-scale MOX plant, with a design annual throughput of 120 tons of heavy metal (uranium plus plutonium). This was completed in 1997 but did not open until 2001.[445] It immediately encountered technical problems and its annual production capacity was down-rated to 40 tons of fuel. Very little MOX was ever produced and the plant closed in 2011 having operated at an average of just over 1 percent of its original rating. This failure meant that there was no alternative to plutonium storage for the stockpile at Sellafield, which, as of the end of in 2013, had reached 123 tons, of which 99.6 tons was UK-owned. [446] This is, by some distance, the world's largest stockpile of civilian separated plutonium.

The great bulk of plutonium separated in the United Kingdom from Magnox reactors and AGRs has had no long-term management strategy other than long-term storage. This became increasingly unacceptable and, in 2011, under some international pressure, the UK Government announced that it would, for the first time since the cancellation of its breeder reactor development program, seek to develop an active strategy for plutonium disposal.[447] The option initially considered was to use plutonium in MOX fuel for new light water reactors while immobilizing a limited volume of contaminated plutonium stocks.

A new regime to manage the back end

BNFL had been set up as a state-owned company in 1971 to take over from the UK Atomic Energy Authority (UKAEA) the ownership of the UKAEA's potentially commercial fuel cycle facilities. This included fuel fabrication and the B205 reprocessing plant at Sellafield. BNFL later built THORP and the MOX facilities as well as acquiring in 1997 the ageing Magnox reactors. Because the Sellafield site was complex and many of its facilities interdependent, BNFL in 1971 also took over virtually all of the Sellafield site, including a wide range of waste processing plants and stores. BNFL was constituted as a company, and the UK Government required it to try and make a profit.[448]

In the late 1980s, the United Kingdom, under Prime Minister Margaret Thatcher, became a world leader in neo-liberal economic policy, privatizing almost all utilities and introducing market competition wherever feasible. BNFL was only marginally profitable with liabilities that vastly exceeded its assets; there also was the important issue of nuclear material security. But government pressure on BNFL to be profitable intensified in the early 1990s.[449] In this climate, the company had no institutional incentive to clean up the often hazardous radioactive wastes at the Sellafield site. To do so would eat into its bottom line. Clean-up activities were therefore neglected in the pursuit of profit from reprocessing.

From around 2000, however, there were significant political changes. New nuclear power plants were for a time off the United Kingdom's policy agenda,[450] and it became increasingly clear that, in the absence of state action, reprocessing would have a limited life:

- The Magnox reactors were coming to the end of their lives, which meant that B205 would close. Closing B205 would be useful because it was the source of the largest radioactive discharges to the sea from the United Kingdom and the OSPAR (Oslo-Paris) Convention for the Protection of the Marine Environment of the North-East Atlantic requires discharges to be close to zero by 2020;[451] and
- There were no new overseas orders for reprocessing at THORP and the new private owners of the AGRs after 1996 not only refused to sign new reprocessing contracts, but also made strong efforts to escape as far as they could from pre-existing contracts to reprocess AGR fuel.[452]

A new approach — market-oriented in relation to reprocessing, and with a new impetus towards clean-up, especially at Sellafield — was confirmed in a major policy paper issued by the government in 2002. Any future planned reprocessing contracts would need to:[453]

- Be consistent with the overall plan to clean up Sellafield;
- Offer a positive return to the taxpayer; and
- Be consistent with the United Kingdom's environmental objectives and international obligations.

As virtually all the plutonium — the stockpile of which was rapidly growing in the 2000s (Figure 9.1) — and most of the United Kingdom's nuclear wastes were concentrated at BNFL's Sellafield site, BNFL was obviously a candidate to be re-oriented as a waste-management company.

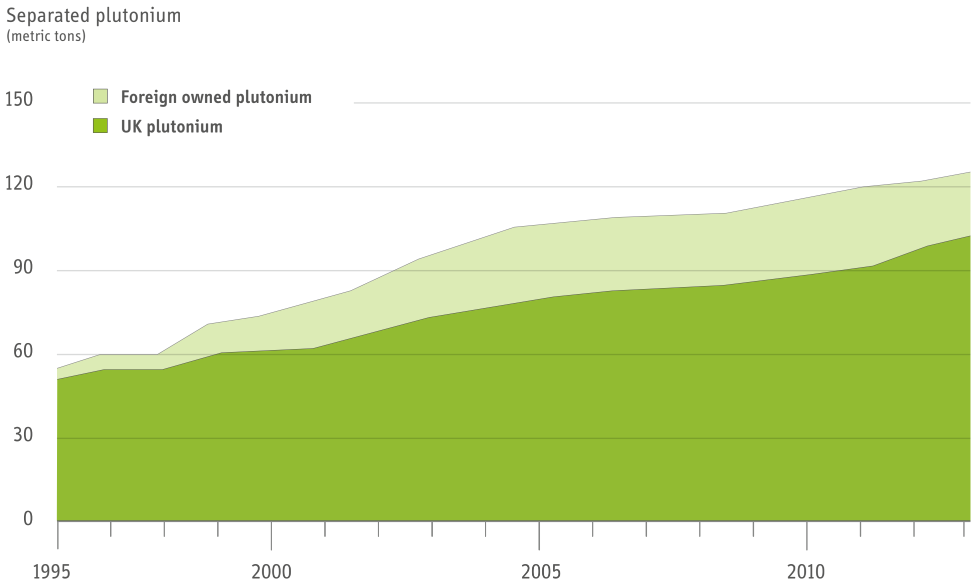

Figure 9.1. Separated plutonium stockpile in the United Kingdom, 1995–2013. *Source: IAEA, "Communication Received from the United Kingdom… Concerning its Policies Regarding the Management of Plutonium, INFCIRC/549/Add.8/17, 15 August 2014, and previous annual reports.*

BNFL had lost credibility with Government, however, as a result of the MOX data falsification incident reported above as well as an ill-fated venture into the U.S.clean-up market by its overseas arm BNFL Inc., where the company lost some $1 billion on two contracts.[454] BNFL also appeared reluctant to allow other companies to participate in the limited clean-up efforts that were being undertaken. The UK Government's 2002 White Paper therefore announced a major change in the institutional structure at the back end of the United Kingdom's nuclear fuel cycle. A new Government-owned body, which became the Nuclear Decommissioning Authority (NDA), would own all public sector back end sites and facilities, including all those previously owned by BNFL and the UKAEA.[455] This meant that, for the first time, there would be an institution whose primary mission was to manage and clean up the back end, including managing reprocessing and the plutonium stocks. Attempts were made to re-structure BNFL and give it new roles, but agreement between the company and Government proved impossible and BNFL was finally shut down in 2009.

The NDA was created by the UK Energy Act of 2004 and came into existence in 2005. It inherited ownership of the reprocessing plants as well as the radioactive wastes, but its mandate was now to minimize the total cost of the overall clean-up process. In so doing, it was required to act on its judgment of the economic viability of THORP and SMP and not on "strategic" or non-economic considerations. It also was required to look closely at the issue of separated plutonium management, though it took time for it to do so.

The end of reprocessing

There has never been a decisive moment when the UK Government announced that reprocessing would come to an end. In line with its neo-liberal approach to the fuel cycle, it has argued since the late 1990s that it would be customer demand, or its absence, that would determine the lifetime of the two reprocessing plants.

UK Government expectations that reprocessing would come to an end pre-date the formation of the NDA. For B205 an intended closedown date of 2012 was announced by BNFL in 2000.[456] For THORP an expectation of closure became public in 2002, when the Department of the Environment announced that "the continued operation of THORP beyond about 2016 will be dependent on new business".[457] There have been no further contracts. The 2016 date was unexpectedly late as it was announced in 2002 that THORP would complete its contracts by 2010–11.[458] These announcements were not, however, formal declarations of closure.

The fact that neither B205 nor THORP is yet closed is primarily due to the fact that operational problems have slowed the rate at which their existing reprocessing commitments have been fulfilled. These problems have affected the performance of both the reprocessing plants and the associated operations upstream (fuel reception for B205) and downstream (high-activity waste storage tanks, evaporators and vitrification plants, all of which are shared by both reprocessing plants).

THORP

THORP's operating performance has been poor since 2002. There have been a number of causes: the extended shutdown of between 2005 and 2008 because of a long-undetected leak of radioactive material; the effective capacity down-rating that followed this incident; and the forced closure in 2009 because of evaporator constraints. This has meant that the fulfillment of THORP's contracts has been postponed by at least eight years beyond the earlier expected date of 2010–11. When NDA reported its assessment of the options for managing oxide fuels in late 2011, it announced that the closure date for THORP would be 2018.[459] Although NDA did invite views on whether or not reprocessing might be extended beyond 2018, it was explicit that, on cost-effectiveness grounds, closure in 2018 was its strongly preferred strategy.

NDA's *Credible Options* report offered three options for managing oxide fuels:

- Complete the reprocessing contracts;
- Reprocess less than the contracted amounts; and
- Reprocess more than the contracted amounts.

The third option was ruled out by the fact that there were no prospective new contracts, and that — if any fuel unexpectedly became available for reprocessing after 2018 — investments described as being in the multi-billion- pound range would be required to refurbish THORP and the radioactive waste processing facilities.[460] NDA argued that completion of the reprocessing contracts (Option 1) was the most cost-effective option because the facilities needed were all existing assets. NDA did however concede that support facilities, in particular the High Activity Radioactive Waste Storage Tanks (HASTs), which require continuous cooling, were potentially vulnerable to breakdown. This might require THORP to close earlier than 2018.

The argument that Option 2 would be more expensive than Option 1 seems difficult to make, and NDA did not publish its cost calculations. The extra costs expected under Option 2 involved

- Building extra storage capacity for AGR fuel;
- Managing the small amount of fuel susceptible to corrosion when stored; and
- Implementing alternative options for managing some fuels, for example transferring these fuels to another reprocessing facility (i.e., in France).

NDA's analysis implied that these three categories of cost would be greater than the operating costs associated with continued reprocessing. Only the third category of cost, transferring fuel to another reprocessing facility, could in principle have been at all significant, however. Eighty-five percent of the remaining contracted fuel for reprocessing was from UK AGRs, however: 2400 tons as against only 400 tons of overseas fuel.[461] Électricité de France (EDF), which had taken ownership of the AGRs, would have been happy not to have its fuel reprocessed,[462] and the storage cost would be low relative to reprocessing.

The only potential difficulty would have been with owners of the 400 tons of overseas spent fuel. An obvious strategy would have been to offer these owners "virtual reprocessing." Here the NDA would send back quantities of plutonium and vitrified (glassified) high-level waste from existing Sellafield stocks equivalent to those that would have resulted from reprocessing, while storing the original fuel at very low cost compared to continued operation of the reprocessing plants.

Virtual reprocessing had been suggested to the UK Government repeatedly.[463] It is therefore difficult to avoid the conclusion that cessation of reprocessing earlier than 2018 would have been found to be the most cost-effective option had NDA explicitly considered it. The NDA did not seriously consider virtual reprocessing, however, in its published analysis in 2011. Instead, it used the argument that the 2004 Energy Act required that reprocessing contracts be honored — although the Act did not disallow re-negotiation if all parties consented to it.

The NDA's Preferred Option paper of June 2012 strongly endorsed the conclusions of the Credible Options report, and re-iterated that the expected date of THORP closure remained 2018 while noting the continuing risk that THORP's support facilities might not operate reliably over the remaining six years.[464]

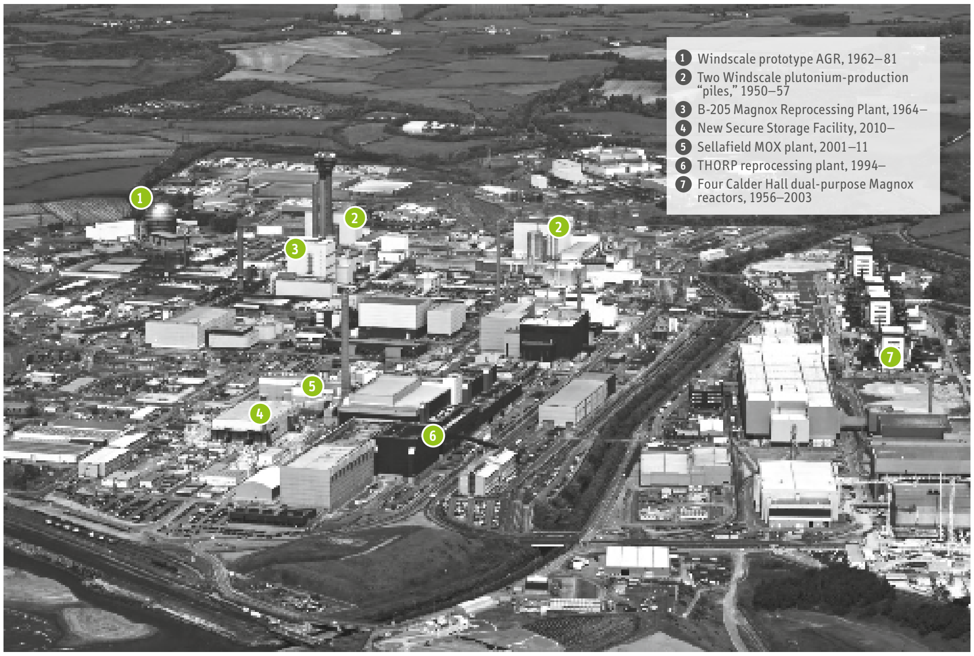

Figure 9.2. The Sellafield site in the United Kingdom, 2008. *Source: Sellafield Ltd.*

The two NDA options reports provide very strong evidence that continuing reprocessing at THORP, beyond the scope of the current reprocessing contracts, would involve very high and unjustifiable costs. Nevertheless, there remain strong supporters for extending reprocessing in the United Kingdom. A trade union report in 2007 called for the planning of a second oxide reprocessing plant at Sellafield. And, in 2011, a Royal Society report authored mostly by scientists with a history of work in or close association with the nuclear industry, argued that the assumption that reprocessing should be ended should be “revisited” and that THORP should either be refurbished or a new reprocessing facility built.[465] Most recently a report primarily authored by ex-BNFL employees on contract to the Smith School of Enterprise and the Environment at the University of Oxford, argued in two out of its four future UK scenarios that THORP should be refurbished and AGR fuel currently planned for long-term storage, plus overseas fuel, should be reprocessed.[466]

However, these three papers all fail to recognize:

- The multi-billion pound investments that would be needed to keep reprocessing going; and
- The problem that there have been no contracts for reprocessing in the United Kingdom for over two decades, and none is in sight.

In March 2014, the UK Government finally recognized that some virtual reprocessing was desirable after a DECC consultation proposed that some 30 tons of ‘difficult’ overseas-owned fuel should be subject to virtual reprocessing in order to save public money and allow THORP to close sooner than otherwise would be possible.[467] This of course raises the question of why the other 270 tons of overseas-owned fuel still awaiting reprocessing might not be dealt with by virtual reprocessing as well. To date, however, the Government has been silent on this.

B205

The B205 closure issue is of less international interest than THORP because it was a plant dedicated solely to the metallic fuel from the increasingly obsolete Magnox plants, and it had no planned application beyond servicing those reactors. The closing date was therefore always expected to be soon after the last Magnox reactor closed. BNFL’s year-2000 announcement of a closedown date of 2012 was later amended to 2016 due to Magnox lifetime extensions as well as declining technical performance at B205 and its supporting plants. The date then was pushed back further to a range of 2020 to 2028.[468] Given that B205 has the highest Sellafield discharge levels to the sea, this means that the United Kingdom’s OSPAR Convention commitment to achieve as “close to zero emissions” of radioactivity to the Atlantic by 2020 probably will be seriously compromised.

As of the end of 2014, all but one of the UK’s Magnox reactors had been closed and the final unit at Wylfa was scheduled to close in December 2015. Magnox fuel is no longer being manufactured, placing a clear physical limit of the quantities of Magnox fuel that will be reprocessed in B205. There are, however, currently plans to undertake limited reprocessing in B205 of exotic fuels from Dounreay and elsewhere. Given that there are risks that B205, which was 50 years old in 2014, and/or the supporting facilities at Sellafield could fail, an earlier closedown date might prove necessary.

In the event of such an early shutdown, there would be the significant technical challenge of finding ways to store wet Magnox fuel in ways that avoided dangerous corrosion. This suggests in turn that the NDA might want to spend large sums to keep the B205 enterprise going, if it is technically possible to do so. However, there seems little doubt that the remaining tonnage to be reprocessed is more or less fixed and that Magnox reprocessing will cease by the early 2020s.

Managing the separated plutonium

It has taken the United Kingdom most of the 20 years since the abandonment of its breeder reactor development program in 1994 to start considering what might be acceptable long-term options for the management of UK-owned plutonium. In the meantime, this plutonium has been stored as plutonium oxide powder in Sellafield. As outlined earlier, the favored method for managing overseas-owned plutonium was to fabricate it into MOX and return it to customers, but this came to a halt in 2011 when the Sellafield MOX plant was abandoned. The UK Government has offered to take title to the overseas-owned plutonium at Sellafield. This means that a long-term management strategy is needed for a total stockpile of separated material that could amount to about 140 tons when the contracted reprocessing ends.[469]

The detailed history of the UK policy discussion on plutonium disposal has been described in an IPFM report on plutonium disposal options.[470] There have been a number of studies on this subject by BNFL, the Royal Society, the NDA, and independent analysts. The primary debate is over whether to use the plutonium in fuel for new reactors or to immobilize it and dispose of it directly.

The preference of the NDA, whose experts are mostly inherited from BNFL, is to use the plutonium in MOX in new LWRs that the UK Government is encouraging foreign vendors to build in the United Kingdom. The NDA and the Department of Energy and Climate Change (DECC) have issued reports arguing that this option would be less costly than direct disposal but have refused to release the analyses on which these conclusions are based, claiming that they contain "proprietary" information. In any case, the LWR option awaits the construction of the reactors and then contracts with the owners to use MOX fuel. In 2014, NDA worried that "the appetite of developers [proposing to build new LWRs in the UK] to ultimately include MOX in their considerations remains uncertain".[471]

In the meantime, GE Hitachi and Candu Energy have respectively proposed to build two dedicated sodium-cooled fast-neutron or two heavy water reactors at Sellafield to irradiate the plutonium. NDA has placed "low valued [but unspecified] contracts with both parties" to develop these proposals.[472]

The apparent interest in engaging with the UK plutonium disposal issue on the part of Candu Energy, GE Hitachi (and of course Areva for LWR MOX) means that NDA now hopes that it can conduct a competitive process between alternative fuel-use proposals, while reserving the right to revert to a sole provider route if necessary.[473] The absence of an external technology vendor for immobilization options contributes to the difficulties immobilization options have in finding a place in the neo-liberal climate of UK public decision-making.

Cleanup cost

While reprocessing is being phased out as an unnecessarily expensive way of managing spent fuel, past reprocessing has left a huge public sector liability for cleanup. The NDA manages cleanup at all publicly owned UK nuclear sites, but its primary focus and heaviest operating expenditures are at Sellafield. While not all liabilities and expenditures at Sellafield are the product of reprocessing, the great bulk of them are. As at 2002, the total long-term liability for cleaning up Sellafield was estimated at £27.5 billion.[474] By 2014 this estimate had increased to £79.1 billion (in both cases undiscounted).[475] Allowing for the fact that the NDA has spent more than £10 billion on remediating Sellafield since its formation in 2005, the total escalation in the Sellafield liability over the 12 year period to 2014 amounts to around 130 percent in real terms.[476] Current annual spending at Sellafield is £1.8 billion and still rising.

This £79.1 billion (~$120 billion) is part of an overall future NDA liability that has now reached £110.1 billion across its whole estate, and the Authority now gives a range of future liability estimates from £88 to £218 billion. At the high end of this range, NDA estimates that Sellafield could be responsible for a *further* £75 billion of expenditure,[477] for a total potential liability at Sellafield of just over £150 billion (~$220 billion). These remarkable figures reflect both a past unwillingness to face the scale of the problem, especially under the stewardship of BNFL, and the time taken to understand just how complex and expensive it will be to remediate some of the "high hazards" at the site, especially "Legacy Ponds and Silos" that date back 50 years and more.

Conclusion

In every country that has engaged in civilian reprocessing, the commitment has always been made on government initiative. Decisions in favor of reprocessing (and MOX) have rarely taken account of the relative costs of reprocessing and spent-fuel storage. When reprocessing became subject to a neo-liberal government — the United Kingdom from the late 1980s onwards — it became subject to a market-based analysis of spent fuel options, and customers (utilities) were allowed to decide whether or not to reprocess. This led to a rapid retreat from reprocessing in the United Kingdom and it became inevitable that the practice would cease once the entanglements of earlier contracts were overcome. Reprocessing would have already ended in the United Kingdom if the two reprocessing plants and their associated support facilities had been able to work at somewhere near their nominal capacity. As it is, reprocessing will come to an end in the United Kingdom within a few years, with no prospect of a revival.

Many decades of reprocessing in the United Kingdom, with minimal use of the separated plutonium and no plutonium disposal strategy, have left a legacy of the world's largest stockpile of civilian plutonium. The United Kingdom is now slowly moving to formulate a long term policy for its disposal, in a process that seems to have an inherent bias towards fuel use. This apparent bias is reinforced by the way in which the public sector, under a neo-liberal order, mimics the (presumed) operation of markets. In the case of the NDA this results in a desire to conduct a competitive process between up to three international nuclear technology suppliers, all of whom offer only versions of fuel use. Immobilization has no corresponding industrial champion.

10. Transmutation

A primary rationale offered for reprocessing and fast-neutron reactors today is that fissioning of the long-lived transuranic isotopes in spent fuel would reduce the associated long-term hazard. Some of the isotopes of plutonium and other transuranic radioisotopes (neptunium, americium, curium) in spent fuel have half-lives of thousands to millions of years (Table 10.1). It is argued that, since no repository can guarantee that radionuclides will not escape and contaminate surface water during such a long time, it would be better to fission the transuranics into shorter-lived species. The case is usually illustrated graphically by showing the ingestion toxicity of spent fuel with and without the contained transuranics (also called "actinides" because their chemistry is similar to that of the element actinium) (See Figure 10.1).

Transuranic isotope	**Mass percent at 53 MWt-days/kgLEU** [478]	**Half-life** (years)	**Decays into**
Plutonium-238 (Pu-238)	2.4	87.7	Uranium-234
Plutonium-239 (Pu-239)	45.7	24,000	Uranium-235
Plutonium-240 (Pu-240)	21.9	6,500	Uranium-236
Plutonium-241 (Pu-241)	5.3	14.4	Americium-241
Plutonium-242 (Pu-242)	7.0	380,000	Uranium-238
Total plutonium	**82**		
Americium-241 (Am-241)	8.9	432	Neptunium-237
Americium-243 (Am-242)	1.8	7400	Neptunium-239
(Plutonium plus americium)	**93**		
Neptunium-237 (Np-237)	6.6	2.14 million	Protactinium-233
Curium-243 (Cm-243)	0.0051	28.5	Plutonium-239
Curium-244 (Cm-244)	0.37	18.1	Plutonium-240
Curium-245 (Cm-245)	0.039	8500	Plutonium-241
Total	**100**		

Table 10.1. Mix of long-lived transuranic isotopes in spent low-enriched-uranium light water reactor fuel with a burnup of 53 MWt-days/kgU after 20 years cooling. The total mass of the transuranics is 1.3 percent of the mass of the uranium originally in the spent fuel.

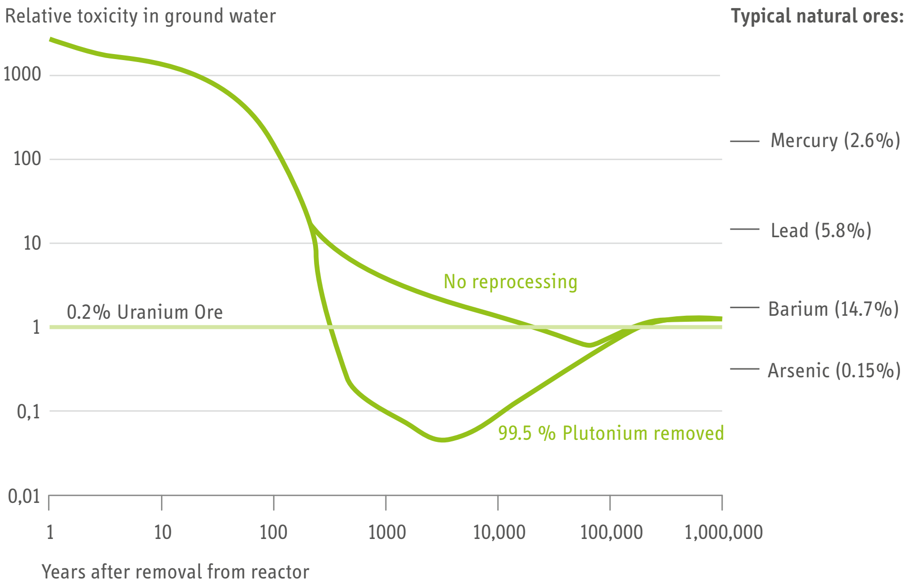

Figure 10.1. Ingestion toxicity of spent fuel in a repository in perspective. The figure shows as a function of time the ingestion toxicity of a homogenized mix of spent fuel and the repository rock in which it is emplaced for a heavy water reactor fueled with natural uranium in comparison to various ores. It is assumed that the concentration of the spent fuel uranium in the rock is approximately 0.2 percent by weight. The measure of toxicity is proportional to the amount of water that would be required to dilute the material down to the limit allowed in drinking water. The increase of the toxicity of the spent fuel at around 100,000 years is most likely due to the ingrowth of the uranium-238 decay product, thorium-230 (half-life 75,000 years). It will be seen that removal of 99.5 percent of the plutonium would reduce the toxicity by about a factor of twenty, several thousand years after burial. For spent light water reactor fuel and with the removal of the other transuranics as well, the reduction in toxicity would be by about a factor of one hundred.[479]

Transmutation of the transuranics would involve fissioning them into (mostly) shorter-lived fission products. Figure 10.1 shows that this would signficantly reduce the ingestion toxicity in the period from 100 to 100,000 years. As will be seen below, however, it would not necessarily reduce significantly the hazard from a deep underground repository.

Thus far, the only transuranic element that has been separated and used on a large scale is plutonium. In France, which reprocesses most of its low-enriched uranium spent fuel, the plutonium is mixed with uranium to produce "mixed-oxide" (MOX, uranium-plutonium) fuel, which provides 30 percent of the fuel of 24 of France's 900 MWe light water reactors or the equivalent of 10 percent of the fuel used in France's reactors.

The other transuranic elements — neptunium, americium, and curium — are not currently separated from the dissolved spent fuel in any country and, in countries that reprocess their spent fuel, are disposed with the fission products in the solidified high-level reprocessing waste. This reflects the original purpose of reprocessing, which was first to separate plutonium for nuclear weapons and then to provide the initial fuel for plutonium breeder reactors.

A single recycle of plutonium in a light water reactor, as practiced in France, reduces the amount of plutonium in spent fuel by about 40 percent.[480] Multiple reuse of plutonium in light water reactors has not been attempted on a commercial scale because the recycled plutonium would contain an increasing fraction of plutonium isotopes that are not fissionable by the slow neutrons that dominate in light water reactors. Also, because there is a significant probability of a series of successive neutron captures without fission in a slow-neutron reactor, multiple recycles of neptunium, plutonium, americium and curium would produce an increasing fraction of curium-244, which fissions spontaneously at a high rate. The resulting penetrating neutrons would constitute a major radiation hazard in a fuel fabrication plant and require very costly remote fuel fabrication behind heavy shielding or long intervals between recycles to allow the 18-year half-life curium-244 to decay.[481]

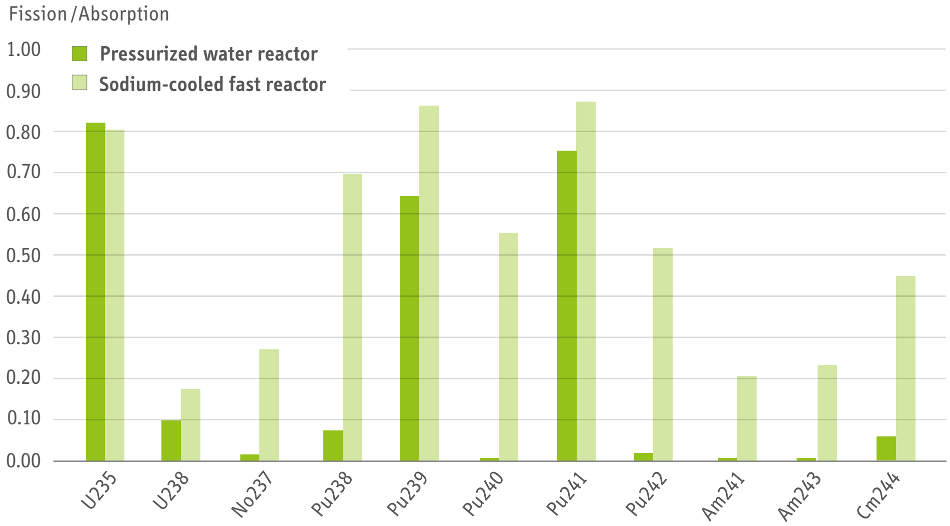

Figure 10.2. Fission probabilities for slow and fast neutrons. The figure shows the different probabilities of the slow-neutrons in a water-cooled pressurized water reactor core and the fast-neutrons in a sodium-cooled fast reactor core fissioning uranium, neptunium, plutonium, americium and curium isotopes. A series of non-fission neutron absorptions are what ultimately produce heavy isotopes such as curium-244 from uranium-238. *Source: "Le Projet ASTRID," Société Français de Energie Nucléiare, SFEN/GR21, 2013, p. 6.*

One thousand years of fast reactors

Advocates of sodium-cooled reactors point out that the fast-neutrons that mediate the chain reactions in these reactors have a much lower probability of being absorbed without fission by some of the transuranic isotopes than the slow neutrons that mediate the chain reactions in water-cooled reactors (Figure 10.2). This would dramatically reduce the buildup of curium-244, which is produced as a result of a succession of six non-fission neutron absorptions starting with uranium-238.

Transmutation would require the separation of the transuranics from spent low-enriched uranium fuel and then multiple recycles in the fuel of a fast-neutron reactor. It would take centuries or more before a reduction such as is shown on Figure 10.1 could be achieved. A very small fraction of the transuranics might be going into the geological repository but a huge inventory would be circulating in the fast reactor cores and their fuel cycles. Even assuming 99.9 percent extraction of the transuranics at each recycle, for a constant-power scenario in which fast-neutron reactors fission transuranics at the same rate that light water reactors produce them, the inventory reduction factor at 100 years would only be 85 percent at most and it would take thousands of years to get a 99 percent reduction.[482] That is, it would take thousands of years before the quantity of transuranics circulating in the above-ground fuel cycle would be down to one hundredth of the amount that would have been deposited in a geological repository if the spent fuel were directly disposed without reprocessing. If instead it were decided to phase out nuclear power and use fast reactors to eliminate the legacy of transuranics, the reduction would be more rapid but it would still take at least 150 years to eliminate 99.5 percent.[483]

Widespread interest in transmutation

Nevertheless, the governments of most of the advanced nuclear states have accepted the argument that separation and transmutation of transuranics are required to reduce the hazard from spent fuel to an acceptable level. This rationale has become critical to sustaining support for continued development of fast-neutron reactors:

- In 2006, France's Parliament added to its Environmental Code a mandate for the Atomic Energy Commission (CEA) to assess the industrial prospects for the partition and transmutation of the long-lived radioactive isotopes in spent fuel and to build a pilot plant by 2020.[484] In response, the CEA proposed to build a 600 MWe sodium-cooled fast-neutron reactor, ASTRID.[485] France's economy is currently struggling and the project would be costly. The final decision on whether or not to proceed has slipped to 2019.[486]

- Belgium proposes to build, with financial support from the European Commission, a 50-100 MWt subcritical lead-bismuth-cooled fast-neutron reactor, MYRRHA.[487] The reactor would be driven by spallation neutrons generated by a beam of protons. Although it would be a general-purpose research facility, a primary stated mission is to "demonstrate the physics and technology of an Accelerator Driven System (ADS) for transmuting long-lived radioactive waste." Its proponents argue that fast-neutron reactors such as France's proposed ASTRID could fission the plutonium in spent fuel while accelerator-driven systems could be used to fission the "minor" non-plutonium transuranics.[488]

- In Japan, the Ministry of the Economy, Technology and Industry (METI) argues that plutonium recycle in light water reactors and fast-neutron reactors would reduce from about 100,000 years to 8,000 years and 300 years respectively the time required for the toxicity of the high-level waste to decay to the same level as the original natural uranium.[489]

- South Korea asserted, in its negotiations during 2012-14 over a new Agreement of Nuclear Cooperation with the U.S., that it should have the same right to reprocess as Japan. The primary rationale given is the incorrect claim (see below) that separation and recycle of transuranics in fast-neutron reactors would "efficiently increas[e] the capacity of a final spent fuel repository approximately one hundred-fold."[490]

- Russia still emphasizes the plutonium-breeding mission of fast-neutron reactors but has added the objective of finding "optimal ways of managing the recycling of minor actinides and fission products."[491]
- Even the United States Department of Energy, whose programs for commercializing reprocessing and breeder reactors were cancelled by Congress in the early 1980s, when describing the purpose of its long-term nuclear fuel cycle research and development program, states, "The final strategy is a full recycle approach with extensive processing to remove some elements from the used fuel, reuse some of them in fast reactors, possibly transmute others and minimize the volume and toxicity of the final waste products."[492]

Considerable fast reactor capacity would be required to keep up with the spent fuel currently being generated. The world's 330 GWe of light water reactor capacity annually discharges about 6,700 tons of spent fuel containing about 74 tons of transuranics.[493] Putting a ceiling on the quantity of transuranics by fissioning them at a rate equal to the rate of their creation by light water reactors would require the equivalent of 110 GWe fast-neutron reactors, assuming the highest capacity factor achieved by any fast reactor to date (Russia's BN-600).[494] If the transuranics are mixed with uranium as in MOX, which a U.S. National Academy of Sciences study believed may be required for safety reasons,[495] the required capacity could be 2.5 times higher, i.e., 275 GWe, almost as large as the LWR capacity producing the transuranics.

The separation and transmutation of transuranics therefore would require a major transformation of the nuclear-energy sector and public acceptance of the construction of a very large number of sodium-cooled reactors, which have attracted opposition in the past because of their special safety issues.[496]

Hazards from spent-fuel repositories in perspective

Despite the fact that many opponents of nuclear power focus on the hazard from spent fuel disposal, it is difficult to argue that spent fuel will be more dangerous if buried 500 meters underground than when it was in a reactor core where a brief loss of coolant could result in a meltdown and a Fukushima-scale release of radioactivity to the atmosphere. Or that it is more dangerous than spent fuel in a cooling pool where a loss of coolant could result in an uncontained spent fuel fire and a much larger release.[497]

This risk comparison would only apply to a community that had both a nuclear power plant and a spent fuel repository. It happens, however, that, in Finland and Sweden, two of the three countries that have managed thus far to obtain political acceptance from local communities for a geological repository for radioactive waste (the third is France), the communities that have volunteered to host spent fuel repositories already host nuclear power plants.[498] These communities therefore already have accepted the hazards from fuel in reactor cores and cooling pools.[499]

The ingestion hazard from spent fuel shown in Figure 1 is not a good measure of the hazard that deeply buried spent fuel would pose to a population on the earth's surface 500 meters or so above. What is missing is an analysis of possible mechanisms for exposure. In any case, as also is shown in Figure 1, the earth's crust already contains many toxic materials including lead, arsenic, mercury and, of course, uranium

Uranium and its radioactive decay products provide perhaps the most relevant comparison because it is their radioactivity that dominates the hazard from spent fuel in the long term. Also, we are already familiar with the hazard from the radioactivity of uranium, thorium and their decay products in the earth's crust. Natural uranium and thorium in near surface rocks and construction materials contribute an estimated average radiation dose of about 2 mSv per year to human beings via ingestion, external radiation and from inhalation of radon, a decay product of uranium-238.[500] The resulting estimated increase in lifetime cancer risk is about 1.5 percent, i.e., if one's lifetime risk of getting cancer were 40 percent in a world without uranium and thorium, their presence increases it to about 41.5 percent.[501]

Mixing radioactive waste indiscriminately into the earth's crust in the way that natural processes have deposited uranium and thorium would be irresponsible. The comparison does give some perspective, however, on the nature and magnitude of the hazard. Placing spent fuel in repositories engineered to protect the spent fuel from ground-water flow 0.5 kilometer or more below the surface is likely to reduce the risk to humanity by a substantial factor.

Probability of transuranic migration to the surface

As with natural uranium in the crust, in order to do damage, the radionuclides in a spent fuel repository or their decay products would have to be transported to the surface where humans live.[502] The most important determinant of their natural mobility is the solubility of the various chemical species in the waste in the deep ground water. In the case of deep underground repositories in granite or basalt rock with low water flow, the oxygen in the water has been depleted by chemical reactions with the rock and the transuranics are relatively insoluble.[503] As a result, even though transuranics may dominate the toxicity of spent fuel in place, they are not expected to dominate the toxicity of the mix of radionuclides that water transports to the surface. Calculations for Sweden's proposed repository site, which is in deep granite, find that neptunium-237 typically will contribute about 10 percent of the water-borne dose and plutonium less than one percent. By comparison, the uranium decay product, radium-226, accounts for about 60 percent of the dose from the buried spent fuel but its dose would ordinarily be dwarfed by the dose from natural uranium in the rock.[504] Calculations for France's proposed repository site, which is in a thick clay layer, find that the transuranics will hardly move at all.[505]

There is also the possibility that human actions could bring to the surface radioactivity from a deep geological repository. The company developing Sweden's spent fuel repository considered the consequences of accidentally drilling down through a spent-fuel container in a repository and found that, if a significant portion of the fuel in a canister were brought to the surface, the doses could substantial. But the consequences would be much more localized and easier to clean up than those from an airborne release from a reactor or spent fuel pool accident. Even if the drill hole were not sealed properly, the analysts concluded that the releases from adjoining canisters would not be significantly increased — presumably because of the clay buffer layer in which each spent fuel cask is to be embedded in Sweden's repository design.[506] As of 2014, the company's conclusions were being subjected to review in Sweden's repository licensing process.

Lack of repository volume-reduction benefits

Areva, the government-owned company that operates France's La Hague reprocessing plant and hopes to sell similar reprocessing plants to China and the United States,[507] claims that reprocessing causes a "reduction in the volume of waste by a factor of five."[508] Japan's Ministry of Economy, Trade and Industry (METI) makes a similar claim.[509]

The comparison being made is between the volume of a ton of spent low-enriched fuel and the volume of the high-level waste from reprocessing that spent fuel. It leaves out, however, the volume of the long-lived intermediate- and low-level wastes produced by reprocessing and plutonium recycle that also must be buried in a deep repository.

Careful calculations for the case of France have shown that, within uncertainties, if all the radioactive waste streams from reprocessing and MOX fuel fabrication that require deep burial are included, the excavated volume of a geological repository for reprocessing waste and spent MOX fuel are the same as for the original low-enriched uranium spent fuel.[510]

The waste volume comparison ignores the fact that the area of a deep geological radioactive waste repository is determined not by the volume of the waste but rather by its heat output.[511] In the Swedish and French repository designs, for example, in order to provide an extra barrier to water flow, the canisters of high-level waste are surrounded by bentonite clay. This clay must be kept below 100 °C to retain its full water retarding and ion absorbing properties.[512] This limits the amount of heat-generating waste that can be put into each canister and also requires a minimum spacing between neighboring canisters to keep them from significantly raising each other's temperatures.

One ton of spent MOX light water reactor fuel and the high-level waste from the approximately seven tons of spent low-enriched uranium (LEU) fuel that must be reprocessed to obtain enough plutonium to fabricate it generate about 1.2 times as much radioactive decay heat between 10 and 200 years after discharge as eight tons of unreprocessed spent LEU.[513] Reprocessing and one recycle of plutonium in MOX therefore do not result in a significant benefit in reducing the area of a geological repository.

Economic and environmental costs of separations and transmutation

Thus, the doses from a well-designed deep repository are not expected to be large and fissioning the transuranics, as proposed by advocates of sodium-cooled reactors, would not significantly reduce these doses. What about the costs?

At the request of the U.S. Department of Energy, the U.S. National Academies organized a systematic cost-benefit study of transmutation that was published in 1996. The study group found that, for 62,000 tons of spent light water reactor fuel, approximately the amount that it estimated would have accumulated in the United States as of 2011,[514] reprocessing the spent fuel and using sodium-cooled reactors to fission 99.5 percent of the transuranics it contained would take 150 years and cost $500 billion.[515] The report concluded:[516]

> "none of the dose reductions seem large enough to warrant the expense and additional operational risk of transmutation".

Similar conclusions were arrived at by France's Nuclear Safety Authority (ASN) and France's Institute of Radiological Protection and Nuclear Safety (IRSN) in their criticisms of France's Atomic Energy Commission for promoting sodium-cooled reactors for transmutation.[517] The same argument has been made by Japan's senior advisor on radioactive waste disposal.[518]

Dose reductions or increases?

Because of the radioactive releases from reprocessing plants, it is quite possible that there would be a net dose increase from reprocessing and transmutation as a result of routine releases of radioactive gases and possible accidental releases from liquid high-level waste processing and stores.

Radioactive gases released by reprocessing

Reprocessing, as currently practiced, releases difficult-to-capture long-lived radioactive gases from spent fuel — most importantly, 5,700-year half-life carbon-14 in the form of carbon dioxide. These gases will increase environmental radiation doses to current and future generations. The UN Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) estimated in 2000 that that the collective global dose commitment over the next 10,000 years from civilian reprocessing prior to 1998 will be about 200,000 person-Sieverts.[519] That would result in about 20,000 cancer cases.[520] These consequences would be worldwide, in contrast to the local effects of leakage from a repository.

Explosions involving high-level liquid wastes

There is also the possibility of catastrophic releases of radioactivity to the environment from reprocessing plants (see Chapter 12). There have been a number of accidental explosions at reprocessing plants resulting in the dispersal of liquid radioactive waste to the atmosphere. The most catastrophic occurred in the Soviet Union in 1957 when the cooling system of a tank of high-level waste failed, it boiled dry and the residue exploded. The downwind contamination required the long-term evacuation of an area of 1000 square kilometers,[521] about the same area that has been subject to multi-year evacuation as a result of the 11 March 2011 accident at the Fukushima Daiichi Nuclear Power Plant.[522] Other lesser accidents have happened because of the use of organic chemicals in the standard PUREX process to separate plutonium and uranium from the high-level waste. The high radiation level in the liquid radioactive waste degrades these chemicals and they react with the nitric acid used to dissolve the spent fuel to form a "red oil" that can explode if heated above 135 °C.[523]

Occupational doses

The workers in reprocessing and plutonium fuel fabrication plants receive radiation doses that would not be incurred if the spent fuel were disposed directly into a repository. If reprocessing and fast neutron reactors drastically reduced the need for uranium mining and milling, however, the added doses from reprocessing would be offset by reduced doses to workers engaged in those activities.[524]

Overall, however, the dose-reduction benefits from reprocessing could well be negative.

Plutonium "mines"

A final major benefit cited for transmutation is the elimination of the danger of a spent fuel repository becoming a "plutonium mine" for countries or groups interested in making nuclear weapons — especially after a few centuries when the gamma activity of the short-lived fission products mixed with the plutonium in the spent fuel will have died down. This hazard must be compared, however, to other ways a future society might try to acquire nuclear weapons.[525]

Furthermore, it is disingenuous to argue for separating and recycling plutonium, with the resulting quick access created for countries and potentially subnational groups to a nuclear-weapon option, while simultaneously arguing that plutonium is a security threat when buried at a depth of 500 meters or more.

Nevertheless, Glenn Seaborg, who promoted a worldwide "plutonium economy" while he chaired the powerful U.S. Atomic Energy Commission (AEC) during the 1960s, later used the plutonium-mine argument in an attempt to discredit those warning that the spread of reprocessing was spreading the bomb:[526]

> "those who advocate the disposal of spent fuel…do not necessarily occupy the high ground in the non-proliferation debate… only burning or transformation to another element through irradiation can do the job".

In 1974, a few years after Seaborg had stepped down from chairing the AEC, India conducted its first test of a nuclear explosive using some of the plutonium that it had separated for its breeder reactor program with the assistance of the U.S.AEC.[527]

Conclusions

Based on the above review of the costs of benefits of chemically separating plutonium and other transuranics in spent power reactor fuel for transmutation, it is difficult to disagree with the already cited conclusion of the 1996 review by the U.S. National Academy of Sciences that "none of the dose reductions seem large enough to warrant the expense and additional operational risk of transmutation."

Reprocessing makes nuclear power significantly more costly and has therefore been abandoned except in a few countries where governments require their utilities to reprocess. Deploying the fast neutron reactors that would be required to fission many of the transuranic isotopes would make nuclear power still more costly. This is why, despite 50 years of efforts by some countries to get their nuclear utilities to commercialize these reactors, none have done so.

A major security cost of reprocessing spent fuel to separate out plutonium and possibly the minor transuranic elements in preparation for their irradiation in fast neutron reactors is that it provides governments with a nuclear-weapon option and lowers the barriers to terrorist acquisition of nuclear-weapon materials.

On the other side of the balance, the expected environmental benefits of transmutation in reducing the risk of radioactive contamination of the surface environment by deeply buried spent nuclear fuel are small and probably exceeded by the radiological impacts of routine and accidental releases of radioactivity by spent-fuel reprocessing plants.

Finally, the realization of the claimed benefits of transmutation in reducing the risks from transuranics one hundred-fold would require a commitment to reprocessing and fast neutron reactors of hundreds to thousands of years — far beyond any realistic energy-planning horizon.

11. Economics

There have been many studies of the economics of reprocessing, both generic and for specific countries. The great majority have found that reprocessing to recycle the separated plutonium into fresh fuel is substantially more costly than treating spent uranium fuel as waste.

The reasons for undertaking another review are:

1. A few studies have concluded that there is no significant difference between the costs of the two fuel cycles, especially a recent and influential report from the OECD's Nuclear Energy Agency (NEA); [528] and
2. There continues to be interest in a few countries in developing fast neutron reactors despite their lack of technical and economical success thus far.

Analyzing the economics of reprocessing requires a consideration of the economics of the "front end" of the nuclear fuel cycle, the processes involved in producing fresh fuel, as well as the "back end," the activities involved in dealing with the fuel after it has been irradiated and discharged from the reactor, i.e., the management of spent fuel. It is necessary to include because the savings in enriched uranium permitted by the use of plutonium and uranium recovered through reprocessing do offset to some degree the extra costs of reprocessing.

Recycling plutonium (and sometimes also uranium) is often described as "closing" the fuel cycle, while disposal of spent fuel as waste is labeled the "open" fuel cycle. These terms are misleading, however, and the use of the plutonium recovered through reprocessing spent fuel to further fuel light water reactors as currently practiced could be better described as "twice-through." This is because there are no operational plans anywhere in the world to recycle the plutonium more than once. In practice, spent mixed-oxide (MOX, uranium-plutonium) fuel is always stored.[529] The plan is either to dispose of the spent MOX fuel directly or store it for a very long period for possible future use in fast neutron reactors in case they are ever built in significant numbers. The uranium recovered by reprocessing today is almost always stored, so only the plutonium, about one percent by mass of spent fuel, is recycled in some countries — notably France. In other countries — notably the United Kingdom — all the products of reprocessing, including the separated plutonium, are stored.

Storage of spent MOX fuel will be necessary for long periods because fast neutron reactors are not expected, even by proponents, to be successfully commercialized before the second half of the century.[530] Even if the ambition for repeated recycling were to be realized in a fully functioning system based on fast neutron reactors, the fission products would require disposal, so even the so-called "closed" fuel cycle is not fully closed; in other words, the radioactive waste produced during the different steps in the fuel chain would still require a deep geological repository.

While most studies of reprocessing economics stick to the two currently relevant alternatives of once-through and twice-through cycles, some also include a fast-neutron reactor-based cycle.[531] Because the uncertainties are very substantial, the usefulness of economic analysis of the fast reactor fuel cycle is limited. The two most recent studies that include the fast reactor cycle, however, both concluded that the overall costs of this cycle will most likely be substantially higher than for either of the other two cycles. The primary reason is the widely-accepted view that the capital cost of fast-neutron reactors will be significantly higher than for light water reactors, even when account is taken of hoped for "learning curve" effects.[532]

Non-economic factors

Governments have historically regarded policy for nuclear power as a "strategic" issue, and decisions have generally been made at high political levels. This is because there are three strategic considerations with regard to the nuclear fuel cycle:

1. Reprocessing spent fuel gives access to weapons-usable separated plutonium, whereas storing spent fuel positions a country much further from a nuclear-weapon option;
2. A large fraction of the nuclear community has always regarded uranium-efficient fast neutron reactors as the inevitable culmination of civilian nuclear technology and has therefore always lobbied hard in favor of reprocessing as an apparently necessary step towards this long-term vision;[533] and
3. The idea that reprocessing helps an energy-import-dependent country to achieve higher levels of energy security by reducing its need for fresh uranium.

Governments therefore may be willing to pay a substantial economic premium to achieve wider objectives via reprocessing. But they and their citizens will nevertheless be interested in the size of the economic premiums they may have to pay to achieve such objectives. Furthermore, there has been a move over the last 20 years or so, across several countries, towards a more market-based framework for nuclear-energy decision-making. This is largely a consequence of movements towards a more liberalized and sometimes privatized and competitive structure for electric utilities,[534] making them more sensitive to the relative costs of different options.

Some Governments therefore have begun to devolve to electric utilities decisions on fuel cycle choice that were previously made at the state level. The most far-reaching case to date has been in the United Kingdom, where the Government now expresses indifference between a once-through and a twice-through fuel cycle, and explicitly regards the issue as one for the utilities to decide for themselves.[535] Competitive pressures and the direct importance of economic factors in fuel cycle decisions also have been growing in other countries in the European Union as a consequence of Europe-wide efforts at liberalization and in large parts of the United States as a result of de-regulation.

Costs

Most analyses of fuel cycle economics have used market-based costs where they exist and used industry-based estimates of costs where there is no market or other substantive experience (e.g. for geological repositories). The objective here is, as far as possible, to use costs that reflect real resource use; i.e., the costs to society including external costs. Because substantial amounts of market power exist in the fuel cycle, market prices may not reflect social cost.

At the front end of nuclear fuel cycle, the uranium market is reasonably competitive, with a range of firms and countries offering supply.[536] At the back end, only France offers international reprocessing and MOX fuel fabrication services,[537] and can charge its domestic customer (Électricité de France) a different price than its international customers.

In practice it is difficult in the case of fuel cycle services to make defensible adjustments to market prices for market power and external costs. In general, therefore, this paper will be interested in market-based prices. The relevant costs here include all capital costs. Marginal or operating cost-related contracts that may be offered after a plant is fully paid for are not relevant to decisions on whether or not to build new plants.

The other issue regarding costs is the adjustment of future expenditures and income by use of a discount rate, in which future costs are valued progressively less the further into the future they are expected to fall. Economists have debated for decades about the rate at which to discount per year (few economists support no discounting at all). Arguments in favor of low discount rates (of the order of 1 percent to 2 percent per annum) have become dominant in recent years when considering potentially distant costs, such as those due to climate change.[538] In the present case, the only long-term costs where discount rate differences could matter are for waste repositories, and it will be argued later in this chapter that these costs will not vary much between once-through and twice-through cycles. The issue of discounting therefore will be ignored here as it plays no significant role in discriminating between the costs of the two cycles.

Comparing once-through and twice-through fuel cycle costs

While the discussion below mainly concentrates on the recent study on fuel cycle costs published by the NEA in 2013,[539] it is important to first offer a brief review of some other studies conducted over the last two decades. Virtually all have used reasonably transparent methodology and have come to the conclusion that the once-through fuel cycle is less costly than twice-through. The 2013 NEA study lists some of these studies.[540] It also explains some of their assumptions and presents their overall results. These are expressed in terms of the 'cost premium' for the twice-through cycle. Table 11.1 shows these premiums and includes the NEA 2013 study for comparison.

Study	MIT (2011)	Harvard (2003)	Rothwell (2011)	NEA (1994)	NEA (2006)	NEA[541] (2013)
OT Cost (US$/MWh)	8.2	6.5	7.5	9.4	5.6	6.7
TT Cost	10.3–11.3	8.1	12.4	10.4	6.4	7.3
TT Premium	26–37%	25%	65%	11%	14%	20%

Table 11.1. Costs of once-through and twice-through fuel cycles in selected studies. *Source: The economics of the back end of the fuel cycle, Nuclear Energy Agency, OECD, 2013, Table 3.10, p. 107.*

These studies consistently show a higher cost for the twice-through cycle, irrespective of precise methodology and assumptions, or time period when the study was carried out. And where the economics of the two cycles have been subject to a clear market test, as in the current plans for future reactors in the United Kingdom, all of the potential developers (EDF, GE Hitachi and Westinghouse) have made it clear that they regard the once-through cycle as the less costly option.[542] This was a material factor in the UK's 2012 decision to close its THORP reprocessing plant.

A recent study by Rothwell *et al.* (2014) reaches very similar conclusions to the Rothwell 2011 study in Table 11.1, using similar input assumptions.[543] It provides an illustration of the gap between the costs of the two fuel cycles by expressing it in different terms. If uranium prices rose by 0.5 percent annually and reprocessing costs fell by 2 percent annually, it would take 80 years before the two cycles had the same overall fuel cycle cost.[544]

Other studies of the economics of reprocessing also have all reached the same conclusion about the relative costs of the two cycles. Studies by the governments of France and Japan, are particularly interesting as those governments have been, and remain, strongly committed to reprocessing:

- The *"Charpin Report"* in 2000 was commissioned by France's Prime Minister and obtained data from all the major facilities in France's nuclear industry.[545] The most relevant scenario compared the costs of the full fuel cycle had France's light water reactors operated completely on a once-through or twice-through cycle. The conclusion was that the twice-through fuel cycle costs 24 percent more.[546]
- Japan's Atomic Energy Commission (JAEC) published a study in 2005 that evaluated four scenarios for spent fuel management on a whole-fuel cycle cost basis.[547] Its basic results showed an advantage to the once-through cycle of between 25 percent and 70 percent depending on the scenario chosen, mostly due to the high cost of reprocessing.[548] In 2011, the JAEC updated its cost study and found twice-through ranging from 60 percent to 100 percent more costly than once-through when the discount rate was varied from 0 to 5 percent per year.[549]

Recent studies of fuel cycle costs in China and India also find, with admittedly limited data, that the once-through cycle would be less costly in both those countries. China only has a small-scale pilot reprocessing plant at this point. The reported €20 billion ($25 billion) price of the 800-ton/year capacity reprocessing plant that Areva has offered to sell to China is comparable to the price of Japan's Rokkasho reprocessing plant.[550] In the case of India the authors of an independent study made a series of assumptions about the costs of reprocessing favorable to the twice-through cycle but still found that the once-through cycle would be significantly cheaper.[551]

The overall margin of advantage for the once-through cycle in the examples above has been shown for the fuel cycle as a whole, where most of the fuel, even in the second round of the twice-through cycle, is LEU-based. If the narrower comparison is made between the cost, ton for ton, of MOX and LEU fuel, the cost difference widens very substantially. The Charpin report, mentioned above, showed that 4300 tons of additional LEU fuel would have been required, had no MOX ever been used, at a cost of 33 billion francs. In the reprocessing scenario 4800 tons of MOX would have been produced at a cost, including the cost of reprocessing, of 177 billion francs.[552] The corresponding costs were 7,700 francs/kgLEU and 36,900 francs/kgMOX. In this direct comparison MOX fuel was almost five times more costly that LEU. A similar comparison by Japan's Atomic Energy commission estimated the same ratio for the Rokkasho reprocessing and J-MOX plants at 12.3.[553]

There is just one study that shows the economics of the two cycles as approximately the same.[554] This study was carried out by the Boston Consulting Group (BCG) for Areva, which then used the results to make a case to the G.W. Bush Administration that the United States should buy a combined reprocessing and MOX plant. The costs of uranium, enrichment and geological disposal used by BCG were within the range of those made in the studies reported in Table 11.1. The costs of reprocessing and MOX fabrication were supplied by Areva, however, and were very much lower than in all the other studies. Table 11.2 below shows the different values for the cost per kilogram of spent fuel reprocessed and MOX fuel fabricated as assumed by the BCG study and the studies listed in Table 11.1.

Study	MIT (2011)	Harvard (2003)	Rothwell (2011)	NEA (1994)	NEA (2006)	BCG (2006)	NEA (2013)
Reprocessing of LEU fuel	$4,179	$1,179	$2,446	$1,001	$1,075	$677	$579–737
Fabrication of MOX fuel	$2,508	$1,769	$2,643	$1,362	$1,344		

Table 11.2. Reprocessing and MOX fuel fabrication costs. All figures are in U.S.2010$ per kilogram of heavy metal. The costs assumed in the BCG and NEA (2013) report assumed an integrated plant.[555] *Source: The economics of the back end of the fuel cycle, Nuclear Energy Agency, OECD, 2013, Table 3.9.*

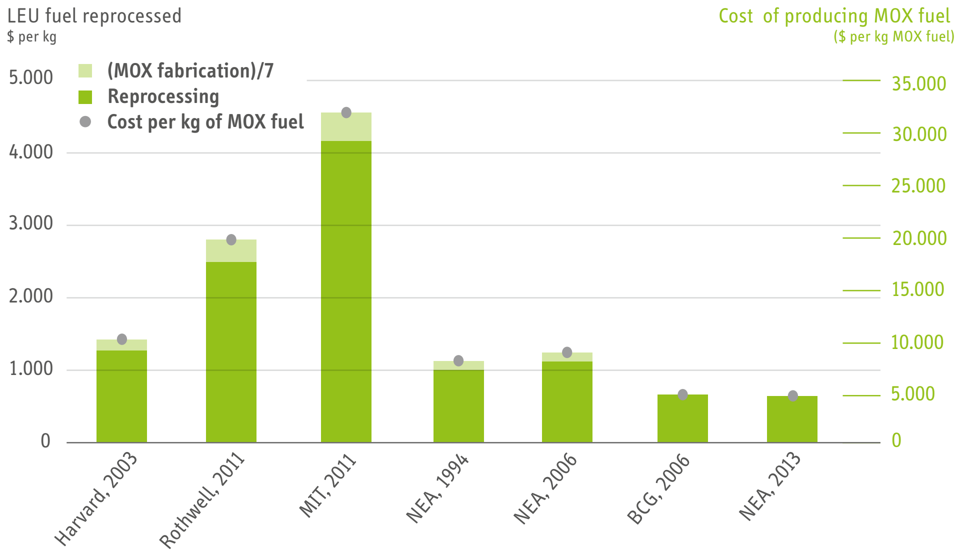

Figure 11.1. Cost of processing LEU fuel, which includes the costs of reprocessing and MOX fuel fabrication. For all but the Boston Consulting Group (BCG) study done for Areva and the NEA (2013) report, whose estimates were based on the BCG study, the per kilogram cost of MOX fuel fabrication has been divided by seven to reflect the fact that approximately 7 tons of LEU fuel are reprocessed to produce enough plutonium for one ton of MOX fuel. In the case of the BCG and NEA (2013) report, the reprocessing and MOX plants were assumed to be integrated and only one number was given.

The presentation of Table 11.2 in the NEA report and in the associated Appendix 6 does not make it clear how the MOX fuel fabrication costs should be added to the reprocessing costs to give a figure that can be compared on a like-for-like basis with the cost of the "integrated" plant assumed by BCG. Given that the reprocessing of about seven tons of low-enriched uranium (LEU) fuel is required to separate enough plutonium for one ton of MOX, the MOX cost should be divided by about seven before adding it to the reprocessing cost to achieve direct comparability with the combined BCG figure of $677. Compared on this basis, the assumed BCG costs for reprocessing and MOX fabrication is between 15 percent and 57 percent of the costs used in the other studies (see Figure 11.1).

The overall conclusion of the BCG study — that the twice-through fuel cycle has comparable costs to those of the once-through fuel cycle — therefore is mostly the result of an assumption made by a commercially interested party about an "integrated" plant that has never been built. This point has been labored here because the NEA study of 2013 also makes the assumption of an integrated plant for reprocessing and MOX fabrication and uses the BCG/Areva numbers to argue that the cost of the twice-through cycle is within the range of uncertainty of the once-through cycle.

The NEA study of 2013

The NEA study is based on data provided by its member states. It is a comprehensive and mostly well-documented study, aiming to show systematically the cost differences between different fuel cycles.[556] It shows these differences considering both back end costs alone, and overall fuel cycle costs. Besides including a large range of assumed cost inputs, the NEA models a range of scenarios, with variations involving:

- Discount rates of 0 percent and 3 percent per annum;
- Sizes of nuclear systems of 25 TWh, 75 TWh, 400 TWh (reference case) and 800 TWh –corresponding roughly to nuclear systems capacities of about 4, 10, 60 and 110 GWe respectively (assuming an 80 percent capacity factor). France, which generated 404 TWh in 2013 and is the only country with both a reprocessing and MOX plant, appears to be the reference case. The United States, China in the future, or a group of countries sharing back end facilities might correspond to the 800 TWh case.
- Three cost levels, low, high and reference, where the low and high figures are derived from the extreme values provided by member states.[557]

The combination of 2 discount rates, 4 system sizes and 3 cost levels yields 24 different cost outcomes, and sensitivity tests are also included, for example to reflect possible differences in factors such as the price of uranium and the cost of reprocessing.

The NEA concentrates on producing results for "idealized" fuel cycles, which means it assumes equilibrium conditions with no undue delays in moving from one stage of a cycle to the next.[558] Among the countries currently reprocessing, France is the only country that approximates this ideal case. The others (India, Japan, Russia and the United Kingdom) have been reprocessing for decades in the expectation that the plutonium will eventually be recycled; India and Russia have been focusing on recycling in breeder reactors and not in MOX for light water reactors, which is the subject of the NEA report. The NEA assumptions about reprocessing and MOX fuel fabrication also are "idealized" in a quite different sense, in that they assume a technology that does not yet exist and lower-bound costs much lower than historical experience.

The NEA's results

The headline conclusion of the NEA study is that, under most circumstances, the once-through cycle will have an economic advantage averaging 20 percent across all scenarios over the twice-through cycle.[559] There are two qualifications, however:

1. Of the 24 cases shown on a full fuel cycle basis, three (all for the 800 TWh/year case) show twice-through to be cheaper.[560]
2. The NEA argues for its reference case (in effect, France) that the uncertainty ranges ("error bars") around all its estimates are much larger than the differences in cost estimates between the once-through and twice-through cycles.[561] The error bars simply reflect the low and high cost estimates that member states have provided. The low cost estimates were provided by France, i.e., the numbers for an integrated plant provided by Areva to the Boston Consulting Group shown in Table 11.2 and discussed above. This means that the "error bars" are not based on any real world experience. The clear message of the NEA report, however, is that it is impossible to make a definitive case that the once-through cycle will, in any given real-world circumstances, be cheaper than twice-through and "the difference between the total fuel cycle costs of the three options considered in the reference cost scenario are within the uncertainties." [562]

Therefore, despite showing that, in the reference and the great majority of other cases, the once-through cycle is expected to be somewhat and sometimes substantially less expensive than twice-through,[563] the NEA study qualifies this result by arguing that

1. The cost advantage of the once-through cycle is not always the case where nuclear system capacities are very large (800 TWh per annum),
2. Where an advantage appears to exist for the once-through fuel cycle, the result is not robust because the "error bars" on its cost estimates are much larger than the cost differences between the two cycles.

The NEA study therefore suggests that countries choosing between the two cycles should make their choices on other than economic grounds because "For the recycling options, additional costs from reprocessing are being offset by the savings on fuel costs at the front end" [564]

To understand why the NEA's conclusions differ from those of other studies, we examine below the costs that

- Are different between the two cycles, and/or
- Make a significant difference to the overall outcome.

A simple way of thinking about the similarities and differences of once and twice-through fuel cycles is to imagine two consecutive rounds of fuel use with currently available technology. In the first round, the two cycles have identical front ends: uranium is purchased, enriched and fabricated into fuel. At the back end of the first fuel round, however, once-through fuel is stored for disposal. We assume disposal will be in deep geological repositories in all cases. For the back end of the first round in the twice-through cycle, spent fuel is stored and then reprocessed. This results in the separation of uranium and plutonium and the creation of both high-level radioactive waste that is "vitrified" (glassified) and then eventually sent to a deep repository plus a variety of intermediate and low level wastes, some of which also will go to the repository.

The second round of the once-through cycle is almost the same as the first round. In the twice-through cycle, most of the fuel is low-enriched uranium but about one eighth is a different kind of fuel (MOX) produced in a different fuel fabrication facility. MOX contains reprocessed plutonium mixed into depleted uranium from uranium enrichment at a concentration of six to eight percent with no uranium enrichment needed.[565] At the back end of this second round in the twice-through cycle, MOX fuel is stored for disposal in a geological repository.[566]

The first question is then what are the cost *differences* between the two cycles, and second whether or not the differences are large enough to cause a significant difference in their overall costs.

The four issues that meet the criteria of cost difference between the cycles and/or significance in terms of the overall results are the costs of:

- Final waste disposal, because these are potentially large costs and it is sometimes argued that they will be significantly less in the twice-through cycle;
- Uranium, as the twice-through cycle uses less uranium than once-through;
- Reprocessing in the twice-through cycle; and
- Fabrication of MOX fuel in the twice-through cycle.[567]

For these four issues, the plausibility of the NEA assumptions are discussed below and the resulting impacts on the overall cost comparison are assessed.

Waste disposal costs

The NEA makes the assumption that spent MOX fuel will need to be disposed of rather than being stored indefinitely. The comparison therefore is between:

- For the once-through fuel cycle, two rounds of spent uranium fuel (UOX) disposal; and
- For the twice-through cycle, a first round of disposal of wastes from reprocessing LEU fuel, plus a second round of disposal of spent UOX and MOX fuel.

The proportion of the total fuel cycle costs represented by disposal in both fuel cycles is small in the NEA analysis, and similar for the two cycles. For example, only for the 25 TWh cases at a zero discount rate (three out of the 24 cases) does the disposal cost for either cycle amount to more than 18 percent of the total fuel cycle cost. The difference in disposal cost between the two cycles is in no case more than 10 percent.[568]

These two factors — that waste disposal cost is a small element in total fuel cycle cost, and that it is very similar between the two cycles — mean that disposal does not offer any significant cost advantage to the twice-through cycle in the NEA's own analysis. This is at first sight surprising given the NEA's assertion that the volume of high-level waste to be disposed of in the twice-through cycle is five times less than in the once-through cycle.[569] However:

- Some long-lived intermediate-level waste needs to be emplaced in the repository as well as high level waste. According to the NEA, this reduces the volume reduction factor by half. [570] According to one independent analysis of Areva waste data, it eliminates the volume reduction altogether;[571]
- At the second fuel cycle round, it is necessary in the twice-through cycle to dispose of the spent MOX fuel. Spent MOX is substantially hotter than spent LEU fuel, and — according to the NEA — requires 2.5 times more underground volume per ton relative to spent UOX fuel; [572]
- A high proportion of the cost of any repository is fixed. For example, the construction of tunnels or shafts to a depth of several hundred meters underground will be similar irrespective of the volume of the repository chambers.

Waste disposal costs are therefore not significant as a potential cause of cost advantage to the twice-through cycle.

Uranium costs

The original rationale for the twice-through fuel cycle was that uranium would become scarce and expensive. It would then follow that the savings in uranium use made possible by the use of the plutonium to fuel the transition to plutonium breeder reactors would give the 'closed' cycle a long-term advantage over the open cycle. The current twice-through cycle can only offer savings in uranium use of a maximum of 22–25 percent if all reprocessed uranium is recycled, or 12 percent if only the plutonium is recycled.[573]

As the twice-through cycle uses less uranium than the once-through cycle, there is some level of uranium prices at which it would become less costly. The prospects for uranium prices are therefore a major issue. The NEA assumes a constant future price of uranium of $130/kgU at 2010 prices, a higher figure than used in any of the Table 11.1 studies. It also provides data on uranium prices between 1980 and 2011 in constant 2010 U.S. dollar terms (see Figure 1.2). This shows considerable fluctuations in price but no upward long-term trend. An average price for 31 years of NEA price data is around $110/kgU (at constant 2010 prices).[574] Only in five of the 31 years has the price been above $130/kgU. Nevertheless an assumption of $130/kgU seems a reasonable starting point, provided enough sensitivity testing is done to check the impact of variations in price.

The NEA provides brief but useful sensitivity analyses of the impact of higher and lower uranium prices on the costs of the two cycles. The conventional — and useful — way of presenting the results of such sensitivity testing is to find the uranium 'breakeven' price. This is the price at which the once-through and twice-through fuel cycles would cost the same. The NEA does not provide such breakeven prices but interpolation of its sensitivity tests for its "reference" case of a 400TWh/year system size at 0 and 3 percent discount rates allows rough breakeven prices to be calculated.

The NEA finds that a 50 percent increase in the price of uranium would lead to a 33 percent and a 27 percent increase in the total fuel cycle cost for the once-through and twice-through fuel cycles respectively. On the basis of this linear relationship, for a zero percent discount rate, the price of uranium would have to rise by a factor of five — to $650/kgU — for the cost of the once-through fuel cycle to equal that of the twice-through fuel cycle. For a 3 percent discount rate, the price of uranium would have to rise to several thousand dollars/kgU.

No serious analysis is currently suggesting that the price of uranium will increase dramatically in the foreseeable future. Nevertheless, it is worth briefly exploring the possible future of uranium prices, especially as the NEA claims that the breakeven uranium price at which fast reactors would become more economic than the once-through cycle could be as low as $170/kgU.[575]

The long-term trend of uranium prices will be determined, as in the case of other commodity prices, by the interplay of long-term supply and demand. Based on reports of incomplete estimates of national uranium resources, the NEA and IAEA have concluded:[576]

> "If estimates of current rates of uranium consumption in power reactors are used, the identified resource base would be sufficient for over 150 years of reactor supply. Exploitation of the entire conventional resource base would increase this to well over 300 years."

A recent and comprehensive review concludes similarly that there "is a strong case for the abundance of already known uranium resources…to meet the foreseeable future of nuclear power" including for an IEA scenario of deployment of 2000 GWe of nuclear power (five times current levels) by 2100.[577] Since at least the 1970s, geologists have consistently argued that there is no foreseeable resource constraint on uranium.[578]

Demand for uranium primarily depends on the level of reactor capacity. The price spike that occurred in the 2006–2011 period was mainly a consequence of exaggerated expectations of a "nuclear renaissance." The IAEA undertakes projections for nuclear capacity in 2050 each year. These projections have been falling. In 2014, it predicted a range of 413 GWe to 1092 GWe, i.e., between a 10 percent and 190 percent increase relative to 2014.[579] Global nuclear electric power production peaked in 2006 and has fallen since, especially after the Fukushima accident.[580] Global capacity may rise again in the next decades as more reactors come on line in China, Russia and some developing countries, but that is not certain because there will be many retirements as well. For the past 20 years, new nuclear capacity has been coming on line at an average rate of about 3 GWe per year. But the reactor fleets in the U.S., Western Europe, Japan, and Canada, which together account for 72 percent of global capacity, are aging. Seventy two percent of global nuclear capacity has operated for 25 years or more and no power reactor has yet operated for more than 45 years (Figure 11.2). If, in the future, reactors retire on average when they complete their 45th year, retirements during the next 20 years will average about 13 GWe per year.

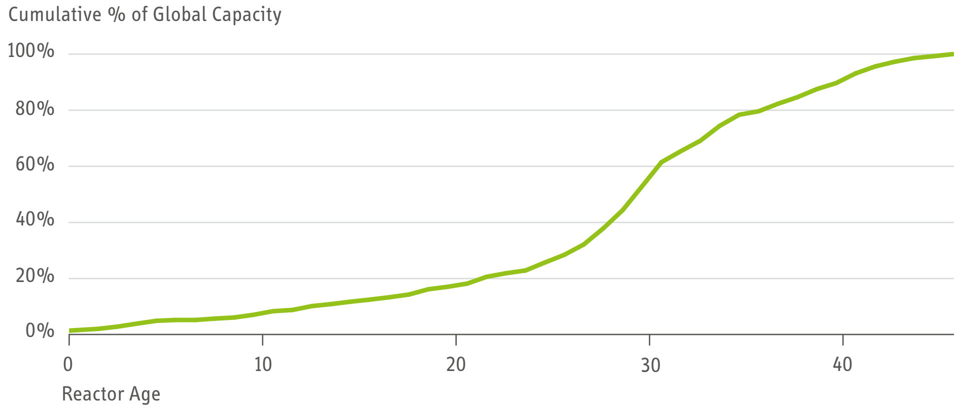

Figure 11.2. Age distribution of global nuclear capacity in late 2014. Global nuclear generating capacity as of the end of 2014 was 375 GWe. *Source: Data from Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, 12 April 2015,* www.iaea.org/PRIS/WorldStatistics/OperationalByAge.aspx

Reprocessing and MOX fabrication costs

The NEA treatment of reprocessing and MOX fabrication costs is surprising. While data for all the other fuel cycle activities have come from NEA member states and relate to current and/or historical experience, all the data here came from a single commercially interested source (Areva) and involve conjectures about future plants. It was assumed that, in any future back end facilities, reprocessing, vitrification of reprocessing liquid wastes and MOX fabrication would be integrated.[581] These activities were then lumped together as a single cost item.

The high estimate is based on Areva's reported historical cost of the two reprocessing plants at La Hague on the English Channel and the Melox MOX fuel fabrication plant in the south of France. The central ("reference") estimate was based on Areva's estimate for the 2006 Boston Consulting Group (BCG) study that, if La Hague and Melox were rebuilt as an integrated plant, including a vitrification facility, their total capital cost would be reduced.[582] The low cost estimate was based on another Areva estimate for the 2006 BCG study for a case with "significant improvements and economies of scale".[583]

The Boston Consulting Group included in its report an explicit disclaimer: "BCG reviewed… proprietary data provided by Areva, but did not undertake any independent verification of the facts contained in these source materials".[584]

Thus essentially all of the data used for reprocessing and MOX fuel fabrication costs in the NEA study come from a single commercially interested source, are proprietary, and therefore not accessible to review by the NEA team or anyone else.

Two tests can be applied to the plausibility of the Areva-derived NEA (2013) assumptions

1. The costs of reprocessing and MOX fabrication assumed in the independent studies shown in Figure 11.1 above; and
2. The actual costs of reprocessing and MOX fabrication experienced in the real world.

It is obvious from Figure 11.1 that the NEA (2013) report is inconsistent with the independent studies — especially that done by MIT in 2011.

With regard to real world experience, the most recent is that of the Areva-designed Rokkasho Reprocessing Plant in Japan, where a MOX plant based on an Areva design is being built on the same site.[585] The capital cost of the reprocessing plant is ¥2.19 trillion (~$22 billion),[586] or $700–1200 per kg "heavy metal" (HM, uranium plus plutonium) throughput for capital cost alone, for discount rates ranging from 0 to 3 percent, if it operates at full design capacity of 800 tons per year for 40 years. Its operating cost over that period has been estimated by Japan's Atomic Energy Commission, a defender of the plant, as ¥11.7 trillion (~$120 billion) or $3650/kgHM for a total of $4350–4850/kgHM.[587] In 2011, Japan's Atomic Energy Commission estimated the cost of fuel fabrication at the new co-located MOX plant at 15 percent of that of the cost of reprocessing.[588] This would raise the combined cost of reprocessing and MOX fabrication to $5000-5600/kgHM.

Both of these plants have suffered from major delays and could be unrepresentative of the possible costs of future plants — though large and controversial nuclear facilities are not standard industrial projects. These most recent cases show, however, that it is implausible to argue, as Areva and NEA do, that future plants will be much less expensive compared to La Hague and Melox.

The NEA model shows that a 50 percent increase in integrated plant reprocessing cost would raise the overall fuel cost of the twice-through cycle by 15 to 18 percent, depending on the discount rate.[589] The mid-range estimate for the Rokkasho plants is 8 times higher than the mid-range number assumed in the 2013 NEA study. Assuming that the scaling is linear from the 50 percent cost increase case, a 700 percent increase in overall reprocessing and MOX costs would raise the overall cost of the twice-through fuel cycle by more than 200 percent.

It therefore is clear that the NEA's conclusion that the once-through fuel cycle has only a marginal and uncertain economic advantage over the twice-through cycle is largely due to its unreasonably low cost assumptions for reprocessing and MOX fuel fabrication. When numbers based on real world experience are used, it becomes clear that the once-through cycle has an unambiguously substantial economic advantage over the twice-through cycle.

Conclusion

The current choice facing utilities or Governments on the nuclear fuel cycle is either to treat spent fuel as waste or to reprocess it and use the separated plutonium (and possibly, though rarely, separated uranium) in the same kinds of reactor. For the next several decades, there are no realistic prospects for more than a single recycle of plutonium in existing reactors. Independent studies of the economics of the two cycles conclude that, in addition to offering better protection against proliferation risk, the once-through cycle is cheaper than twice-through.

A recent and comprehensive review from the NEA, with mostly transparent methodology, challenged this consensus. It argued that, although in most circumstances the once-through cycle would be cheaper, its advantage is usually small and the uncertainties attaching to this result ("error bars") are much larger than the average cost differences between the cycles.

We have examined the basis for these conclusions and find them to be faulty. The NEA report has two significant problems:

1. It wrongly argues that the cost (and volume) of a final repository in the twice-through cycle will be lower than for the once-through cycle, although correction for this would make little difference to its quantitative results.
2. It uses proprietary projections from an interested private company, Areva, to conclude that the future costs of reprocessing and MOX fabrication will be radically lower than either the costs assumed in other studies, or (more important) the real-world costs of the recent Areva-designed reprocessing and MOX plants in Japan and Areva's proposed price for building a reprocessing plant in China.

Given that the main economic appeal of reprocessing was always based on the savings in increasingly scarce and expensive uranium, a serious difficulty for the economic competitiveness of the twice-through cycle is that it uses almost as much uranium as once-through (savings of 12 percent if only plutonium is recycled, as is normally the case today, rising to 25 percent if reprocessed uranium is recycled as well.) This means that, even using all the NEA input assumptions, including a reference case that assumes reprocessing and MOX fuel-fabrication costs far below historical experience, the breakeven price for uranium — the price that would make the costs of the two cycles equal — is $650/kgU, five times higher than the NEA's assumed future price and about six times higher than the historic average.

The overall conclusion is that the pre-NEA consensus about the relative costs of the two fuel cycles is robust. The once-through or open fuel cycle will be reliably and substantially cheaper than the twice-through or reprocessing cycle in virtually all future circumstances.

12. Radiological Risk

A reprocessing plant contains huge inventories of radioactive material, some of which could be released to the environment by an accident or an attack. The potential for such a release should be considered in decisions about designing and building a new reprocessing plant or continuing the operation of an existing plant.

This chapter includes some of the major findings in a technical report on radiological risk at reprocessing plants that recover plutonium and uranium from spent light water reactor fuel.[590] Appendices to that report discuss the reprocessing plants at La Hague in France, and Rokkasho in Japan. The report gives particular attention to two types of incidents that could result in a large release of radioactivity to the atmosphere:

1. A fire in a spent-fuel pool following loss of water; or
2. Dryout of a tank containing high-level liquid waste (HLLW).

The chapter ends with some conclusions and recommendations of ways in which the risk at an existing reprocessing plants could be reduced.

The radiological and program risks associated with a particular nuclear facility are partly determined by the facility's design and also by other aspects of its "risk environment" such as site characteristics (e.g., earthquake or flooding potential, distance from population centers) and the potential for an attack. Many of these factors are likely to change with time.

The safety design of a nuclear facility reflects a "design basis" envelope of hazards that the facility is designed to withstand without a major release of radioactivity. Some hazards may not be taken explicitly into account. For example, protection against an aircraft crash is not included in the design basis for the reprocessing plants at La Hague.[591]

Potential release sources and mechanisms

A commercial reprocessing plant receives spent fuel that has been stored, after its discharge from a reactor, for a period that ranges between years and decades. Short-lived radioisotopes in the fuel (e.g., I-131, with a half-life of 8 days) therefore have already decayed. A reprocessing plant typically provides, however, storage for spent fuel from tens of reactors and for the radioactive waste from reprocessing that fuel. Its inventory of longer-lived radioisotopes is, therefore much greater than the inventory at a single reactor. The fission product, cesium-137, is of special concern because it is long-lived, with a 30-year half-life, and emits a penetrating gamma ray when it decays. Cesium-137 contamination is the primary reason for the prolonged evacuation of large areas around the Chernobyl and Fukushima Daiichi sites.

Spent fuel pools

At La Hague, there are four water-filled pools with a total capacity for spent fuel containing 17,600 metric tons of "heavy metal" (uranium and plutonium). For comparison, the core of a PWR with a generating capacity of 1.1 GWe contains about 90 tHM of fuel.

Typically, in cooling pools today, spent fuel is stored in racks almost as densely as in a reactor core. To prevent criticality, each fuel assembly is stored vertically, surrounded by neutron-absorbing plates designed to prevent criticality via chain reactions involving adjoining fuel assemblies. For that configuration, in case of loss of water from the pool, removal of the radioactive decay heat from the fuel through convective cooling and infrared radiation would be comparatively feeble, resulting in rising fuel temperatures. At a temperature on the order of 1,000 °C, the zircaloy (zirconium alloy) cladding of the fuel would begin to burn in air or steam. That outcome could result in a propagating fire that could lead to a substantial atmospheric release of cesium-137.[592]

If pool cooling were interrupted, water could be lost by boiling off, but that process would be comparatively slow. Events that could cause rapid loss of water from a spent-fuel pool include breach of a pool wall or floor by earthquake or attack. Even after spent fuel became exposed, there would be a delay, typically of several tens of hours, before the temperature of the zircaloy cladding rose to the point where ignition could occur. During that time, site staff could potentially prevent a fire by performing mitigating actions, such as restoring the water level in the pool. Access needed for mitigating actions could, however, be precluded by a high radiation field around the pool, or attackers could use incendiary material to ignite the zircaloy immediately after water loss.

High-level liquid waste

When a spent fuel assembly enters a reprocessing plant, its contents are dissolved in nitric acid. The resulting nitrate solution passes through various chemical processes that separate the spent fuel into three primary streams:

- Uranium that can potentially be re-used in nuclear fuel;
- Plutonium that also can potentially be re-used in nuclear fuel;[593] and
- Fission products and transuranic isotopes other than plutonium.

The processes involve the mixing, separation, and concentration of nitrate solutions and liquid organic chemicals — typically, tributyl phosphate (TBP) diluted by kerosene or a similar hydrocarbon — in devices such as pulsed columns, mixer-settlers, and evaporators. These devices are housed in process cells whose walls are made of reinforced concrete, to provide shielding and structural support. Each process cell is ventilated via a filtered pathway that leads to a vent stack.

TBP and its diluent could burn in air. Many of the liquid streams are highly radioactive, leading to radiochemical reactions. “Red oil,” a well-known product of such reactions, can explode if heated above 130 °C in a confined space. Hydrogen is produced in some liquid streams by radiolysis and could accumulate to explosive concentrations inside vessels or process cells.

A breach of a process cell or failure of filtration in a cell’s ventilation pathway would be necessary for a radioactive release to occur. A fire, explosion, or attack could cause a release directly. Or, it could do so indirectly, by disabling cooling and transfer systems, leading to boiling and dryout of a liquid by radioactive self heating. Volatile radioactive material could be released during and after the dryout.

The largest potential for release from a liquid stream is from the tanks that hold HLLW — liquid containing concentrated fission products and transuranic isotopes — pending its transfer to a vitrification facility to be converted into glass blocks inside stainless-steel canisters. The HLLW tanks are equipped with cooling coils and jackets to remove decay heat, and ventilation systems to prevent accumulation of radiolytic hydrogen in the gas spaces of the tanks.

At Rokkasho there are two main tanks for storing HLLW, each with a capacity of 120 cubic meters. If filled to capacity with HLLW from reprocessing of 5-year-old spent fuel, each tank would contain about 1,400 PBq of cesium-137 and produce about 720 kilowatts (kWt) of decay heat. If cooling of such a tank were interrupted, the HLLW could begin to boil after about eight hours, tank dryout could be complete after about 110 hours, and the solid residue could reach a temperature of 1,000 °C after about 120 hours.[594]

The radiological risk posed by high-level radioactive waste is substantially reduced after it is vitrified (i.e., glassified). The canisters of vitrified waste are typically stored in air-cooled vaults designed so that natural convection of air around the waste canisters will keep their temperature below 650 °C, to avoid degradation of the glass.[595] Blockage of the airflow around the canisters could lead to melting or an attack could release some radioactive material into the environment. Overall, however, the potential for a release from vitrified waste is substantially lower than the potential for a release from a HLLW tank.

Plutonium stores

The tanks that store separated plutonium as a nitrate solution, pending its conversion to oxide powder, are also potential sources of large releases, as are the containers of oxide powder. Plutonium aerosol, if inhaled, is an extremely potent carcinogen.[596]

At Japan's Tokai Pilot Reprocessing Plant, as of late 2013, 670 kg of plutonium in nitrate solution was stored in nine tanks with a total capacity of 4.7 cubic meters. The liquid inventory of 3.5 cubic meters produced a heat load of 7.7 kWt. According to Japan's Nuclear Regulation Authority, if cooling of these tanks were interrupted, boiling of a tank could begin within a time as short as 23 hours. If ventilation of the tanks were interrupted, radiolytic hydrogen could accumulate in the gas space to a volumetric concentration of 4 percent, which is potentially explosive, in a time period as short as 11 hours.[597]

History of radiological incidents at reprocessing plants

In 2005, the OECD's Nuclear Energy Agency (NEA) published a report summarizing some of the radiological incidents that have occurred at non-reactor facilities in the nuclear fuel cycle, including reprocessing plants.[598]

The most severe incident occurred in September 1957 in the USSR, when a tank containing HLLW from which most of the cesium-137 had been removed, exploded at the Chelyabinsk-65 (now Ozersk) nuclear complex near Kyshtym in the Urals. The 300 cubic meter stainless steel tank was one of a group of twenty housed in a concrete structure. It received HLLW from an acetate process, not the PUREX process that is used in commercial reprocessing today. After the tank's cooling system failed, the site managers mistakenly assumed that the tank's contents would remain in a safe state. Instead, the HLLW eventually dried out, leaving a residue of sodium nitrate and acetate salts that exploded with an energy release that has been estimated at between 2.4 and 100 tons of TNT equivalent.

The explosion blew into the atmosphere 70 to 80 tons of solid radioactive material with a radioactive content of about 740 PBq (20 million Curies), including about 40 PBq of 29-year half-life strontium-90 and its short-lived decay product, yttrium-90. Most of the material was deposited locally but about 10 percent drifted downwind. About 11,000 people were evacuated from contaminated land, over an area of about 1,000 square kilometers (Figure 12.1).

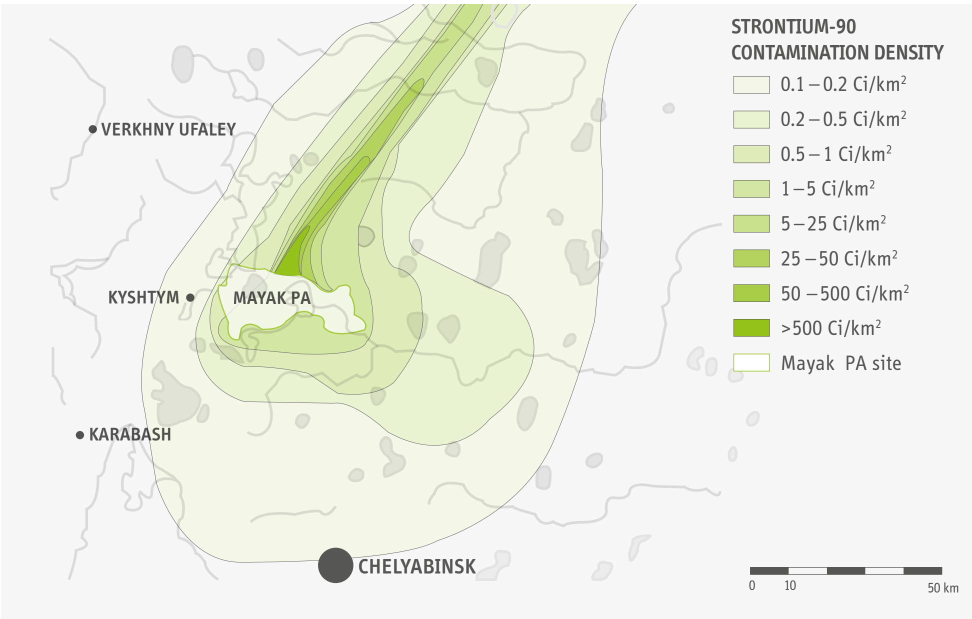

Figure 12.1. Strontium-90 contamination from 1957 explosion at the Mayak Production Association reprocessing site.[599] The explosion involved a tank storing high level liquid waste at the Soviet military reprocessing plant near Kyshtym in the Urals.

The NEA also reviewed less severe incidents including the following:

- A 1973 fire in the "head end" (spent-fuel dissolution portion) of the UK's B204 reprocessing plant at Sellafield that contaminated 35 workers with ruthenium-106 and ended the plant's operation.

- A 1980 fire that destroyed the electric power distribution control room at France's La Hague reprocessing plant preventing use of offsite power or power from four fixed generators on the site. After 30 minutes, however, mobile generators were deployed to provide power needed to maintain the HLLW tanks and other sensitive facilities in a safe state. Offsite power was restored on the same day using a temporary connection, and no major release occurred.
- A 1997 fire and explosion at Japan's Tokai reprocessing plant, that ended the use of a facility where liquid radioactive waste was being immobilized in bitumen.

In April 1993, an explosion occurred in a process tank at the Tomsk reprocessing plant in Russia. The tank was in a cell whose top was at ground level, with a building above. A runaway chemical reaction in the process tank caused it to rupture from internal overpressure. A secondary explosion, involving material released from the tank, occurred in the equipment room above the tank cell and breached the exterior wall of the equipment room, causing a radioactive release to the environment (Figure 12.2). High radiation dose rates within the building, combined with unsafe structural conditions, precluded access to the damaged tank and cell.[600] The Tomsk incident therefore demonstrated clearly that radioactive contamination and other influences can preclude mitigating actions during an incident.

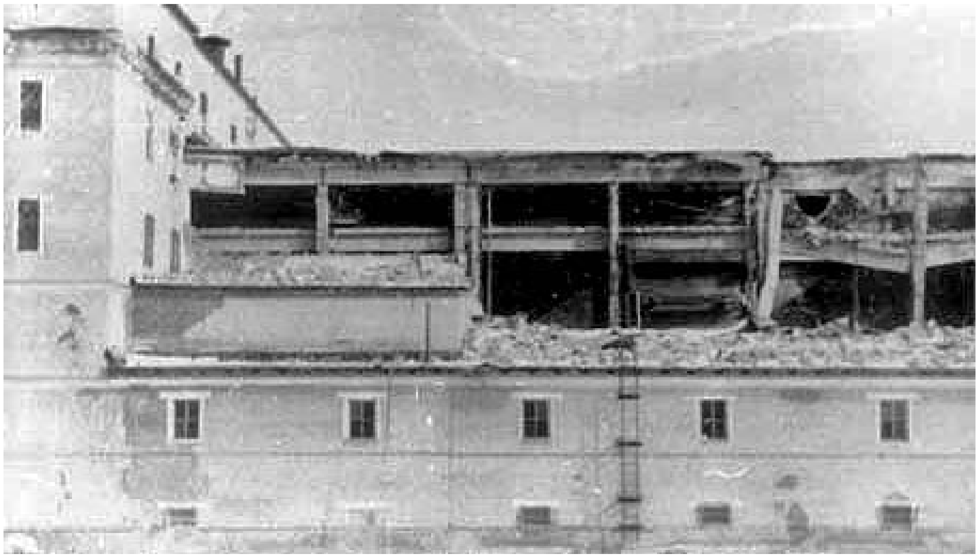

Figure 12.2. After the 1993 process tank explosion at the Tomsk reprocessing plant. *Source: The Radiological Accident in the Reprocessing Plant at Tomsk, International Atomic Energy Agency, 1998.*

Assessments of radiological risk at reprocessing plants

Probabilistic risk assessment (PRA) has been developed to assess radiological risk at nuclear facilities. PRAs done for commercial reactors have identified weaknesses in maintenance practices and the design of systems, and have improved planning for onsite and offsite response to emergencies. PRAs cannot, however, predict the probabilities of serious incidents because they cannot account for gross errors in design, construction, or operation, or for malevolent acts or institutional failures. The core-melt incidents at Three Mile Island in 1979, Chernobyl in 1986, and Fukushima in 2011 were primarily attributable to institutional failures.[601]

PRA techniques have been applied to particular scenarios at particular locations in reprocessing plants. For example, a study of the Rokkasho reprocessing plant published in 2013 by its owner, Japan Nuclear Fuel Limited (JNFL), considered a scenario in which cooling of HLLW tanks was interrupted, leading to self-boiling of the HLLW.[602] JNFL estimated that one cubic meter of liquid would be boiled off per hour from each of two tanks, for a period of 24 hours, after which they assumed that cooling of the tanks would be restored and boiling would cease before dryout. JNFL assumed a value of the airborne release fraction that was one-twentieth of the value recommended in a U.S. Nuclear Regulatory Commission (NRC) handbook and focused its attention exclusively on inhalation dose, ignoring the potentially more significant impacts of land contamination.[603] JNFL then asserted that the offsite impacts of this scenario provided an upper bound to the impacts of potential accidents at the Rokkasho plant.

In contrast, during the 1960s, analysts at Oak Ridge National Laboratory (ORNL) in the United States examined scenarios in which a HLLW tank boiled dry. They concluded that a substantial fraction of the tank's inventory of cesium-137, together with large amounts of other radioisotopes, could be released to the atmosphere. The potential for a similar scenario affecting HLLW tanks at Sellafield (then known as Windscale) in the United Kingdom was partially addressed during the Windscale Inquiry of 1977, at the instigation of the non-governmental Political Ecology Research Group (PERG). Pressed by PERG, which drew upon ORNL analyses, British Nuclear Fuels Limited (BNFL), the owner of the Sellafield site, argued that a dryout scenario was, as a practical matter, "incredible," i.e., too low in probability to be worth considering. BNFL further asserted, without supporting data or analysis, that the release of radioactive material to the atmosphere would be significantly reduced by a number of effects including deposition of material along the release pathway. The issue remained unresolved when the Windscale Inquiry closed.[604]

In 1978–1979, the government of Lower Saxony, West Germany sponsored the Gorleben International Review (GIR), in which independent experts conducted an assessment of a proposal to build a reprocessing plant and associated facilities at Gorleben. Risk scenarios considered by the GIR included a zircaloy fire in a spent-fuel pool, and dryout of a HLLW tank. The review concluded that such events could be initiated by a variety of events, including malevolent acts or societal dislocation.[605] After subjecting the findings of the GIR to a semi-public hearing, the Lower Saxony government accepted the findings on a number of points and rejected the proposal to build a reprocessing plant at Gorleben.[606]

During the decades since, the nuclear industry or the regulatory authorities in countries that reprocess could have done detailed modeling and experiments to develop a thorough understanding of the potential for dryout of a HLLW tank. Instead, they have examined at most, as in the JNFL example discussed above, a truncated scenario in which tank cooling is assumed to be restored before dryout occurs. That limited approach is evident, for example, in a sequence of reports on HLLW tank risk that were published by the UK Nuclear Installations Inspectorate (NII) during the period 1995–2001.[607]

For a spent-fuel pool equipped with high-density racks, the GIR found of special concern a scenario in which some water remained in the pool, thereby blocking airflow into the bottom of the boxes enclosing the fuel assemblies. With neither water nor convective air cooling, even old fuel could heat up to a temperature at which a zircaloy-steam fire could begin that could release a substantial fraction of the pool's inventory of cesium-137 to the atmosphere.

During the decades since the GIR did its work, the U.S. Nuclear Regulatory Commission (NRC) has done a number of theoretical and experimental studies of the potential for a spent-fuel fire. Despite numerous requests from state and local governments and citizen groups across the United States, however, the NRC has consistently refused to study a scenario in which residual water would be present in the lower part of a pool.[608]

A zircaloy fire in a reprocessing plant spent-fuel pool or dryout of a HLLW tank could release hundreds of PBq of cesium-137 to the atmosphere. The largest inventory of cesium-137 that is available for release in this manner is at La Hague. In mid-2011, four spent-fuel pools at La Hague contained, in total, about 50,000 PBq of cesium-137. For comparison, it has been estimated that about 85 PBq of cesium-137 were released during the Chernobyl accident and 20 to 53 PBq during the Fukushima accident, of which about 6 PBq fell on Japan.[609]

On average, more than 90 percent of the cesium-137 released to the atmosphere from a nuclear facility would be transported beyond 50 km and about 50 percent beyond 1,000 km before being deposited. [610] The NRC has estimated that, for average atmospheric conditions, a release of 330 PBq of cesium-137 from a spent-fuel fire at the Peach Bottom site in Pennsylvania would lead to the long-term displacement of 4.1 million people.[611] France's Institut de Radioprotection et de Sûreté Nucléaire (IRSN) has estimated that a release of 100 PBq of cesium-137 at the Dampierre site in France would cause US$410 to 8,060 billion of economic damage.[612]

Plant design and radiological risk

A reprocessing plant combines characteristics of a chemical and a nuclear facility. Like other chemical facilities, it has the potential for internal fires and explosions, and releases of hazardous materials to the environment. It also has:

- The potential for criticality;
- The unstoppable self-heating of radioactive material; and
- The hazard that can be associated with a small mass of radioactive material. For example, 3 kilograms (10 PBq) of cesium-137 can cause the evacuation of hundreds of square kilometers of land for decades.

A design approach known as inherently safer technology (IST) is increasingly being used in chemical engineering.[613] The principles were first fully articulated in 1977 by Trevor Kletz, a specialist on chemical process safety, who argued that, instead of using safety systems and procedures to mitigate hazards, the objective of risk management should be to eliminate them where feasible. That goal can be accomplished by reducing the quantities of hazardous material used in processes, using less-hazardous materials, or developing technology that allows processes to proceed under milder conditions.

IST principles were applied to some extent to the design of the proposed reprocessing plant at Wackersdorf, in Bavaria. Although Germany subsequently rejected reprocessing, and the project was cancelled in 1989, the basic design of that plant was established by 1983.[614] It was strongly influenced by the considerations that led Lower Saxony to decide that it would not license a reprocessing plant featuring high-density storage of spent fuel in pools, or storage of a large inventory of HLLW in tanks requiring continuous active cooling and other services.

The Wackersdorf design had onsite storage of spent fuel in dry casks prior to reprocessing. Such casks are cooled passively by convective air circulation over their exterior surfaces. The inventory of HLLW in the Wackersdorf design would have been limited to buffer storage in four passively-coolable tanks, each having a capacity of 25 cubic meters. The Wackersdorf design therefore would have posed a substantially lower radiological risk than the Gorleben design, assuming a similar risk environment in each case.

Radiological risk would not have been eliminated with the Wackersdorf design. However, it can be used as a yardstick to compare the radiological risks posed by the three large reprocessing plants that were actually built in the same period and later in the United Kingdom, France, and Japan.

UK's Thermal Oxide Reprocessing Plant (THORP)

THORP began operating at Sellafield in 1994 and is scheduled to cease operating around 2020. Its design capacity is 1,200 tons of spent fuel per year (tHM/yr). It has reprocessed zircaloy-clad fuel from light water reactors (LWRs) and stainless-steel-clad fuel from the UK's advanced gas-cooled reactors (AGRs). When the fuel is received on site, it is stored in a pool with the LWR fuel inside multi-element "bottles" (MEBs, i.e., canisters). As of the end of 2014, most of the contracted LWR fuel had been reprocessed. In the future, the pool will hold only AGR fuel. There has been no published investigation to determine if loss of water could cause a cladding fire in the THORP spent-fuel pool, for either LWR or AGR fuel.

The high-level liquid waste generated by THORP is stored in the B215 facility, which has served all the reprocessing plants at Sellafield. In 1955, the original B215 facility had eight HLLW tanks, each with a capacity of 70 cubic meters. Subsequently, thirteen larger tanks, each with a capacity of 150 cubic meters, were added, the last in 1990. THORP waste is stored in the larger tanks. Each of these tanks requires continuous, forced cooling, ventilation and stirring to remain in a safe state.

The radiological risk posed by B215 was discussed during the Windscale Inquiry of 1977 and was a subject of intense public attention again in the UK and Ireland during 1994 – 2001. The Nuclear Installations Inspectorate never fully conceded that B215 poses a substantial radiological risk but, in 2001, agreed to limit its inventory of HLLW. The NII ordered that the maximum volume of HLLW stored at B215 would have to be reduced from 1,575 cubic meters in 2001 to 200 cubic meters in 2015.[615] Ten years later, in 2011, however, the NII's successor, the Office for Nuclear Regulation (ONR), substantially relaxed the 2015 limit because its enforcement would have constrained reprocessing operations at Sellafield.[616] This experience demonstrates that to be effective, a risk-reduction measure must be built into the design of a facility. Also, it is clear that B215, and THORP by extension, pose a HLLW radiological risk substantially higher than the best-practice yardstick set by the Wackersdorf design in the early 1980s.

France's UP2 and UP3 reprocessing plants at La Hague

UP3 began operating in 1989. A companion plant — UP2 — began operating in 1966 and was upgraded in 1976 and 1994. Each of these plants has a design throughput of 1,000 tHM/yr, but their combined throughput is limited to 1,700 tHM/yr. The plants have four inter-connected spent-fuel pools with a combined capacity for 17,600 tHM of fuel. The first pool entered service in 1978 and the fourth in 1985. The pools are built so that ground level is at about mid-height of the fuel assemblies. All fuel in these pools has zircaloy cladding and is stored in high-density racks that are arranged in clusters, with some open space between (Figure 12.3).

The configuration of the pools at La Hague is a cause for concern in the context of a possible attack. Breach of a pool wall at grade level, creating a hole with a diameter on the order of one meter, could drain the pool down to the mid-point of the fuel within about an hour and leave residual water in the lower part of the pool. An earthquake or aircraft crash might have a similar outcome. The presence of residual water would maximize the potential for a steam-zircaloy fire. In the absence of any thorough, published study of this situation, it is prudent to assume that there would be negligible cooling for the above-water portion of the fuel in the central region of each rack cluster. In that case, mixed-oxide (MOX) fuel that has cooled for seven years after discharge from a reactor could ignite about 26 hours after it became exposed, and conventional fuel of the same age could ignite after about 49 hours.[617] The resulting steam-zircaloy fire could potentially spread to the rest of the rack cluster and across the pool.

The UP3 reprocessing plant has seven HLLW storage tanks and the UP2 plant has eight, each tank has a capacity of 120 cubic meters. According to Areva, only nine of these tanks are used routinely for storage of HLLW at La Hague. Additional HLLW is held in feed tanks that serve the site's vitrification facilities. All of the tanks that store HLLW require continuous, forced cooling, ventilation and stirring to remain in a safe state. The buildings that house these tanks are located partly below ground. From a design perspective, these tanks have a radiological-risk profile similar to that of the HLLW tanks at Sellafield's B215 facility.

Thus, the UP3 and UP2 plants at La Hague pose a radiological risk substantially higher than the best-practice yardstick set by the Wackersdorf design in the early 1980s. At La Hague, in view of the site's large inventory of spent fuel and the partially above ground configuration of its spent-fuel pools, there is an especially high risk of a zircaloy fire. There is also a substantial risk of HLLW tank dryout after a few days loss of tank cooling.[618]

Figure 12.3. Clusters of dense-packed spent fuel in La Hague pool, 2012. *Source: Sortir du nucléaire.*

Japan's Rokkasho reprocessing plant

The Rokkasho Reprocessing Plant has not yet begun commercial operation, although it reprocessed 430 tons of spent fuel during testing in 2006 – 2008. Its purpose is to reprocess zircaloy-clad fuel from light water reactors, with a nominal throughput of 800 tHM/yr. Its three spent-fuel pools were completed in 1999, each with a capacity of 1,000 tHM. The fuel in these pools is stored in high-density racks that fill the pools wall-to-wall. The normal water level in the pools is at ground level, which is a lower-risk configuration than that of the pools at La Hague. As at La Hague, however, there are voids alongside and below each pool, into which water could drain if the wall or floor of a pool were breached.

HLLW is stored at Rokkasho in two tanks, each with a capacity of 120 cubic meters, with a third tank of 120 cubic meters capacity available as a spare. When in use, each tank must have continuous, forced cooling, ventilation, and stirring to remain in a safe state. From a design perspective, the Rokkasho tanks have a radiological-risk profile similar to that of the HLLW tanks at Sellafield and La Hague.

Thus, the Rokkasho reprocessing plant too poses a radiological risk substantially higher than the best-practice yardstick set by the Wackersdorf design in the early 1980s. At Rokkasho, there is substantial potential for a zircaloy fire in a spent-fuel pool or for an incident leading to HLLW tank dryout. The overall radiological risk of reprocessing at Rokkasho might be somewhat lower than at La Hague, if the risk environment were equivalent.

At Sellafield, La Hague, and Rokkasho, site managers have prepared to implement mitigating actions in an emergency. For example, they have acquired portable pumps and electricity generators whose purpose, during an emergency, would be to maintain sensitive facilities such as HLLW tanks and spent-fuel pools in a safe state. Also, they have acquired fire-fighting equipment such as “foam tenders” — vehicles that can spray foam to suppress fire and, perhaps, to inhibit a radioactive release.

Such measures might succeed in preventing a delayed release but they would be irrelevant for a sudden release. Such a release might result, for example, from an attack on a HLLW tank or an accidental explosion in a HLLW evaporator. Also, there are many potential scenarios in which mitigating actions would be hindered or precluded by factors such as high levels of radiation. Overall, mitigating actions cannot fully compensate for fundamental deficiencies in plant design.

Conclusions and recommendations

Today’s commercial reprocessing plants have the potential to suffer incidents that could release hundreds of PBq of cesium-137 and large quantities of other radioisotopes into the atmosphere — an order of magnitude more than the release at Chernobyl. That release potential arises primarily from storage of thousands of tons of spent fuel in pools prior to reprocessing, and from storage of a backlog of years of production of high-level liquid radioactive waste in tanks instead of turning it into glass on a just-in-time basis. Events precipitating a release could include earthquakes, internal explosions, or malevolent acts. Some release scenarios involve a cascading sequence of incidents in which an early incident creates a radiation field that precludes mitigating actions to prevent larger releases.

The nuclear industry and its regulators in countries that reprocess have never sought to develop a thorough understanding of radiological risk at reprocessing plants. As a result, the level of knowledge about that risk is substantially below the level of knowledge that has been acquired by doing PRAs for commercial reactors. Even those PRAs can yield, at best, a lower bound to radiological risk because of their inability to adequately address issues such as institutional failure and human malevolence.

The design of the proposed reprocessing plant at Wackersdorf, Germany involved the partial application of principles of inherently safer technology. That early 1980s design established a standard of "best practice" for the minimization of radiological risk. The THORP plant at Sellafield, the UP2 and UP3 plants at La Hague, and Rokkasho plant all pose radiological risks substantially higher than the Wackersdorf yardstick. From a safety perspective, the designs of these plants were obsolete when they were built.

If these plants are operated in the future, their radiological risk could be substantially reduced by measures including:

1. Transferring most stored spent fuel from pools to dry casks;
2. Reducing the inventory of HLLW to a low level by vitrifying it on a just-in-time basis;
3. Retrofitting mitigating measures such as passive backup cooling; and
4. Enhancing site security, including active or passive defense against attacks from the air.

Endnotes

Chapter 1. Introduction

[1] R. Chidambaram, "'India Is Not Isolated' Interview with AEC Chief R. Chidambaram," *Frontline*, 29 November 1996.

[2] Anthony V. Nero, *A Guidebook to Nuclear Reactors*, University of California Press, 1979, pp. 166–167.

[3] Between 1920 and 1970, U.S. electricity consumption doubled on average every 10 years (7-percent annual growth). Historical Statistics of the United States: Colonial Times to 1970, U.S. Bureau of the Census, 1975, p. 820. The global situation was similar. These growth rates were expected to continue. Since 1970, however, the growth of U.S. electric power use has declined to about 1 percent per year. See www.eia.gov/forecasts/AEO/MT_electric.cfm. Global annual electric power growth has averaged about 3 percent per year. See www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=2&pid=2&aid=12&cid=regions&syid=1980&eyid=2012&unit=BKWH.

[4] The United States Atomic Energy Commission (AEC) was the most influential organization promoting breeder reactors in the 1950s and 1960s. The AEC experienced a uranium shortage for its uranium enrichment complex during the 1950s when its enrichment capacity was building up faster than its supply of natural uranium. To mitigate this shortage, the AEC fed reprocessed uranium from its plutonium production reactors into the enrichment plants.

[5] Franz E. Simon, "Nuclear Power: A British View," *Bulletin of the Atomic Scientists*, Vol. 9, No. 4, May 1953, p. 125.

[6] Paul R. Josephson, Red Atom: Russia's Nuclear Power Program from Stalin to Today, W. H. Freeman and Company, 2000, p. 50.

[7] R.B. Fitts and H. Fujii, "Fuel Cycle Demand, Supply and Cost Trends," *IAEA Bulletin*, Vol.18, No.1, 1975, p. 19. We use the U.S. GDP deflator to compare currencies at different times in this report. See research.stlouisfed.org/fred2/series/GDPDEF. Note, a pound of U_3O_8 contains 0.385 kg of uranium.

[8] Kenneth S Deffeyes and Ian D MacGregor, "World Uranium Resources," *Scientific American*, January 1980, 68.

[9] *Uranium 2014: Resources, Production and Demand*, OECD Nuclear Energy Agency and International Atomic Energy Agency, 2014, p. 130.

[10] Gavin M. Mudd, "The Future of Yellowcake: A Global Assessment of Uranium Resources and Mining," *Science of The Total Environment*, Vol. 472, 15 February 2014, p. 604. The author also points out that the "actual U supply into the market is, effectively, more an economic and political issue than a resource constraint issue."

[11] Enriched to 4.4 percent at a depleted uranium assay of 0.2 percent uranium-235 and with a burnup of 53 MWt-days/kgU, one kilogram of natural uranium would produce about 53,000 kilowatt-hour of electrical energy. At a price of $100/kgU, the contribution of the cost of natural uranium would be about 0.2 cents/kilowatt-hour. In 2014, the projected cost of electricity from new U.S. nuclear power reactor in 2019 was 9.6 cents/kilowatt-hour, *Annual Energy Outlook*, Energy Information Agency, 2014.

[12] *Fast Breeder Reactor Programs: History and Status*, International Panel on Fissile Materials, 2010; S. Rajendran Pillai and M. V. Ramana, "Breeder Reactors: A Possible Connection between Metal Corrosion and Sodium Leaks," *Bulletin of the Atomic Scientists*, Vol. 70, No.3, 2014, pp. 49–55.

[13] F*ast Breeder Reactor Programs,* op.cit.

[14] The even numbered plutonium isotopes, plutonium-238, plutonium-240 and plutonium-242, are not fissioned efficiently by the slow neutrons in water-cooled reactors.

[15] See for example M. Nagano, S. Sakurai, and H. Yamaguchi, "Basic Evaluation on Nuclear Characteristics of BWR High Burnup MOX Fuel and Core," in International Atomic Energy Agency, ed. *Recycling of Plutonium and Uranium in Water Reactor Fuel*, International Atomic Energy Agency, 1995, pp. 25 – 33.

[16] France has been the largest user of MOX fuel. In 2000, a study was done for the Prime Minister. J-M. Charpin, B. Dessus, and R. Pellat, *Economic forecast study of the nuclear power option*, Report to Prime Minister, July 2000, fissilematerials.org/library/cha00.pdf (Translated from French).
It included two scenarios: one in which 67 percent of France's spent low-enriched uranium (LEU) fuel was reprocessed and the recovered plutonium was recycled in MOX and one in which no LEU fuel was reprocessed. In both scenarios, it was assumed that France's existing light water power reactors would be retired after 45 years. The comparison was made in Appendix I of the report. In the no-reprocessing scenario, 4300 tons of additional LEU fuel were produced at a cost of 33 billion Francs. In the reprocessing scenario, 4800 tons of MOX fuel were produced at an extra cost (including reprocessing) of 177 billion Francs. The costs were therefore 7,700 Francs/kgLEU and 36,900 Franc/kgMOX. Thus, MOX fuel was found to be 4.8 times more costly. In 2011, Japan's Atomic Energy Commission estimated the same ratio for the Rokkasho Reprocessing and MOX Plants as 12.3, "Estimation of Nuclear Fuel Cycle Cost," 10 November 2011, www.aec.go.jp/jicst/NC/about/kettei/seimei/111110_1_e.pdf , Slide 28 for a 0 percent discount rate, assuming 7.5 kg of LEU spent fuel reprocessed per kg of MOX fuel produced.

[17] The construction of Japan's dry-cask storage facility in Mutsu, completed in 2013 with a capacity of 3,000 tons, cost, including casks, about ¥0.1 trillion (~$1 billion) or about $330/kgU, web.archive.org/web/20130425165144/http://www.rfsco.co.jp/about/about.html (in Japanese).

[18] IAEA, "Communication Received from France Concerning its Policies Regarding the Management of Plutonium," INFCIRC/549/Add.5/18, International Atomic Energy Agency, 15 August 2014 and INFCIRC/549/Add. 5a, 6 April 1998. The buildup of France's stock of unirradiated plutonium appears to be due to an accumulation of unusable MOX fuel, see Chapter 3.

[19] Noboru Oi, "Plutonium Challenges: Changing Dimensions of Global Cooperation," *IAEA Bulletin*, 40, no. 1, 1998, p. 15. The nine countries are Belgium, China, France, Germany, Japan, Russia, Switzerland, the United Kingdom and the United States.

[20] The Plutonium Management Guidelines were published by the International Atomic Energy Agency in INFCIRC/549 on 16 March 1998. Lessons from their negotiation are discussed in chapter 6 of *Global Fissile Report 2013*, International Panel on Fissile Materials, 2013.

[21] *Global Fissile Materials Report 2013*, International Panel on Fissile Materials, 2013, Appendix 1.3 and INFCIRC/549 declarations to the International Atomic Energy Agency through the end of 2013.

[22] The fission neutrons mediating the chain reactions in water-cooled reactors lose most of their energy after a few collisions with the light nuclei of the hydrogen atoms in the water. Neutrons lose much less energy in collisions with the heavier nuclei of sodium.

[23] Irradiation of MOX fuel in light water reactors only reduces the amount of plutonium it contains by about 30 percent. The quantity of the isotopes plutonium-238 + plutonium-240 + plutonium-241 + plutonium-242 (+ americium-241, the decay product of plutonium-241) which constitute 44 percent of the plutonium in the fresh fuel, increases slightly while the quantity of plutonium-239, which constitutes the other 56 percent, decreases by a little more than half. These specific figures are for MOX fuel with 43 MWt-days/kg burnup made with plutonium from LEU fuel with the same burnup that has been in storage for 10 years. See *Plutonium Fuel: An Assessment*, OECD Nuclear Energy Agency, 1989, Table 12B.

[24] *Nuclear Wastes: Technologies for Separations and Transmutation*, National Academy Press, 1996, p. 3. With regard to "additional operational risk," the report refers to proliferation risk associated with the processing of plutonium in a fuel cycle involving transmutation (p. 108). The radiological risks of fuel cycles were found to be small with or without transmutation (p. 111). The financial costs of reprocessing were found to be large (p. 117).

[25] U.S. Department of Energy, *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives*, DOE/NN-0007, Washington, D.C., January 1997, pp. 37–39, www.ccnr.org/plute.html

[26] Anthony Andrews, *Nuclear Fuel Reprocessing: U.S. Policy Development*, Congressional Research Service, RS22542, 2008.

[27] During the G.W. Bush Administration (2001–2008), the United States briefly promoted a Global Nuclear Energy Partnership program under which the U.S. posture was, in essence, "We will reprocess but you don't need to because the weapon states and Japan will do it for you."

[28] Sources: *Global Fissile Material Report 2013*, International Panel on Fissile Materials, 2013, p. 25; David Albright, Frans Berkhout and William Walker, *Plutonium and Highly Enriched Uranium 1996*, Oxford University Press, 1997, Table 6.2; Mycle Schneider and Yves Marignac, *Spent Fuel Reprocessing in France*, International Panel on Fissile Materials, 2008; M. Gili et al., "Direct Dismantling of Reprocessing Plant Cells, the Eurex Plant Experience," Waste Management Conference Tucson, Arizona, 23–27 February 2003. "Japan Atomic Energy Agency to close [Tokai] nuclear fuel reprocessing plant," *Japan Times*, 29 September 2014.

[29] Costs at the Rokkasho plant are estimated at about $2 billion per year. See "Estimation of Nuclear Fuel Cycle Cost and Accident Risk Cost", Statement, Japan Atomic Energy Commission, 10 November 2011 and Japan Atomic Energy Commission Technical Subcommittee on Nuclear Power, Nuclear Fuel Cycle, etc. Data Sheet 1, "Estimation of Nuclear Fuel Cycle Cost," *op. cit.*, slide 30. Japan's Atomic Energy Commission has estimated that reprocessing will increase the cost of nuclear power in Japan by about 1 Yen per kilowatt-hour (~$0.01/kilowatt-hour) or about $100 billion over the 40-year operational life of the Rokkasho Reprocessing Plant assuming that 32,000 tons are reprocessed. See "Estimation of Nuclear Fuel Cycle Cost and Accident Risk Cost," Japan Atomic Energy Commission, 10 November 2011.

[30] Construction of the Rokkasho Reprocessing Plant began in 1993, acceptance of spent fuel for reprocessing there began in 1998, and active tests were carried out between 2006 and 2008. As of the end of 2014, commercial operations were planned beginning in September 2016. See "Rokkasho Reprocessing Plant Timeline," Citizens Nuclear Information Center, www.cnic.jp/english/topics/cycle/rokkasho/rokkashodata.html#time.

[31] The United Kingdom's Sellafield reprocessing site was taken over by the Nuclear Decommissioning Authority in 2004. Despite the expenditure of about £2 billion pounds per year on cleanup, however, www.nda.gov.uk/what-we-do/costs/, the undiscounted estimated cost to completion keeps increasing. The 2014 estimate was £70 billion ($116 billion), U.K. Parliament, Public Accounts Committee - Forty-Third Report, *Progess at Sellafield*, 3 February 2014, www.publications.parliament.uk/pa/cm201314/cmselect/cmpubacc/708/70802.htm. On the problem of dealing with the accumulated plutonium, see Frank von Hippel and Gordon MacKerron, *Alternatives to MOX: Direct-disposal options for stockpiles of separated plutonium*, International Panel on Fissile Materials, 2015.

[32] UK Department of Energy and Climate Change, *Sellafield MOX Plant – Lessons Learned Review* (redacted, 18 July 2012).

[33] UK Department of Energy and Climate Change, "Management of the UK's Plutonium Stocks: A consultation response on the long-term management of UK-owned separated civil plutonium," 1 December 2011, p. 5. As of the end of 2013, the United Kingdom had in storage 23.8 tons of foreign-owned separated plutonium, IAEA, "Communication Received from the United Kingdom of Great Britain and Northern Ireland Concerning its Policies Regarding the Management of Plutonium," International Atomic Energy Agency, INFCIRC/549/Add.8/16, 18 July 2013. As of the same date, Japan declared that it had 17.1 tons of separated plutonium stored in the United Kingdom. See "The Current Situation of Plutonium Management in Japan," Japan Atomic Energy Commission, 16 September 2014 (in Japanese).

[34] China declared zero separated civilian plutonium to the International Atomic Energy Agency as of the end of 2009 and then a total of 13.8 kg in each of its annual declarations for the ends of the years 2010, 2011, 2012 and 2013. China also reported to the International Atomic Energy Agency that it generated 20 MWe-hours of electric energy with its 25 MWe Experimental Fast Reactor in 2011, the year the reactor was connected to the grid and zero for the years 2012 and 2013. See Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, 12 April 2015, www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=1047.

[35] A total of 39 of these VVER-440 reactors were built: two in Armenia (one of which is shutdown), four in Bulgaria (all shutdown), four in the Czech Republic (all operational), two in Finland (both operational), five in East Germany (all decommissioned), five in Hungary (all operational), eight in Russia (six operational), eight in Slovakia (four operational, and two under construction since 1987), and two in Ukraine (both operational). See Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, 12 April 2015, www.iaea.org/PRIS.

[36] A total of 25 of these VVER-1000 reactors were built: two in Bulgaria; two in the Czech Republic; eight in Russia and thirteen in the Ukraine. See Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, 12 April 2015, www.iaea.org/PRIS. Russia has proposed to sell modernized versions to Belarus, Finland, Hungary and possibly also to Bangladesh, Turkey and Vietnam. See Bangladesh, *Nuclear Intelligence Weekly*, 4 Oct. 2013; Belarus, *Nuclear Intelligence Weekly*, 8 November 2013; Finland, *Nuclear Intelligence Weekly*, 18 April 2014; Hungary, *Nuclear Intelligence Weekly*, 11 April 2014; Turkey, *Nuclear Intelligence Weekly*, 18 April 2014; and Vietnam, *Nuclear Intelligence Weekly*, 21 March 2014.

[37] "Ukrainian used fuel store under construction," *World Nuclear News*, 27 August 2014.

[38] See, for example, Alexander Panin, "Hungary Gets $14 Bln Loan for Nuclear Plant," *Moscow Times*, 15 January 2014.

[39] According to their 1974 Agreement of Cooperation, South Korea cannot reprocess spent fuel made from low-enriched uranium produced in the United States. Under the 1978 U.S. Nuclear Nonproliferation Act, this requirement is extended to spent fuel irradiated in reactors that contain U.S. technology. Apparently this requirement applies to all of South Korea's light water reactor spent fuel.

[40] For a discussion of and rebuttal to these arguments, see Masafumi Takubo and Frank von Hippel, *Ending reprocessing in Japan: An alternative approach to managing Japan's spent nuclear fuel and separated plutonium*, International Panel on Fissile Materials, 2013.

[41] Park Seong-won, Miles A. Pomper, and Lawrence Scheinman, "The Domestic and International Politics of Spent Nuclear Fuel in South Korea: Are We Approaching Meltdown?" Korea Economic Institute: Academic Paper Series, Vol. 5, No. 3, 2010. For a critique of these arguments, see Frank von Hippel, "South Korean Reprocessing: An Unnecessary Threat to the Nonproliferation Regime," *Arms Control Today*, March 2010, and Chapter 7 of this report.

[42] Jacques E. C. Hymans, "Veto players and Japanese nuclear policy after Fukushima," in Anne Allison and Frank Baldwin, eds, *Japan: The Precarious Years Ahead*, New York University Press, to be published.

[43] The Carter Administration's decision to oppose even private reprocessing was triggered by India's use for a "peaceful nuclear explosion" of some of the first plutonium it separated using some of the technology and training provided in part by the United States.

[44] Richard J. Samuels and James L. Schoff, "Japan's Nuclear Hedge: Beyond 'Allergy' and Breakout," in Ashley J. Tellis, Abraham M. Denmark, and Travis Tanner, eds. *Asia in the second nuclear age*, The National Bureau of Asian Research, 2013.

[45] William Walker, *Nuclear Entrapment: THORP and the Politics of Commitment*, Institute for Public Policy Research, 1999.

Chapter 2. China

[46] Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, 12 April 2015, www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=CN

[47] The Information Office of the State Council, China's Energy Policy 2012, 24 October 2012. news.xinhuanet.com/english/china/2012-10/24/c_131927649.htm.

[48] In October 2012, after comprehensive post-Fukushima safety inspections of all plants in operation and under construction, China's State Council issued a new "Medium- and Long-Term Nuclear Power Development Plan (2011 – 2020)". See "Wen Jiabao chairs executive meeting of the State Council,"(Chinese) website of the Central People's Government of the People's Republic of China, 24 October 2012, www.gov.cn/ldhd/2012-10/24/content_2250357.htm.

[49] Xu Mi, "Fast Reactor Development for a Sustainable Nuclear Energy Supply in China," presentation at Harvard-Tsinghua Workshop on Nuclear Energy and Nuclear Security, 14 – 15 March 2010, Beijing, China; and Gu Zhongmao, "The Sustainable Nuclear Energy Needs Closed Fuel Cycle," presentation at Harvard-Peking University Workshop on Economics of Nuclear Reprocessing, 15 October 2011, Beijing, China.

[50] According to some Chinese nuclear experts, CNNC's proposal is to build the 200 tHM/year plant even if the deal with Areva is approved. The idea would be to lay the basis for a CNNC-designed large-scale commercial reprocessing plant. Personal communications with Chinese nuclear experts, July 2013.

[51] Personal communications with Chinese nuclear experts, July 2013 and March 2014.

[52] In October 2010, China established a spent fuel disposal fund. Commercial nuclear power plants operating for more than 5 years are required to pay a 0.026 Yuan/kilowatt-hour ($0.004/kilowatt-hour) spent fuel disposal fee. The fund is to be used for the transportation, storage and reprocessing of spent fuel, the management of high-level reprocessing waste, and other "back end" fuel cycle requirements. See www.mof.gov.cn/zhengwuxinxi/caizhengwengao/2010nianwengao/wengao6/201009/t20100903_337280.html (in Chinese).

[53] Personal communication with Professor Liu Xuegang at INET at Tsinghua University, 30 May 2013.

[54] L.M. Zheng and C. Shen, "Status and technology of interim spent fuel dry storage facility for PHWR nuclear power plants," *Nuclear Safety*, Vol. 1, No. 1, 2005, pp. 39 – 44 (in Chinese). The Macstor-400 holds 400 tons of spent fuel in 40 canisters embedded in a reinforced concrete monolith penetrated by passages for convective air cooling.

[55] This estimate assumes that, from 2014 to 2020, PWRs discharge around 20 tons/GWe each year and that, thereafter, the figure goes down to 15 tons/GWe. The 500-ton pool at the pilot plant was full in 2014. It is assumed that new PWRs will be constructed with 20 years pool-storage pilot plant was full in 2014. It is assumed that new PWRs will be constructed with 20 years pool-storage capacity.

[56] See, for example, Matthew Bunn et al., *Interim Storage of Spent Nuclear Fuel – A Safe, Flexible, and Cost-Effective Near-Term Approach to Spent Fuel Management*, joint report from the Harvard University Project on Managing the Atom and the University of Tokyo Project on Sociotechnics of Nuclear Energy, June 2001.

[57] Li Jue, Lei Rongtian, Li Yi and Li Yingxiang, eds., *China Today: Nuclear Industry*, China Social Science Press, Beijing, 1987, pp. 219– 220 (in Chinese).

[58] Hui Zhang, "China's HEU and Plutonium Production and Stocks," *Science and Global Security*, Vol. 19, 2011, pp. 68– 89. belfercenter.ksg.harvard.edu/files/huizhangSGS2011.pdf.

[59] M. Xu, "Fast reactor development strategy targets study in China," *Journal of Nuclear Science and Engineering,* Vol. 28 No. 1, 2008, pp. 20– 25 (in Chinese).

[60] Personal communication with an expert at the Institute of Nuclear and New Energy Technology at Tsinghua University, 30 May 2013.

[61] See, for example, www.mof.gov.cn/zhengwuxinxi/caizhengwengao/2010nianwengao/wengao6/201009/t20100903_337280.html (in Chinese).

[62] Personal communication with CNNC personnel.

[63] The pilot reprocessing plant started operating on 21 December 2010. China declared in its annual report to the IAEA a stock of 13.8 kg of separated civilian plutonium "in product stores at reprocessing plants" as of the end of 2010. In August 2014, China reported that, as of the end of 2013, its total civilian stock of separated plutonium was still 13.8 kg, indicating that no additional plutonium had been separated during 2011–2013. IAEA, "Communication received from China Concerning Its Policies Regarding the Management of Plutonium," INFCIRC/549/Add.7/10, IAEA, 8 July 2011; and INFCIRC/549/Add.7/13, AEA, 15 August 2014.

[64] news.bjx.com.cn/html/20130426/431263.shtml (in Chinese).

[65] news.bjx.com.cn/html/20131011/464115.shtml (in Chinese).

[66] Personal communications with Chinese nuclear experts at CNNC, July and December 2013.

[67] www.qstheory.cn/kj/zzcx/201103/t20110304_70899.htm (in Chinese). Oddly, China's 12th five year energy plan has the CNNC's 200-ton per year LWR spent fuel reprocessing demonstration project being completed by 2020, even though CNNC is still working on feasibility studies that would have to be approved by the National Development and Reform Commission. Personal communication with CNNC personnel, July and December 2013.

[68] Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, 12 April 2015, www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=1047.

[69] "CEFR: China experimental fast reactor runs at full capacity," *Xinhua*, 19 December 2014, www.cs.com.cn/english/ei/201412/t20141219_4595461.html.

[70] Xu Mi, "Fast reactor development for a sustainable nuclear energy supply in China," presented at Harvard-Tsinghua workshop on Nuclear Policies, 14 March 2010, Beijing, China.

[71] www.chinadaily.com.cn/hqsj/hqlw/2012-01-25/content_5021148.html (in Chinese).

[72] www.jiangle.gov.cn/2010/12/16280.htm (in Chinese).

[73] Personal communication with a Chinese expert, December 2013.

[74] It was reported in March 2014 that the conceptual design was completed and the primary process design was ongoing. See Wan Gang (Minister of MOST), "An authoritative interpretation on China's FBR development," 14 March 2014, www.ns.org.cn/c/cn/news/2014-03/14/news_1138.html.

[75] Personal communication with Xu Mi in the CEFR program at the CIAE, 15 March 2010.

[76] China Academy of Engineering, *Study on strategy for China's medium- and long-term energy development (2030,2050)*, Science press, Beijing 2011 (in Chinese).

[77] China's uranium production capacities are based on: *Uranium 20xx: Resources, Production and Demand*, OECD Nuclear Energy Agency and International Atomic Energy Agency, 2003 to 2014 (multiple publications); China's uranium imports are from www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China--Nuclear-Fuel-Cycle/; China's annual uranium demands are based on the following assumptions: PHWRs require about 88 tons natural uranium per GWe-year, and PWRs require about 173 tons natural uranium per GWe-year with new PWR cores requiring three times that amount.

[78] Assuming that only pressurized water reactors will be used for the new nuclear power plants, and that refueling the reactors with low-enriched uranium fuel will require about 173 tons of natural uranium annually per GWe before 2020 and about 150 tons thereafter, and that producing the initial core for each new reactor will require the equivalent of about three times the annual requirement of natural uranium.

[79] In 2006, CNNC established as a wholly owned subsidiary—the China National Nuclear Oversea Uranium Resource Development Company—responsible for overseas uranium exploration and resource evaluations, and construction of and investments in natural uranium mining and milling. In 2010, CNNC contracted with Canada to supply 8,865 tU by 2025. CNNC has commenced exploration projects in Africa (Niger, Namibia, and Zimbabwe) and has already established control of an estimated 43,000 tons of uranium resources there. CNNC's subsidiary China Nuclear Energy Industry Corporation (CNEIC) has established trade relations in natural uranium with Kazakhstan, Canada, Australia, and Namibia. By the end of 2009, the leadership of CNNC announced that it had already secured over 200,000 tU overseas reserves, and imports of 6,000 to 7,000 tons each year through international trade. See, for example, cn.reuters.com/article/chinaNews/idCNCHINA-1324520091214 (in Chinese).

[80] In recent years, China General Nuclear Power Corporation (CGPNC, name changed from China Guangdong Nuclear Power Corporation) also has been actively pursuing overseas uranium supplies. In 2010, it signed with Areva to buy 20,000 tons by 2020, with Canada to buy 112,000 tons by 2025, and with Kazakhstan to buy 24,200 tons by 2020. In 2013, the head of CGNPC stated that it had secured approximately 308,000 tons of overseas natural uranium resources by the end of 2012, and that more would be acquired (see, for example, He Yu, the president of the board of CGPNC, "Uranium resource for China's NNP can meet the needs of its nuclear power development," *Xinhua*, 13 March 2013, www.cec.org.cn/redianxinwen/lianghuihuanyuan/dianlirenwu/2013-03-13/98671.html (in Chinese). Sinosteel Corporation has established a company in Australia: Sinosteel-Southern Australia Uranium Mining company, which will begin mining work at two uranium deposits in southern Australia. All the uranium produced will be sold to China. www.areva.com/EN/operations-2404/china-taishan-12.html#tab=tab4.

[81] chronicle.augusta.com/news/business/2012-03-22/sc-plant-readies-nuclear-fuel-chinas-first-ap1000-reactor. Enriched uranium products for the first four AP1000 reactors from 2010 to 2021 will be supplied by Tenex from Russia, under the 2008 agreement. www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China-Nuclear-Fuel-Cycle/.

[82] "National Energy and Technology Plan during the 12th five-year period (2011 – 2015)," www.nea.gov.cn/131398352_11n.pdf.

[83] Pan Ziqiang and Qian Qihu, eds., *Strategy study on geological disposal of high-level radioactive wastes*, Atomic Energy Publisher, 2009.

[84] www.qstheory.cn/kj/zzcx/201103/t20110304_70899.htm (in Chinese).

[85] Gu Zhongmao, “Sustainable nuclear energy needs a closed fuel cycle,” presented at Harvard - Peking University Workshop on Economics of Nuclear Reprocessing, 15 October 2011, Beijing.

[86] *Ibid.*

[87] The origins of the selection of the Beishan site go back to 2006 when the Atomic Energy Authority, Ministry of Science and Technology, and Ministry of Environmental Protection jointly issued a *Planning guide for research and development on geological disposal of high level radioactive waste*. In 2007, the State Council approved a “Medium- and Long-term Nuclear Power Development Plan (2005–2020)” that laid out China’s plan for final disposal of high level radioactive waste. The geological disposal project is receiving several hundred million RMB of research funding in the 12th five-year energy development plan (2011–2015). The plan includes three stages: establishment of an underground laboratory and selection of one or two candidate repository sites (2006–2020); selection of final repository site (2021–2040); and construction of the repository (2040–2050).

[88] Ju Wang, “On area-specific underground research laboratory for geological disposal of high-level radioactive waste in China,” *Journal of Rock Mechanics and Geotechnical Engineering*, Vol. 6, 2014, pp. 99–104.

[89] The bentonite clay is to come from Gaomiaozi, Inner Mongolia.

[90] Kari Ikonen and Heikki Raiko, Thermal Dimensioning of Olkiluoto Repository for Spent Fuel, Working Report 2012-56, www.posiva.fi/files/3143/WR_2012-56.pdf

[91] *Ibid.*

[92] Kari Ikonen and Heikki Raiko, *Thermal Dimensioning of Olkiluoto Repository for Spent Fuel*.

[93] Personal communication with CNNC experts.

[94] *Ibid.*

[95] Assuming average inflation rate in China since 2005 is 3 percent and a purchasing power parities (PPP) exchange rate for 2014 of 4.2 Yuan to the dollar. For PPP conversion factor see data.un.org/Data.aspx?d=MDG&f=seriesRowID:699).

[96] According to the Chinese expert, exponential scaling is one of the most common methodologies to estimate the costs of larger projects based on the designs of smaller-scale projects. The capital cost, C of a hypothetical facility with capacity M is scaled to that of an existing facility with capital cost C_o and capacity M_o, with the scaling factor represented by γ: $C/C_o = (M/M_o)^\gamma$. The scaling exponent is typically between 0.6 and 1.0. For extrapolating the cost of a reprocessing plant from 50 tons/year to 800 tons/year, the Chinese expert used a value of $\gamma = 0.85$. Based on this approach, $C(800) = C(50) \times (800/50)^{0.85}$ = $7.2 billion.

[97] Personal communication with CNNC experts.

[98] Statement of Peter R. Orszag, Costs of Reprocessing Versus Directly Disposing of Spent Nuclear Fuel, CBO testimony before the Committee on Energy and Natural Resources, United States Senate, 14 November 2007. www.cbo.gov/sites/default/files/cbofiles/ftpdocs/88xx/doc8808/11-14-nuclearfuel.pdf.

[99] The factor for interest relative to zero interest is $f = nr/[1-(1+r)^{-n}]$, where r is the interest rate and n is the lifetime in years where interest during construction is assumed to be included in the capital cost.

[100] See, for example, Matthew Bunn et al., *Interim Storage of Spent Nuclear Fuel*, op. cit.

[101] Personal communication with Hu Chuanwen, January 2008.

[102] Personal communication with Chinese experts, August 2014.

Chapter 3. France

[103] An earlier version of this chapter was presented on 10 April 2014 to the French National Assembly's Enquiry Committee into the Past, Present and Future Costs of the Nuclear System. See François Brottes (Président), Denis Baupin (Rapporteur), *Rapport fait au nom de la Commission d'Enquête relative aux coûts passes, presents et futurs de la filière nucléaire…*", Tome I, 5 June 2014, and transcript of oral evidence *Compte rendu, Commission d'Enquête… — Thème: Retraitement et MOX-Réacteurs de 4ème génération, Audition de M. Mycle Schneider, consultant,* Compte rendu n°41, 10 April 2014.

The author, Mycle Schneider, is grateful to Yves Marignac, Director of WISE-Paris, and Manon Besnard, Research Associate of WISE-Paris, for their significant contributions to this chapter.

[104] The Senate has considerably modified the draft legislation. A mixed National Assembly–Senate arbitration committee failed to agree on a compromise. A key dissent was the 2025 target date for the reduction of the nuclear share. In March 2015, the National Assembly set up a Special Commission to examine the Senate version of the bill and report to the plenary prior to the second reading.

[105] For a detailed discussion see Mycle Schneider, "*Fast Breeder Reactors in France*" in Fast Breeder Reactor Programs: History and Status, International Panel on Fissile Materials, 2010, pp. 17–35.

[106] See Chris Eales and Richard Sverrisson, "Cracks emerge in French elite's stranglehold on nuclear power," *Montel Magazine*, May 2014.

[107] Areva and EDF have been in a fierce battle for several years over a number of issues, including the two final operating years of the EURODIF uranium enrichment plant (EDF preferred cheaper Russian uranium enrichment services) and reactor-building projects (the highly problematic construction of Areva's first two European Power Reactors in Finland and France and the lost bid for the construction of four units in the United Arab Emirates).

[108] Areva/EDF, joint press statement, "AREVA and EDF create long-term used fuel management partnership," 19 December 2008. The 2040 timeframe is particularly surprising since, according to Areva's *Annual Report* for 2005, the current La Hague reprocessing plants were expected to be shut down around 2025. Although a study of the extension of their lifetimes has never been published, the National Plan 2013–2015 (see hereunder in this chapter) states that both lines, UP2-800 and UP3, are expected to be shut down in 2040.

[109] All quantities indicated in this text in tons refer to metric tons of heavy metal (uranium and plutonium).

[110] Areva/EDF, "AREVA and EDF reach agreement on used nuclear fuel management," 5 February 2010. The press statement disappeared from Areva's website but was still available on the EDF website at press.edf.com as of 17 March 2014.

[111] EDF, Direction Production Ingénierie, Jean Cyr Darby, Letter to the author dated 30 March 2011.

[112] A short-term "gap-filling" agreement between EDF and Areva covered the reprocessing of up to 1,050 tons and the MOX fuel fabrication of up to 120 tons for the year 2013. A total of 1,170 tons were processed during the year, but this may have included some foreign fuel.

[113] "Négociations au long cours pour la Hague," *Le Figaro*, 26 January 2014.

[114] Assemblée Nationale, "Coûts de la filière nucléaire: M. Luc Oursel, PDT du directoire d'AREVA", 7 May 2014, video; see videos.assemblee-nationale.fr/video.5391.couts-de-la-filiere-nucleaire--m-luc-oursel-pdt-du-directoire-d-areva-6-mai-2014, accessed on 9 September 2014.

[115] Areva, Press Release, 1 August 2014, areva.com/EN/news-10274/2014-halfyear-results.html, accessed 9 September 2014.

[116] After years of negotiations, neither Areva nor EDF issued specific press releases announcing the signature of the agreement. Neither party has released any further details. In fact, EDF and the French government (principal shareholder of both companies, owning respectively 85 percent and

87 percent of the shares) did not communicate at all about the signature of the agreement. Areva's loss of €95 million over the first six months of 2014 is explained as "the one-off impact of the treatment and recycling agreement reached with EDF for the 2013–2020 period, with commercial concessions granted to EDF in exchange for greater schedule visibility and increased volumes." However, there are no indications about volumes of spent fuel contracted for reprocessing or MOX fuel to be fabricated.

[117] Standard & Poor's, "French Nuclear Group Areva Downgraded To 'BB+/B' On Expected More Negative Cash Flows; Outlook Negative," 20 November 2014, www.researchandmarkets.com/reports/3041167/research-update-french-nuclear-group-areva.

[118] BB- is one notch off "highly speculative." See Standard & Poor's, "French Nuclear Group Areva Downgraded to 'BB-' on Further Profit Challenges and Cash Burn; Outlook Developing," 5 March 2015, www.researchandmarkets.com/reports/3109064/research-update-french-nuclear-group-areva.

[119] The core of a 900 MW reactor contains 157 assemblies, one quarter of which are replaced every year. In addition to spent fuel, there must at all times be space in the pool for the entire core in case the reactor vessel needs to be unloaded for some reason.

[120] In January 2012, France's Institute for Radiation Protection and Nuclear Safety (IRSN) reported that it could not validate EDF's request because of "numerous missing, incomplete justifications." In February 2012, France's Nuclear Safety Authority (ASN) rejected EDF's proposal because of "substantial missing information." In addition, ASN stated in a letter on EDF's general program of lifetime extension beyond 40 years that, even without dense-packing, "there remains a considerable gap between the safety principles of the [current] cooling ponds and those that would be applied to a new facility." EDF had admitted that the "implementation of efficient means to counter the consequences of prolonged uncovering of the fuel assemblies are not possible in the case of the pools of its operating reactors". ASN requested EDF "to examine from now on other technical solutions for the on-site storage of spent fuel than the current cooling ponds." There was no clear indication as to what "other technical solutions" ASN was alluding to, but it seems to favor the construction of new cooling ponds with higher design safety standards, than dry-cask storage for spent fuel that has cooled for several years, as is practiced at most of the world's nuclear power plants.

[121] It is remarkable that ASN has not raised the same objections to dense-packing of the pools at La Hague as for the reactor pools. The four pools at La Hague contain an enormous amount of spent fuel, equivalent to over 100 reactor cores.

[122] 25,590 tons at Tricastin and 310 tons at La Hague. *Source:* Charles-Antoine Louët, *"Bilan 2012 des flux et stocks de matières,"* Ministère de l'écologie, 12 December 2013.

[123] Depending on the quality of the material, it takes the enrichment of between 120 tons and 170 tons of reprocessed uranium for one reload containing about 18 tons of re-enriched uranium.

[124] Mycle Schneider, "End of reprocessed uranium exports to Russia?" International Panel on Fissile Materials Blog, 29 May 2010, www.fissilematerials.org/blog/2010/05/end_of_reprocessed_uraniu.html

[125] HCTISN (High Commission on Transparency and Information on Nuclear Safety), "Avis sur la transparence de la gestion des matières et des déchets nucléaires produits aux différents stades du cycle du combustible," 12 July 2010.

[126] Cour des Comptes, "Les coûts de la filière électronucléaire," January 2012

[127] *Plan national de gestion des matières et des déchets radioactifs 2013–2015,* February, Ministère de l'écologie, 2013.

[128] *Étude sur les flux de transport de substances radioactives à usage civil*, ASN, July 2014.

[129] There is no plan to increase the number of units authorized to be fueled with MOX beyond 24. The four Cruas units are reserved for reprocessed uranium fuel. The Fessenheim and Bugey reactors were

not designed for MOX use. In the future, it is possible that the EPR, currently under construction at Flamanville, which is designed for MOX use, will operate with MOX fuel. EDF has made clear, however, that it has no intentions to start-up the reactor with MOX and has not requested authorization to use MOX fuel in the reactor.

[130.] *Rapport Annuel 2013*, ASN, April 2014.

[131.] Plutonium could be chemically separated from fresh MOX in a glove box without shielding. Fresh MOX therefore should be secured to a level almost equivalent to that for direct weapon-usable material.

[132.] *Le coût de production de l'électricité nucléaire — Actualisation 2014*, Cour des Comptes May 2014.

[133.] Rapport d'évaluation n°8, Commission Nationale d'Evaluation des recherches et études relatives à la gestion des matières et des déchets radioactifs, June 2014. This report is from the National Evaluation Commission of Research and Studies Relative to the Management of Radioactive Materials and Wastes.

[134.] Loi n° 2006-739 du 28 juin 2006 de programme relative à la gestion durable des matières et déchets radioactifs

[135.] *Inventaire national des matières et déchets radioactifs — Rapport de synthèse* (ANDRA, 2012).

[136.] According to the French government's annual INFCIRC-549 declaration to the IAEA, 15 August 2014.

[137.] French officials call it the "equal flow principle." See, for example, Third National Report on Compliance With the Joint Convention Obligations, ASN, 2008.

[138.] Commission Particulière du Débat Public sur la gestion des déchets radioactifs", Minutes of the public hearing, 15 September 2005.

[139.] Derived from 56 tons x 70.6 percent, as indicated in Areva NC, *Traitement des combustibles usés provenant de l'étranger*, 2014, p. 31.

[140.] Although a large part of the powder and pellets that do not meet the technical specifications (i.e., are "sub-spec") can be recycled within the MELOX plant, excess waste is shipped to La Hague, either in this form or fabricated into scrap MOX assemblies. Fresh MOX assemblies that did not meet design specifications in the fabrication process also are shipped to La Hague to eventually be put through the reprocessing line. This is technically possible for the powder and pellets, but only a small batch containing some tens of kilograms of plutonium has thus far been dissolved to demonstrate the process. There is no operational license yet for the reprocessing of sub-spec MOX assemblies, which would require the implementation of specific procedures and some facility modifications that are still in the project phase.

[141.] Antwort der Bundesregierung auf die Kleine Anfrage der Abgeordneten Sylvia Kotting-Uhl, Cornelia Behm, Harald Ebner, weiterer Abgeordneter und der Fraktion BÜNDNIS 90/DIE GRÜNEN – "Stand der Wiederaufarbeitung deutscher Brennelemente im Ausland und des deutschen Plutonium-Inventares", 31 January 2012.

[142.] Klaus Janberg, personal communication, 15 May 2014.

[143.] "On 30 June 2008, plutonium removal and treatment operations were completed for the Areva La Hague site. As such, between 2003 and 2008, the equivalent of 3 years of production was recycled in the fabrication of new fuels," www.areva.com/EN/operations-1094/the-cadarache-facility-activities--cleanup-and-disassembly.html. Based on the production rate of 40 tons a year shown for Cadarache in Status and *Advances in MOX Fuel Technology* (IAEA, 2003) Table 2, and assuming 6 percent plutonium, this would have been about 7 tons of plutonium.

[144.] J. M. Cuchet et al., "Decommissioning the Belgonucleaire Dessel MOX Plant: Presentation Of The Project and Situation, End August 2013," 15th International Conference on Environmental Remediation and Radioactive Waste Management, 2013, Session 3.11, slide 6. The ownership of the storage MOX from Dessel was transferred to its customers who probably shipped it to La Hague in exchange for payments to Areva and an equivalent amount of plutonium in MOX fuel.

[145] "The authorities demanded that the old MOX facility be shut down. Approval for operation to be resumed also failed to be given in the years that followed. This meant that a fully operative production line was brought to a standstill from one day to the next, leaving an inventory of 2.25 Mg [2.25 tHM] of plutonium in various stages of processing… Of the material which was suitable for shipment from the start, 550 kg of plutonium in the form of PuO_2 powder and mixed oxides have so far been shipped to England and France." See Helmut Rupar et al., "Decommissioning of Four German Fuel Cycle Facilities," Waste Management 2000 Conference, February 27 – March 2, 2000, Tucson, AZ. It is also reported that "the nuclear fuel that was still in the MOX plant was processed until the plant was cleaned out and placed in "storage elements" which are capable of being stored long-term and could not be used in any nuclear power plants. These storage elements were sent for processing to Areva NC in La Hague, France." See Werner Koenig et al., "Release and Disposal of Materials During Decommissioning of Siemens MOX Fuel Fabrication Plant At Hanau, Germany," *Proceedings of the 11th International Conference on Environmental Remediation and Radioactive Waste Management ICEM2007, September 2 – 6, 2007, Bruges, Belgium*, ICEM07-7205.

[146] ANDRA, "Les essentiels 2015 — Inventaire national des matières et déchets radioactifs" ["The essentials 2015 — National Inventory of Radioactive Materials and Waste "] preview for the working group of the Plan national de gestion des matières et des déchets radioactifs [National Plan for the Management of Radioactive Materials and Waste] (GR-PNGMDR), 13 April 2015, slide 7. When asked about the detail of these 230 tHM and the part that would correspond either to imported material or to material produced in France during MOX fuel production for foreign clients, ANDRA declined to answer and Areva provided no further detail.

[147] These estimates have been drawn by the author from various sources, including from the French government's annual INFCIRC-549a declarations to the IAEA. Quantities in tons of heavy metal.

[148] The pool is called Atelier Pour l'Entreposage du Combustible (APEC).

[149] Based on the quantity of reprocessed fuels and their average plutonium content.

[150] The completion of France's last four 900 MWe reactors overlapped the completion of the first five 1300 MWe reactors in 1984 and 1985. Two reactors, Blayais-3 and -4, that had been licensed for MOX use in May 2013, had not yet been loaded with MOX fuel as of the middle of 2014.

[151] As of 24 March 2015, based on the day of first criticality.

[152] The required modifications would likely include new pressure vessel heads and control rod drive mechanisms.

[153] *Rapport d'évaluation n°8*, Commission Nationale d'Evaluation des recherches et études relatives à la gestion des matières et des déchets radioactifs, 2014.

[154] L'évaluation du plan national de gestion des matières et des déchets radioactifs, PNGMDR 2013 – 2015, Christian Bataille, Christian Namy, Office Parlementaire des Choix et Scientifiques et Technologiques, 18 September 2014.

[155] *Rapport fait au nom de la Commission d'Enquête, op. cit.*, Tome I, 5 June 2014. See also ASN, DG Jean-Christophe Niel, letter to the General Administrator of the CEA, April 2014.

[156] *Rapport fait au nom de la Commission d'Enquête, op. cit.* Tome I, 5 June 2014.

[157] *Ibid*.

[158] *Ibid*.

[159] EDF, *Position d'EDF vis-à-vis de la question de la rentabilité du combustible MOX*, 18 February 1999.

[160] For details on environmental pollution and the challenges of managing the waste streams produced,

see Mycle Schneider and Yves Marignac, *Spent Nuclear Fuel Reprocessing in France*, International Panel on Fissile Materials, 2008.

[161] William Walker, *Nuclear Entrapment: THORP and the Politics of Commitment*, Institute for Public Policy Research, 1999.

[162] *Rapport fait au nom de la Commission d'Enquête, op. cit.*, Tome I, 5 June 2014.

[163] PS-EELV, "2012 – 2017: Socialistes et écologistes, ensemble pour combattre la crise et bâtir un autre modèle de vivre ensemble", undated (November 2012). Our translation.

[164] See, for example, www.lejdd.fr/Election-presidentielle-2012/Actualite/PS-EELV-Areva-fait-enlever-un-passage-de-l-accord-424231; viewed on 19 March 2014.

[165] Statement by Michel Sapin, PS (now Minister for Employment) and Jean-Vincent Placé, EELV, 17 November 2011, Annex to the PS-EELV Agreement.

[166] See, for example, Mycle Schneider and Xavier Coeytaux, "L'industrie du plutonium: de l'effritement d'un mythe à l'urgence d'une reconversion," in *Contrôle, La revue de l'Autorité de sûreté nucléaire (ASN), Ministère de l'Economie, des Finances et de l'Industrie, Ministère de l'Aménagement du Territoire et de l'Environnement,* Paris, France, n° 138, January 2001, p. 94 – 98.

[167] The ASN has clearly stated that this is still a very much open question. Moreover, the new Energy Bill introduces a process under which license extensions to operate beyond 40 years will be subject to a full environmental impact assessment and public inquiry on a case-by-case basis.

[168] ANDRA, "Les essentiels 2015", *op. cit.* In the reference scenario that ANDRA is drawing from the plans declared by the operators, the total amount of plutonium separated in oxide powder form goes down from 52 tHM in the end of 2013 to 33 tHM in the end of 2020. The reduction roughly corresponds to the amount of Japanese plutonium currently stored in France.

[169] The Sellafield MOX Plant (SMP) shut down in 2011 after it had achieved in nine years only about 1 percent of the expected production.

[170] Not including the cost of extracting the plutonium from weapons components. The program aimed at the conversion of 34 tons of excess weapons plutonium into MOX fuel, *Report of the Plutonium Disposition Working Group: Analysis of Surplus Weapon-Grade Plutonium Disposition Options* (U.S. Department of Energy, April 2014) Table 6.1.

[171] Tom Clements, Edwin Lyman, and Frank von Hippel, "The Future of Plutonium Disposition," *Arms Control Today,* July/August 2013. See also Frank von Hippel and Gordon MacKerron, *Alternatives to MOX: Direct-disposal options for stockpiles of separated plutonium*, International Panel on Fissile Materials, 2015.

[172] *Inventaire national des matières et déchets radioactifs – Rapport de synthèse*, ANDRA, 2012. Note that EDF's analysis appears to have assumed that only 22 units could use MOX fuel, whereas the scenarios considered here assume 24 units. The details on the EDF scenario have not been published. Requests for the information by the authors have not received any replies so far.

Chapter 4. Germany

[173] During the Cold War, Germany consisted of two very different entities: the Federal Republic of Germany (FRG) in the West and the German Democratic Republic (GDR) in the East. The latter was part of the Soviet system and, with regard to nuclear energy technology, totally dependent on Russia. Nuclear energy in the GDR was based on Russian-designed plants and spent fuel was contractually returned to Russia. Therefore the GDR did not reprocess and hence is not part of this chapter.

[174] Prior to 1955, activities related to nuclear energy were restricted in Germany under the post-war occupation of the Allied Military Command.

[175] Reprocessing of the AVR fuel was developed on a laboratory scale but never tested on an industrial scale. Germany is currently discussing the possibility of the spent fuel being shipped to the U.S., which supplied the HEU. See www.fz-juelich.de/portal/EN/AboutUs/self-conception/responsibility/avr/FAQ_Transport/fragen-und-antworten.html;jsessionid=06E207C7C204C1C12BF740D45B9C02D7#Antrag

[176] Some say that the advocacy for heavy water by scientists Werner Heisenberg and Karl Wirtz was also in part to show that they had been right when trying to build a heavy water reactor during World War II. They failed because they did not manage to obtain a sufficient quantity of heavy water from Norway. Joachim Radkau and Lothar Hahn, *Aufstieg and Fall der Deutschen Atomwirtschaft [Rise and Fall of Nuclear Power in Germany]*, Oekom, Munich, 2013.

[177] R.B. Kehoe, *The Enriching Troika: A history of Urenco to the year 2000*, Urenco, 2002.

[178] GE had just built, in 1957, a 5 MWe power reactor in Vallecitos, California.

[179] Starting in 1956, exploration was carried out in several areas in Germany, but only three deposits of economic interest were found. In addition to Menzenschwand, there were the Müllenbach deposit in the northern Black Forest and the Grossschloppen deposit in north-eastern Bavaria. See *Uranium 2011: Resources, Production and Demand,* OECD Nuclear Energy Agency and International Atomic Energy Agency, 2012.

[180] Austria, Belgium, Denmark, France, Germany, Italy, Netherlands, Norway, Portugal, Sweden, Turkey, Switzerland, Jean-Marc Wolff, *Eurochemic: European Company for the Chemical Processing of Irradiated Fuels, 1956 – 1990*, OECD Nuclear Energy Agency, 1996, Table 9.

[181] The original purpose of the Marcoule and Windscale/Sellafield facilities was to extract plutonium from gas-graphite reactor and other low-burnup fuel for nuclear weapons.

[182] The three primary reasons for the low throughput were: 1) Cost: from the beginning, WAK's prices were higher than its English competitor; 2) Focus: WAK's main purpose was to do research and development, and each new step towards higher burnup required lengthy licensing; and 3) Technical: there were many problems, including one major leak.

[183] Euratom's powers over nuclear activities in Europe are quite broad. For example, on one occasion, when a fuel fabricator lacked adequate controls over its shipments, Euratom replaced the company's manager temporarily until the situation was rectified.

[184] In 1956, an expert working group on nuclear power under the Organization for European Economic Cooperation came up with an estimate that a reprocessing plant with a design throughput of 500 tons per year would cost $35.5 million to build and would reprocess spent fuel at a cost of $14/kgHM, Eurochemic, *op. cit.* p. 76.

[185] Detlev Möller, *Endlagerung radioaktiver Abfälle in der Bundesrepublik Deutschland [Final Disposal of Radioactive Wastes in the Federal Republic of Germany]* 2009.

[186] Michael Fröhlingsdorf, Udo Ludwig and Alfred Weinzierl, "Abyss of Uncertainty: Germany's Homemade Nuclear Waste Disaster," *Spiegel*, 21 February 2013, www.spiegel.de/international/germany/germany-weighs-options-for-handling-nuclear-waste-in-asse-mine-a-884523.html.

[187] The author was the lead engineer for these spent-fuel storage facilities in 1976 – 77.

[188] During many years, however, K.D. Grill, Gorleben's representative in the Federal Parliament and an ardent defender of the federal policy, received the majority of the county's votes.

[189] Frank Uekötter, *The Greenest Nation? A New History of German Environmentalism*, MIT Press, 2014, p. 97.

[190] *Eurochemic, op. cit.*, p. 113.

[191] It was assumed that the spent fuel would have cooled for at least 7 years and have an average burn-up of 40 and a maximum burnup of 55 GWt-days/tHM.

[192] The Bethe-Tait excursion is an accident scenario that involves the melting and collapse of the core resulting in a rapid increase in its reactivity and a small nuclear explosion. The question has always been what the maximum power of such an explosion could be and whether it could rupture the reactor containment building, H.A. Bethe and J.H. Tait, *An Estimate of the Order of Magnitude of Vigorous Interaction Should the Core of a Fast Reactor Collapse,* Memorandum, April 1956.

[193] W. Marth, *The SNR 300 Fast Breeder in the Ups and Downs of its History*, Kernforschungszentrum [Nuclear Research Center] Karlsruhe, 1994, p. 102.

[194] www.wunderlandkalkar.eu/en

[195] For a report on the CASTOR V performance when filled with 13 PWR fuel assemblies 4 years after discharge and 8 two years after discharge, see Virginia Power Company, Pacific Northwest Laboratory and Idaho National Laboratory, *The Castor-V/21 PWR Spent-Fuel Storage Cask: Testing and Analyses*, Electric Power Research Institute, NP-4887, 1996.

[196] The cost of decommissioning is discussed in Willy Marth, "Die Lange (und Teuere) Geschichte Der Karlsruher Wiederaufarbeitungsanlage WAK" [The Long (and Costly) Story of the Karlsruhe WAK Reprocessing Plant], *Rentnerblog*, 9 December 2012, www.rentnerblog.com/2012/12/die-lange-und-teuere-geschichte-der.html (in German). For a presentation on the WAK decommissioning process see W. Dander and W. Lutz, "Decommissioning of Hot Cells at the Karlsruhe Reprocessing Plant (WAK)," IAEA Workshop on Decommissioning Technologies, 6–10 July 2009, Karlsruhe, Germany.

Chapter 5. India

[197] Itty Abraham, *The Making of the Indian Atomic Bomb: Science, Secrecy and the Postcolonial State*, Zed Books, 1998; George Perkovich, *India's Nuclear Bomb: The Impact on Global Proliferation*, University of California Press, 1999; M. V. Ramana, "La Trahison Des Clercs: Scientists and the India's Nuclear Bomb," in M.V. Ramana and C. Rammanohar Reddy, eds., *Prisoners of the Nuclear Dream*, Orient Longman, 2003, pp. 206–44.

[198] This has become a more prominent argument in recent years. For example, when asked by a parliamentarian about "the manner/method of nuclear waste disposal in the country", one government spokesperson said in March 2013: "India has adopted closed fuel cycle option, which involves reprocessing and recycling of the spent fuel. During reprocessing, only about two to three percent of the spent fuel becomes waste and the rest is recycled. This waste, called high level waste (HLW), is converted into glass through a process, called vitrification. The vitrified waste is stored in a Solid Storage Surveillance Facility for 30–40 years with natural cooling prior to its disposal in a deep geological repository. The need for a deep geological repository will arise only after three to four decades." V. Narayanasamy, *Unstarred Question No. 3686: Disposal of Nuclear Waste*, Lok Sabha, 20 March 2013, www.dae.nic.in/writereaddata/ls101110.pdf#page=6.

[199] David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies*, Oxford University Press, 1997, p. 22.

[200] France, for example, talked about the design of the Marcoule plant while the United States put out a description of its Idaho Chemical (Re)Processing Plant. See Walter C. Patterson, *The Plutonium Business and the Spread of the Bomb*, Paladin, 1984; and Frank J. Rahn, Achilles G. Adamantiades, John E. Kenton, and Chaim Braun, *A Guide to Nuclear Power Technology : A Resource for Decision Making*, Wiley, 1984, p. 609.

[201] Roberta Wohlstetter, *The Buddha Smiles: Absent-Minded Peaceful Aid and the Indian Bomb*, Pan Heuristics, prepared for U.S. Energy Research and Development Administration, 1977; Sharokh Sabavala, "India to Join 'Plutonium Club'," *Christian Science Monitor*, 10 April 1964. See also M. V. Ramana, *The Power of Promise: Examining Nuclear Energy in India*, Penguin India, 2012.

[202] Robert Kupp, *A Nuclear Engineer in the Twentieth Century*, Trafford Publishing, 2006, p. 109. The version of the construction of this plant put out by India's nuclear establishment makes no mention of these inputs. The official DAE history says the plant: "became one of the most important landmarks in the Indian programme, that this plant *entirely designed and built* by Indian engineers, under the leadership of H. N. Sethna and N. Srinivasan could be completed and commissioned by mid-1964 (emphasis added)." See C. V. Sundaram, L. V. Krishnan, and T. S. Iyengar, *Atomic Energy in India: 50 Years*, Department of Atomic Energy, Government of India, 1998, p. 90.

[203] *Global Fissile Material Report 2010*, International Panel on Fissile Materials, 2010, p. 119, 194; Albright, Berkhout, and Walker, *Plutonium and Highly Enriched Uranium 1996*, p. 268.

[204] Sundaram, Krishnan, and Iyengar, *Atomic Energy in India: 50 Years*, p. 90.

[205] A retired bureaucrat involved in science and technology policy making noted that the Trombay plant "failed to work properly for almost seven years after formal commissioning. The chief problem was the separation of plutonium from the fission products. The concentration of the latter in the final product continued to be too high for the material to be handled and used for any purpose." See Ashok Parthasarathi, *Technology at the Core: Science and Technology with Indira Gandhi*, Pearson Longman, 2007, p. 17.

[206] PURNIMA had a small core of about twenty centimeters in diameter and used 22 kg of plutonium in the form of oxide, P. K. Iyengar, Briefings on Nuclear Technology in India, newenergytimes.com/v2/library/2009/2009Iyengar-Briefings%20on%20Nuclear%20Technology.pdf, 2009, p. 101. After carrying out neutronics experiments, PURNIMA was dismantled. Reportedly most of the plutonium was recovered and some of it may have been used in manufacturing the device exploded in 1974.

[207] A. N. Prasad and S. V. Kumar, "Indian Experience in Fuel Reprocessing," in *International Conference on Nuclear Power and Its Fuel Cycle*, Salzburg, Austria, 1977); NF, "Reprocessing Plant at Trombay Ready for Recommissioning," *Nuclear Fuel* Vol. 8, No. 10, 1983, p. 7; T. S. Subramanian, "A Key Reprocessing Facility," *Frontline*, 9 October 1998, p. 92.

[208] The device exploded used about 5 – 7 kg of weapon-grade plutonium. See "Scientist on Cost of Nuclear Weapons," *Economic Times*, 20 May 1998.

[209] It is usually assumed that the 1998 tests used 20 to 30 kg of weapon-grade plutonium.

[210] The FBTR was constructed before any unsafeguarded reactor-grade plutonium was available and was therefore fueled with weapon-grade plutonium. The plutonium inventory of the FBTR's first core has been estimated as 50 kg. See Albright, Berkhout, and Walker, *Plutonium and Highly Enriched Uranium 1996*: *World Inventories, Capabilities and Policies*, 1997, p. 267. One article in a trade magazine in the late 1990s reported higher values. Mark Hibbs, "Kalpakkam FBR to Double Core, Load First Thorium-232 Blanket," *Nucleonics Week*, Vol. 38, No. 48, 1997, p. 10. However, this appears to have been a modified core with a larger number of fuel assemblies.

[211] The solvent was 30 percent tributyl phosphate mixed with kerosene, A. N. Prasad and S. V. Kumar, "Indian Experience in Fuel Reprocessing," *op. cit.*

[212] The cladding was removed using a separate chemical process. The dissolved cladding is classified as Intermediate Level Waste. Anand Gangadharan et al., "Management of Intermediate Level Radioactive Liquid Waste (ILW) at WIP, Trombay," *BARC Newsletter*, December 2013.

[213] AECL, *Canada Enters the Nuclear Age : A Technical History of Atomic Energy of Canada Limited,* Published for Atomic Energy Canada Limited by McGill-Queen's University Press, 1997, p. 217, p. 256. The burnup is the quantity of thermal megawatt days fission energy produced per kilogram of uranium.

[214] Sundaram, Krishnan, and Iyengar, *Atomic Energy in India: 50 Years.*

[215] G. G. Mirchandani and P. K. S. Namboodiri, *Nuclear India: A Technological Assessment*, Vision Books, 1981, p. 73.

[216] *Annual Report 1981 – 1982*, Department of Atomic Energy, 1982, p. 31.

[217] *Annual Report 1982 – 1983*, Department of Atomic Energy, 1983, p. 31. Originally, the plant was intended to reprocess spent fuel from the Boiling Water Reactors (BWRs) at Tarapur as well. Following India's 1974 nuclear test, however, the U.S. Congress passed the Nuclear Non Proliferation Act of 1978 and the United States did not allow any reprocessing of spent fuel from the US-origin Tarapur reactors.

[218] M. R. Srinivasan, *From Fission to Fusion : The Story of India's Atomic Energy Programme*, Viking, 2002, p. 242.

[219] P. K Dey and N. K Bansal, "Spent Fuel Reprocessing: A Vital Link in Indian Nuclear Power Program," *Nuclear Engineering and Design*, Vol. 236, 2006, p. 726.

[220] DAE, *Annual Report 1985 – 1986*, Department of Atomic Energy, 1986, p. 3.19.

[221] This includes spent fuel from the Madras and Narora Atomic Power Stations. See Sundaram, Krishnan, and Iyengar, *Atomic Energy in India: 50 Years, p. 90; Annual Report 2005 – 2006,* Department of Atomic Energy, 2006, p. 34.

[222] The DAE's reason to store rather than reprocess RAPS spent fuel may in part be because of the organization's general aversion to IAEA safeguards.

[223] H. B. Kulkarni, R. S. Soni, and K. Agarwal, "Spent Fuel Storage in India," in *Storage of Spent Fuel from Power Reactors*, International Atomic Energy Agency, 2003, pp. 30 – 36.

[224] R. D. Changrani, D. D. Bajpai, and S. S. Kodilkar, "Storage of Spent Fuel from Power Reactor in India: Management and Experience," in *Storage of Spent Fuel from Power Reactors: Proceedings of a Symposium*, International Atomic Energy Agency, 1999, pp. 65–72.

[225] *Ibid.*, p. 69.

[226] Mark Hibbs, "Tarapur-2 to Join Twin BWR in Burning PHWR Plutonium," *Nuclear Fuel*, Vol. 20, No. 20, 1995, p.18; Mark Hibbs, "PREFRE Plant Used Sparingly, BARC Reprocessing Director Says," *Nuclear Fuel*, Vol. 17, No. 7, 1992, p. 8.

[227] Several Annual Reports of the DAE mention PREFRE as undergoing revamping or being started up after revamping, indicating that it must have been shut down for extended periods of time. See *Annual Report 1991 – 1992*, Department of Atomic Energy, 1992, p. 2.24; *Annual Report 1994 – 1995*, Department of Atomic Energy, 1995, p. 2.2; *Annual Report 1995 – 1996*, Department of Atomic Energy, 1996, p.18; *Annual Report 1997 – 1998*, Department of Atomic Energy, 1998, p. 2.2; *Annual Report 2004 – 2005*, Department of Atomic Energy, 2005, p. 37. In March 2003, it was reported that "PREFRE had been shut for an entire year, and would remain idle for another six months, because of technical problems." See Mark Hibbs, "DAE Reprocessing Program Remains Modest in Scope," *Nuclear Fuel*, Vol. 28, No. 8, 2003, p. 9.

[228] *Annual Report 2010 – 2011,* Department of Atomic Energy, 2011.

[229] R. K. Sinha, "Founder's Day Address," *Nuclear India*, October 2012, p. 8; *Annual Report 2012 – 2013*, Department of Atomic Energy, 2013.

[230] *Annual Report 2012 – 2013*, p. 63.

[231] As the plutonium ages, plutonium-241, decays into americium-241. After a number of years, americium must be chemically separated before the plutonium is fabricated into fuel because the gamma radiation associated with its decay increases occupational radiation doses to workers.

[232] In 1997, it was reported that KARP had two identical reprocessing lines, but that only one line would operate at a time. The first line was expected to operate for seven to eight years and would be decommissioned by 2008-09, when an independent twin reprocessing line would begin operations. See Mark Hibbs, "First Separation Line at Kalpakkam Slated to Begin Operations next Year," *Nuclear Fuel*, Vol. 22, no. 24, 1997, pp. 8–9.

[233] Mirchandani and Namboodiri, *Nuclear India: A Technological Assessment*, p. 72.

[234] *Performance Budget 1986 –87,* Department of Atomic Energy, 1987, p. 19.

[235] *Performance Budget 1985 –86*, Department of Atomic Energy, 1986, p. 39.

[236] Hibbs, "DAE Reprocessing Program Remains Modest in Scope."

[237] Performance Budget 1999 –2000, Department of Atomic Energy, 2000, p. 25.

[238] *Annual Report 2009 –2010*, Department of Atomic Energy, 2010, p. 43.

[239] One indication of the likely time period of the outage might be obtained from the 2005 Annual Report of the DAE, which announced that KARP was undergoing major modifications.

[240] V Narayanasamy, *Starred Question No. 315: Reprocessing Capacity*, Lok Sabha, 24 August 2011.

[241] Sekhar Basu, "Founder's Day Address 2014," *Bhabha Atomic Research Centre*, 30 October 2014, www.barc.gov.in/presentations/fddir14.pdf.

[242] P. K. Iyengar, "Nuclear Power: Policy and Prospects - India," in *Collected Scientific Papers of Dr. P. K. Iyengar,* Bhabha Atomic Research Centre, Library and Information Services Division, 1993, pp. 74–86. See also *Annual Report 1993– 1994*, Department of Atomic Energy, 1994, p. 24; and *Annual Report 1994– 1995*, p. 2.2.

[243] P. K. Dey, "Spent Fuel Reprocessing: An Overview," in *Nuclear Fuel Cycle Technologies: Closing the Fuel Cycle,* Indian Nuclear Society, 2003, pp. IT – 14/1 – IT – 14/16, http://fissilematerials.org/library/barc03.pdf.

[244] Saurav Jha, "Enrichment Capacity Enough to Fuel Nuke Subs," *IBNLive,* 26 November 2011, ibnlive.in.com/news/enrichment-capacity-enough-to-fuel-nuke-subs/206066-61.html; R. Prasad, "'Our Policy Is to Reprocess All the Fuel Put into a Nuclear Reactor,'" *The Hindu*, 28 October 2012, www.thehindu.com/opinion/interview/our-policy-is-to-reprocess-all-the-fuel-put-into-a-nuclear-reactor/article4041223.ece; Prithviraj Chavan, *Unstarred Question No. 389: Integrated Nuclear Recycle Fuel*, Lok Sabha, 2010, www.dae.nic.in/writereaddata/ls101110.pdf#page=6; Kalyan Ray, "First N-Fuel Recycling Plant Soon in Tarapur," *Deccan Herald*, 25 November 2012, www.deccanherald.com/content/294272/first-n-fuel-recycling-plant.html.

[245] Chavan, *Unstarred Question No. 389: Integrated Nuclear Recycle Fuel*.

[246] Narayanasamy, *Starred Question No. 315: Reprocessing Capacity.*

[247] Rama Lakshmi and Steven Mufson, "U.S., India Reach Agreement on Nuclear Fuel Reprocessing," *Washington Post*, 29 March 2010.

[248] M. V. Ramana and Suvrat Raju, "The Impasse Over Liability Clause in Indo-U.S. Nuclear Deal," *India Ink*, 15 October 2013, india.blogs.nytimes.com/2013/10/15/the-impasse-over-liability-clause-in-indo-u-s-nuclear-deal/?_r=0.

[249] Waste is classified as low level (LLW) if it contains less than 3.7 million Bq (0.0001 Curies) per liter, intermediate level (ILW) if it contains between 3.7 million and 370 billion Bq (0.0001 to 10 Curies/liter), and as high level (HLW) if it contains more than 370 billion Bq/liter (10 Curies/liter). See K. Raj, K. K Prasad, and N. K Bansal, "Radioactive Waste Management Practices in India," *Nuclear Engineering and Design*, Vol. 236, 2006, p. 915.

[250] Placid Rodriguez, "Chemical Engineering and Fast Breeder Reactor Technology," in Y. B. G. Varma et al., eds., *Advances in Chemical Engineering*, Allied Publishers, 1996, p. 56.

[251] Nitric acid is removed by adding formaldehyde; this results in the reduction of nitric acid to carbon dioxide, water, and gaseous nitrogen dioxide. See M. Benedict, T.H. Pigford, and H.W. Levi, *Nuclear Chemical Engineering*, McGraw-Hill, 1981, p. 590.

[252] Dey, "Spent Fuel Reprocessing: An Overview," p. 727.

[253] *The Safety of the Nuclear Fuel Cycle*, OECD Nuclear Energy Agency, 2005, pp. 198–205.

[254] Borosilicate glass is known for having a low coefficient of thermal expansion. Because of compositional differences in HLW arising from reprocessing different reactor fuel types, the basic borosilicate matrix has been modified at each plant.

[255] Sinha, "Founder's Day Address."

[256] The DAE has been less than transparent about its plans for geological waste disposal. In 2012, the DAE announced that it had begun looking for a "rock formation that is geologically stable, totally impervious and without any fissures" to store nuclear waste. See PTI, "Scouting for Sites to Store N-Waste: AEC Chief," *The Hindu,* 15 February 2012, www.thehindu.com/todays-paper/tp-national/scouting-for-sites-to-store-nwaste-aec-chief/article2894361.ece.

[257] Baldev Raj, P. Chellapandi, and S. C. Chetal, "Science and Technology of Sodium Cooled Fast Spectrum Reactors and Closed Fuel Cycles in Three Stage Programme of India: Accomplishments and a Way Forward," in R. Rajaraman, ed., *India's Nuclear Energy Programme: Future Plans, Prospects and Concerns,* Academic Foundation, 2013, pp. 175–203.

[258] A. Ravisankar, "An Indian Perspective of the Development of Fast Reactor Fuel Reprocessing Technology," International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13), Paris, 4 March 2013, www.iaea.org/nuclearenergy/nuclearpower/Downloadable/Meetings/2013/2013-03-04-03-07-CF-NPTD/T6.5/T6.5.ravisankar.pdf.

[259] R. Natarajan, "Solvent Extraction in Fast Reactor Fuel Reprocessing," in Solvent Extraction Revisited: Application in Process Industries, Indian Institute of Chemical Engineers, New Delhi, 5 February 2010, www.iichenrc.org/Presentations/event%201/IV%20session/Dr.%20N.%20Natarajan.pdf.

[260] IANS, "Rs 9,600-Crore Nuclear Fuel Facility to Come up at Kalpakkam," *Daily News & Analysis*, 20 July 2013, www.dnaindia.com/india/report-rs9600-crore-nuclear-fuel-facility-to-come-up-at-kalpakkam-1863491.

[261] *Global Fissile Materials Report 2015*, International Panel on Fissile Materials, 2015.

[262] The DAE reported that over the first twenty years of its life, the FBTR operated for only 36,000 hours, corresponding to an availability factor of about 20 percent. See DAE, *Atomic Energy in India: A Perspective*, Department of Atomic Energy, Government of India, 2006. The peak burnup for FBTR fuel is reported to be 165,000 MWd/tHM, but this has been increasing over the years. See K. V. Suresh Kumar, A. Babu, and B. Anandapadmanaban & G. Srinivasan, "Twenty Five Years of Operating Experience with the Fast Breeder Test Reactor," *Energy Procedia*, 2010, Vol. 7, 2011, pp. 323–32; K. V. Suresh Kumar et al., "Fast Breeder Test Reactor. 15 Years of Operating Experience," in *Technical Meeting on Operational and Decommissioning Experience with Fast Reactors,* International Atomic Energy Agency, 2002, pp. 15–27. Assuming an average burnup of 100,000 MWd/tHM, an average lifetime availability factor of 20 percent and an average power of 10 MWt, the total amount of uranium and plutonium required each year would have been 7.3 kg. Approximately two-thirds of the fuel

"elements" (assemblies) in the current FBTR core have a plutonium content of 70 percent. The remaining third have a plutonium content of 55 percent. This implies an average annual use of about 4.75 kg of plutonium, and a total lifetime use since 1988 (when refuelling is likely to have begun) of about 130 kg.

[263.] IGCAR, "Design of Prototype Fast Breeder Reactor," 10 March 2006, www.igcar.ernet.in/broucher/design.pdf.

[264.] H.S. Kamath, K. Anantharaman, and D.S.C. Purushotham, "MOX Fuel for Indian Nuclear Power Programme," in *MOX Fuel Cycle Technologies for Medium and Long Term Deployment*, International Atomic Energy Agency, 1999, pp. 190–99.

[265.] There is a suggestion that each MOX fuel assembly for PHWRs might contain about 0.022 kg of plutonium. See K. Balu, D.S.C. Purushotham, and A. Kakodkar, "Closing the Fuel Cycle-A Superior Option for India," in F*uel Cycle Options for Light Water Reactors and Heavy Water Reactors,* International Atomic Energy Agency, 1998, pp. 25–34. The amount of plutonium used in MOX fuel assemblies for the BWR at Tarapur is likely to be higher.

[266.] *IAEA Annual Report 2013: Additional Annex Information*, International Atomic Energy Agency, 2014, www.iaea.org/sites/default/files/annexinfo.pdf.

[267.] The list of operating reactors and their safeguards status as of 2014 is available at M. V. Ramana, "India Ratifies an Additional Protocol and Will Safeguard Two More Nuclear Power Reactors," International Panel on Fissile Materials Blog, 1 July 2014, fissilematerials.org/blog/2014/07/india_ratifies_an_additio.html.

[268.] Shashikant Trivedi, "1,400-MW Nuclear Plant on Anvil in MP," *Business Standard India*, 6 April 2010, www.business-standard.com/article/companies/1-400-mw-nuclear-plant-on-anvil-in-mp-110040600047_1.html; ENS Economic Bureau, "N-Energy Key to Sustaining Growth Momentum: PM," *Indian Express*, 14 January 2014, indianexpress.com/article/india/india-others/n-energy-key-to-sustaining-growth-momentum-pm/.

[269.] M. V. Ramana, *The Power of Promise: Examining Nuclear Energy in India*, Penguin, 2012.

[270.] In the case of the Koodankulam plant which has two imported Russian LWRs, the first of which only began operating in 2013, the director of BARC has said that "spent fuel will have to be stored for at least 10 years". Ch Sushil Rao, "Kudankulam Nuclear Power Plant's Unit-2 to Be Ready in Eight Months," *The Times of India*, 10 June 2014, timesofindia.indiatimes.com/india/Kudankulam-nuclear-power-plants-unit-2-to-be-ready-in-eight-months/articleshow/36357882.cms. Reprocessing does not seem to be immediately envisaged because it would require IAEA safeguards. The official also indicated that the possibility of constructing additional away from reactor storage has been considered.

[271.] S. C Chetal et al., "A Perspective on the Future Development of FBRs in India," in *Proceedings of the International Conference on Fast Reactors and Related Fuel Cycles: Challenges and Opportunities,* International Atomic Energy Agency, 2009, p. 94; S. Raghupathy, "Status of Fast Reactor Programme in India," *Technical Meeting on Identify Innovative Fast Neutron Systems Development Gaps,* Vienna, Austria, 29 March 2012, www.iaea.org/NuclearPower/Downloads/Technology/meetings/2012-02-29-03-02-TM-FR/12_Raghupathy.pdf.

[272.] Because the PFBR design has a relatively low breeding ratio, it will not be producing excess plutonium in significant quantities. Therefore, the plutonium for the initial core as well as for the first few reloads has to come from reprocessing PHWR spent fuel. See Alexander Glaser and M. V. Ramana, "Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor," *Science and Global Security*, Vol. 15, 2007, pp. 85–105; J. Y. Suchitra and M. V. Ramana, "The Costs of Power: Plutonium and the Economics of India's Prototype Fast Breeder Reactor," *International Journal of Global Energy Issues,* Vol. 35, No. 1, 2011, pp. 1–23.

[273] Kalyan Ray, "India to Get Fast Breeder Reactor in September," *Deccan Herald,* 24 January 2014, www.deccanherald.com/content/382787/india-get-fast-breeder-reactor.html.

[274] M. V. Ramana and J. Y. Suchitra, "Slow and Stunted: Plutonium Accounting and the Growth of Fast Breeder Reactors," *Energy Policy,* Vol. 37, 2009, pp. 5028–36.

[275] M. V. Ramana, "India and Fast Breeder Reactors," S*cience and Global Security,* Vol. 17, No. 1, 2009, pp. 54–67; Ramana, *The Power of Promise*; S. Rajendran Pillai and M. V. Ramana, "Breeder Reactors: A Possible Connection between Metal Corrosion and Sodium Leaks," *Bulletin of the Atomic Scientists,* Vol. 70, No. 3, 2014, pp. 49–55.

[276] *Fast Breeder Reactor Programs: History and Status*, International Panel on Fissile Materials, 2010.

[277] Planning Commission, I*ntegrated Energy Policy: Report of the Expert Committee,* Planning Commission, Government of India, 2006, p. xxii.

[278] "PM Dedicates Tarapur Reprocessing Plant to Nation," *The Times of India*, 7 January 2011; Sanjay Jog, "India's Nuclear Capacity Could Jump Threefold by 2023–24: Modi," *Business Standard India*, 22 July 2014, www.rediff.com/business/report/indias-nuclear-capacity-could-jump-threefold-by-2023-24-modi/20140722.htm.

Chapter 6. Japan

[279] Japan Atomic Energy Commission, *Framework for Nuclear Energy Policy*, 11 October 2005, p. 33.

[280] The shipment to Europe ended in June 2001. *White Paper on Nuclear Energy 2003*, www.aec.go.jp/jicst/NC/about/hakusho/hakusho2003/23.pdf (in Japanese).

[281] See, for example, the classified cable dated 7 February 2007 from the U.S. embassy in Tokyo to the U.S Secretary of State, "Nuclear Terrorism Convention: 'Nudge' Could Help Japan Ratify; Physical Protection Concerns Remain." Paragraphs 6 and 7 read as follows:
"6. (C) On physical protection of nuclear facilities, MEXT's Hokugo and Kudo responded to U.S. questions about the presence of armed guards at Japanese nuclear facilities. They explained that the plant operator, local police and national police determine the threat for individual plants and the necessity for armed guards. Armed national police are present at certain nuclear power plants (NPPs) in Japan, but they do not guard all facilities and contract civilian guards are prevented by law from carrying weapons. Asked about the absence of armed guards at the Tokai-Mura facility, a major plutonium storage site, MEXT responded that an assessment of local needs and resources had indicated that there was not a sufficient threat to justify armed police at the site.
"7. (C) MEXT also responded to U.S. urgings to require pre-employment background investigations of all workers with access to sensitive areas at nuclear facilities. They noted that while some NPP [Nuclear Power Plant] operators voluntarily conduct such background checks on their own employees, requiring background investigations of all contractor personnel with access to NPPs would be very difficult. They added that the GOJ [Government of Japan] is constitutionally prevented from mandating such checks and wishes to avoid raising what is a deeply sensitive privacy issue for Japanese society. However, MEXT did admit that GOJ background investigations may be going on 'unofficially'." cablegatesearch.wikileaks.org/cable.php?id=07TOKYO805&version=1315488573
The U.S. recently obtained from Japan a commitment to ship to the United States, the U.S., UK and French origin plutonium and highly enriched uranium at the Japan Atomic Energy Agency's Tokai Fast Critical Assembly. See "Cooperation at Japan's Fast Critical Assembly," Fact Sheet, White House, Office of the Press Secretary 24 March 2014.

[282] *Fast Breeder Reactor Programs: History and Status*, International Panel on Fissile Materials, 2010, Table 4.1.

[283] Energy Research and Development Database (International Energy Agency), accessed July 2014.

[284] Japan Atomic Energy Commission, *Framework for Nuclear Energy Policy*, 11 October 2005, p. 29.

[285] Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, 12 April 2015, www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=357

[286] *Nuclear Intelligence Weekly*, 8 November 2013, p. 8.

[287] www.enecho.meti.go.jp/en/category/others/basic_plan/pdf/4th_strategic_energy_plan.pdf (provisional translation by the Ministry of Economics, Trade and Industry [METI]). This translation talks about "Monju prototype fast breeder reactor" the original Japanese version only mentions "Monju" without the modifying phrase, "fast breeder reactor".

[288] "Fast reactor research set with France," *Yomiuri Shimbun*, 29 April 2014. The fast neutrons in sodium-cooled reactors are more efficient than the slowed neutrons in water-cooled reactors in fissioning the non-fissile isotopes of the transuranic elements.

[289] www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/007/pdf/007_001.pdf (page 3) (in Japanese).

[290] www.aec.go.jp/jicst/NC/about/announce/siryo02.htm

[291] kakujoho.net/mox/mox.html#id5.

[292] www.aec.go.jp/jicst/NC/tyoki/siryo/tyoki_e/reference.htm

[293] 640 kg loaded into Genkai in March 2011 was unloaded unirradiated in March 2013.

[294] Pavel Podvig, "MOX fuel in Japan: Summary of shipments, use, and storage," International Panel on Fissile Materials Blog, 10 June 2014, fissilematerials.org/blog/2014/06/mox_shipments_to_japan.html; See also fissilematerials.org/blog/MOXtransportSummary10June2014.pdf. Quantities of plutonium loaded for each reactor from Japan Atomic Energy Commission, "The Current Situation of Plutonium Management in Japan", 16 September 2014. www.aec.go.jp/jicst/NC/iinkai/teirei/siryo2014/siryo31/siryo3.pdf (in Japanese). Links to sources of information on shipments may be found at kakujoho.net/ndata/pu_jp.html (in Japanese).

[295] Japan's stockpile of separated plutonium based on its annual declarations to the IAEA under the Plutonium Management Guidelines. For plutonium use data, see Table 1.

[296] ¥11.5 trillion (~$120 billion): ¥2.19 trillion capital cost as of 2012, JNFL, Oct. 2012, www.jnfl.co.jp/jnfl/establishment.html (in Japanese) plus ¥9.35 trillion estimated operating and decommissioning cost, Technical Subcommittee on Nuclear Power, Nuclear Fuel Cycle, etc. Data Sheet 1, 10 November 2011, slide 30, www.aec.go.jp/jicst/NC/about/kettei/seimei/111110_1_e.pdf. For comparison, the estimated cost of the first unit of the Mutsu dry storage facility in Aomori Prefecture, Japan, which has a capacity of 3,000 tons of spent fuel is ¥0.1 trillion (Recyclable Fuel Storage Company, www.rfsco.co.jp/about/about.html, in Japanese). On this basis, the cost for dry cask storage for the amount of spent fuel that would be reprocessed by the Rokkaho Reprocessing Plant operating at its full 800 tons/year capacity for its 40-year planned lifetime therefore would be about ¥1 trillion (~$10 billion).

[297] www.enecho.meti.go.jp/en/category/others/basic_plan/pdf/4th_strategic_energy_plan.pdf (provisional translation by METI).

[298] Japan Atomic Energy Commission, Framework for Nuclear Energy Policy, 11 October 2005, www.aec.go.jp/jicst/NC/tyoki/taikou/kettei/eng_ver.pdf, p. 33.

[299] Nuclear fuel cycle interim report of the JAEC's New Nuclear Policy Planning Council, 12 November 2004, www.aec.go.jp/jicst/NC/tyoki/sakutei2004/ronten/20041112.pdf (in Japanese). For an unofficial English translation, see "New Nuclear Policy-Planning Council Costings for Direct Disposal of Spent Nuclear Fuel," www.cnic.jp/english/topics/policy/chokei/disposalcost.html. See especially the summary table on the evaluation of the four scenarios, www.cnic.jp/english/topics/policy/chokei/longterm4scenarios.html.

[300] www.jnfl.co.jp/transport-schedule/recycle.html (in Japanese).

[301] This includes 5,628 tons of spent light water reactor fuel and 1,510 tons of gas cooled reactor fuel. See reply to Diet member Mizuho Fukushima from METI dated 16 January 2013; summary available at kakujoho.net/ndata/pu_jp.html (in Japanese). All of the high-level waste from France has been received. The cumulative total of high-level waste canisters received as of the end of February 2015 was 1574, including 264 of an expected 900 canisters from the United Kingdom, www.jnfl.co.jp/transport-schedule/high.html (in Japanese).

[302] Including spent fuel at the Fukushima Daiichi and Daiini Nuclear Power Plants as well as that at Japan's other nuclear power plants listed in Table 2, www.enecho.meti.go.jp/info/committee/kihonseisaku/7th/7th-1.pdf (in Japanese), p. 50.

[303] Japan Atomic Energy Commission, "The Current Situation of Plutonium Management in Japan," 16 September 2014. www.aec.go.jp/jicst/NC/iinkai/teirei/siryo2014/siryo31/siryo3.pdf (in Japanese). During 2013, the amount of separated plutonium allocated to Japan as a result of reprocessing of Japan's spent fuel in the United Kingdom increased by 2.3 tons although the physical reprocessing of Japan's LWR spent fuel in the United Kingdom had ended in 2004. According to Japan's Atomic Energy Commission, about one ton more will be allocated to Japan in the future. No additional allocations of plutonium are expected in France. Replies of the secretariat on 13 November and 1 December 2014 to questions from Diet member Tomoko Abe's office.

[304] This is also the case in Russia and the United Kingdom.

[305] IAEA, "Communication Received from Certain Member States Concerning their Policies Regarding the Management of Plutonium," INFCIRC/549/Add. 1, 31 March 1998.

[306] Joint Statement by the Leaders of Japan and the United States on Contributions to Global Minimization of Nuclear Materia, 24 March 2014, www.mofa.go.jp/dns/n_s_ne/page18e_000059.html 29 "National Progress Report, Japan," Nuclear Security Summit 2014, www.nss2014.com/sites/default/files/documents/national_progress_report.pdf

[307] "National Progress Report, Japan," Nuclear Security Summit 2014, www.nss2014.com/sites/default/files/documents/national_progress_report.pdf

[308] Federation of Electric Power Companies of Japan, "Plans for the Utilization of Plutonium to be Recovered at the Rokkasho Reprocessing Plant (RRP), FY2010," 15 March 2010, www.fepc.or.jp/english/news/plans/1203866_1696.html

[309] JNFL's April 11, 2014 modification of the MOX plant licensing application
www.jnfl.co.jp/press/pressj2014/20140411besshi.pdf

[310] The U.S. MOX fuel plant at Savannah River was originally to begin operating in 2007. In 2014, the contractors requested an extension of the deadline for completion to 2025. See *Agreement between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes and Related Cooperation* (2000) and Nuclear Regulatory Commission, "Shaw Areva MOX Services; Mixed Oxide Fuel Fabrication Facility," *Federal Register*, Vol. 79, No. 205, 23 October 2014, p. 63442. The United Kingdom completed its Sellafield MOX plant in 2001 but was only able to get it to operate at an average of one percent of its design capacity and abandoned the project in 2011 (see Chapter 9).

[311] www.jnfl.co.jp/press/pressj2014/pr141031-1.html

[312] At the Rokkasho Reprocessing Plant, 3.6 tons; at the Tokai Pilot MOX Fuel Fabrication Plant, 1.9 tons and at the Tokai Pilot Reprocessing Plant, 0.8 tons, JAEC, "The Current [end 2013] Situation of Plutonium Management in Japan," *op. cit.* 16 September 2014 (in Japanese).

[313] The Table does not include the Fukushima Daiichi and Fukushima Daini Nuclear Power Plants because they are not expected to operate again. See www.enecho.meti.go.jp/info/committee/kihonseisaku/7th/7th-1.pdf, p. 50; and www.meti.go.jp/committee/sougouenergy/denkijigyou/

genshiryoku/pdf/006_03_00.pdf, p. 9, (both in Japanese). Available capacity is the storage capacity minus space for one full core and one reload as of the end of Sep. 2014. Data from METI's Agency for Natural Resources and Energy. The figures for Tokai Daini include the dry-cask storage there.

[314] The METI table shows 1080 tons of spent fuel discharged per 16-month refueling cycle. Using the capacity factor for 2010 of 0.669 [Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, 12 April 2015, www.iaea.org/PRIS/WorldStatistics/ThreeYrsEnergy AvailabilityFactor.aspx] and an average ratio of heat to net electricity of 3.1 for the reactors in Table 2, also from the Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, 12 April 2015, www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=JP gives an average burnup of (38.11 GWe)x(3.1 Gwt/GWe)x0.669x(365 days/yr)/[(0.75 refueling cycle per yr)x(1080 tons per refueling cycle)] = 35.6 GWt-days/ton. In a meeting with a local group on 23 April 2013, Kyushu Electric Power Company said that, due to higher burnups, only 1/4, not 1/3, of the core would be changed in one 16-month refueling cycle, saga-genkai.jimdo.com/2013/04/24.

[315] "Japan may only be able to restart one-third of its nuclear reactors," *Reuters*, 1 April 2014.

[316] The increased capacity would accommodate 1034 additional PWR fuel assemblies, www.nsr.go.jp/activity/regulation/sekkei/data/GN_20130712_01.pdf.

[317] In 1994, the year after the commitment was made to Fukushima prefecture, the central government postponed the second reprocessing plant, committing only that a decision would be made on whether or not to construct it in 2010, Masafumi Takubo, "Wake Up, Stop Dreaming Reassessing Japan's Reprocessing Program," *Nonproliferation Review*, Vol. 15, 2008, p. 71. In 2005, with the Rokkasho Reprocessing Plant still not operating, the commitment was downgraded further in the JAEC's *Framework for Nuclear Energy Policy* to one of beginning to consider the subject of a second reprocessing plant in 2010. See Naoto Ichii Agency for Natural Resources and Energy, METI, "Experience on Reprocessing in Japan," *INPRO Dialogue Forum on Nuclear Energy Innovations: Multilateral Approaches to Sustainable Nuclear Energy Deployment – Institutional Challenges*, 4–7 October 2010, Vienna, Austria.

[318] 6375 BWR spent fuel assemblies, "Concerning the safety of removing the spent fuel from Unit 4 etc. of Fukushima Daiichi," TEPCO, 24 January 2013, http://www.nsr.go.jp/data/000050822.pdf, p. 1. The original weight of low-enriched uranium in each assembly was about 0.17 tons. See "Overview of the Fukushima Daiichi Facilities," www.tepco.co.jp/nu/f1-np/intro/outline/outline-j.html (in Japanese).

[319] criepi.denken.or.jp/result/event/seminar/2010/issf/pdf/6-1_powerpoint.pdf.

[320] "Concerning the safety of removing the spent fuel from Unit 4 etc. of Fukushima Daiichi," *op. cit.*

[321] As of December 2014 there were 28 casks in the area. The downloading to the common pool of fuel from the unit #4 pool about which the safety concern had been the greatest started in November 2013 and ended on 22 December 2014, www.tepco.co.jp/decommision/planaction/removal/index-j.html (in Japanese). 180 fresh fuel assemblies were transferred to the unit #6 pool instead of the common pool due to a shortage of casks to move spent fuel from that pool. See meeting records of 19 June 2014 at www.nsr.go.jp/disclosure/meeting/FAM/201406.html (in Japanese).

[322] criepi.denken.or.jp/result/event/seminar/2010/issf/pdf/6-2_powerpoint.pdf.

[323] "Inspection of Fuel Cladding and Metal Gasket in Metallic Dry Cask at Tokai Daini Power Station," *International Conference on Management of Spent Fuel from Nuclear Power Reactors 2010,* Vienna, www-ns.iaea.org/meetings/rw-summaries/vienna-2010-mngement-spentfuel.asp.

[324] "Further developments re spent-fuel storage facility," Citizens Nuclear Information Center, News Watch 101, July/August 2004, www.cnic.jp/english/newsletter/nit101/nit101articles/nw101.html.

[325] www.nsr.go.jp/kaiken/data/20120919sokkiroku.pdf (in Japanese).

[326] "Anzensei Takameru Imide Kanshiki Chozo Hitsuyo," *Shizuoka Shimbun*, 5 March 2013, blogs.yahoo.co.jp/hamaokagenpatunet/65962011.html (in Japanese); "Kanshiki Chozo ga Joken," *Shizuoka Shimbun*, 1 November 2013, www.at-s.com/news/detail/828835188.html (in Japanese). There are unique circumstances in the Hamaoka case in that, in December 2008 Chubu Electric Power Co. announced its plan to construct a dry cask storage facility as a part of a plan to replace the shutdown Units 1 and 2 with a new Unit 6. The original plan was to start the operation of dry cask storage with a capacity for 4000 assemblies (700 tons) in fiscal year (FY) 2016. Because of this background, there existed in Shizuoka Prefecture more acceptance of dry cask storage than in other prefectures. The local communities and anti-nuclear power groups generally share the governor's view of the safety benefits and are demanding early construction of the facility. On 11 May 2012, a local NGO, Fujinokuni Hamaoka Genpatsu wo Kangaerukai [Fuji society to think about Hamaoka nuclear power plant] sent a letter to the governor, based on a discussion in a symposium it held in Shizuoka city on 7 April 2012, proposing that the Chubu Electric Company "construct a dry cask storage facility that can cool spent fuel not by water but by air and transfer spent fuel there" stophamaokanuclearpp.com/blog/?p=16119. The company applied to NRA for the construction of the drycask falicty to hold 400 tons of spent fuel with the planned beginning of the use in FY2018. See www.chuden.co.jp/corporate/publicity/pub_release/press/__icsFiles/afieldfile/2015/01/26/150126.pdf.

[327] https://www.nsr.go.jp/data/000048183.pdf.

[328] *Ibid*.

[329] www1.saga-s.co.jp/news/saga.0.1194366.article.html;
www.nishinippon.co.jp/feature/energy_kyushu/article/16358.

[330] www.saga-s.co.jp/news/saga/10101/135453.

[331] www.meti.go.jp/press/2014/04/20140411001/20140411001-1.pdf (in Japanese).

[332] "Japan eyes switch to dry storage of spent nuclear fuel," *Nikkei Asian Review,* 20 June 2014, asia.nikkei.com/Tech-Science/Tech/Japan-eyes-switch-to-dry-storage-of-spent-nuclear-fuel.

[333] JAEC's Long-Term Plan of 1987 pointed out the need for interim storage capacity and the Japanese government made a decision in 1997 to have off-site interim storage capacity by 2010, "Wake Up, Stop Dreaming," *op. cit*. Material accompanying the JAEC's 2005 *Framework for Nuclear Energy Policy* stated that, even with a policy of reprocessing all of Japan's spent fuel, three to six offsite interim storage facilities such as that at Mutsu would be required by 2050.

[334] Osamu Tochiyama, chair of METI's technical working group on waste disposal and Director of the Radioactive Waste Disposal Safety Research Center at the Nuclear Safety Research Association, quoted in Daisuke Yamada, "As I See It: Gov't needs to look at options on handling, disposal of radioactive waste," *Mainichi*, 1 May 2014.

Chapter 7. South Korea

[335] Two of South Korea's reactors, Hanul 1 and 2, are of French design.

[336] Japan Atomic Energy Commission, *Framework for Nuclear Energy Policy*, 11 October 2005, p. 33.

[337] Reactors from Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, 30 March 2015, www.iaea.org/pris/CountryStatistics/CountryDetails.aspx?current=KR. Stored spent fuel and storage capacity at Kori, Hanul, Hanbit, and Wolsong; communication from Korea Hydro and Nuclear Power to Jungmin Kang, Visiting Professor, Korea Advanced Institute of Science and Technology, August 2014. Capacity numbers shown do not include space reserved for one full core emergency discharge. Projections based on an assumed thermal to electric power conversion efficiency of 1/3, nuclear power plants operating at an average of 90 percent capacity, and average spent fuel burnups for LWR and heavy water reactor (HWR) fuel of 38.4 and 6.9 GWt-days

per ton heavy metal (GWd/tHM) respectively. Years when full are roughly consistent with those from an official report in which the pools at Kori, Hanbit, Hanul and Wolsong were projected to be full by 2029, 2025, 2029 and 2026, respectively, Korea Radioactive Waste Management Corporation, *Alternatives and Roadmap of Spent Fuel Management in South Korea,* final report, prepared by the Korean Nuclear Society, Korean Radioactive Waste Society and Green Korea 21, August 2011 (in Korean).

[338] Because of safety concerns, we do not favor dense racking spent fuel but it is being done in South Korea and many other countries. For more details on the safety issues, see Robert Alvarez, Jan Beyea, Klaus Janberg, Jungmin Kang, Ed Lyman, Allison Macfarlane, Gordon Thompson and Frank N. von Hippel, "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States," *Science and Global Security*, Vol. 11, 2003, pp. 1–51.

[339] A 2008 analysis by KNHP projected that the spent fuel storage at the Kori, Hanbit and Hanul would be full as 2016, 2021 and 2018 respectively. Re-racking was assumed in the spent fuel pools of some reactors but not in others, Ki-Chul Park, "Status and Prospect of Spent Fuel Management in South Korea," *Nuclear Industry*, August 2008 (in Korean).

[340] The above history from Young-Hee Lee, "Management of High-Level Nuclear Waste and Politics of Expertise: the Case of Korea," *Economy and Society*, Vol. 85, 2010, pp.67–92 (in Korean, translated by the author). An English Powerpoint dated 5 August 2014 is available at www.slideshare.net/hkano/sfreprocessing-gensuikinrev2. See also Park Seong-won, Miles A. Pomper, and Lawrence Scheinman, "The Domestic and International Politics of Spent Nuclear Fuel in South Korea: Are We Approaching Meltdown?" Korea Economic Institute Academic Paper Series, March 2010.

[341] Ji Bum Chung and Hong-Kyu Kim, "Competition, economic benefits, trust, and risk perception in siting a potentially hazardous facility," *Landscape and Urban Planning* Vol. 91, 2009, pp. 8–16.

[342] "S. Korea completes construction of first nuclear waste repository," Yonhap News Agency, 13 July 2014, english.yonhapnews.co.kr/national/2014/07/11/75/0302000000AEN20140711007500320F.html.

[343] *Pyroprocessing Technologies: Recycling Used Nuclear Fuel for a Sustainable Future*, Argonne National Laboratory, undated, www.cse.anl.gov/pdfs/pyroprocessing_brochure.pdf.

[344] *See National Energy Policy: Report of the National Energy Policy Development Group*, May 2001, p. 85. On 3 July 2014, during a briefing of South Korea's Public Engagement Commission on Spent Fuel Management, Dr. Chang confirmed to Frank von Hippel that he had briefed the Cheney group on pyroprocessing.

[345] *Nonproliferation Impact Assessment for the Global Nuclear Energy Partnership Programmatic Alternatives*, National Nuclear Security Administration, December 2008.

[346] "Proliferation Risk Reduction Study of Alternative Spent Fuel Processing Technologies," BNL-90264-2009-CP, 2009, co-authored by analysts from Argonne, Brookhaven, Idaho, Los Alamos, Pacific Northwest and Sandia National Laboratories.

[347] According to KAERI, "its [pyroprocessing's] proliferation resistance has been internationally recognized due to the impossibility to recover plutonium," www.kaeri.re.kr:8080/english/sub/sub04_03.jsp, accessed 13 April 2015. According to Yoon Il Chang, the "IEAL study concluded that 'there is no valid basis for concern that the development and demonstration of the IFR [Integral Fast Reactor, including pyroprocessing] will be prejudicial to U.S. nonproliferation interests," presentation to South Korea's Public Engagement Commission on Spent Nuclear Fuel Management (PECOS), 3 July 2014. IEAL [International Energy Associates Limited] was a consulting group that did a study on the subject for Argonne National Laboratory in 1986.

[348] Park Seong-won, Miles A. Pomper, and Lawrence Scheinman, "The Domestic and International Politics of Spent Nuclear Fuel in South Korea" *op. cit.*

[349] The logic appears to be that, in the past, the United States agreed to R&D on KAERI's DUPIC [Direct Use of spent Pressurized water reactor fuel in CANDU heavy water reactors] program in which the

cladding would be removed from spent light water reactor fuel and the fuel pellets would then be heated, oxidized and turned into a powder that would be fabricated into fuel for South Korea's heavy water reactors, Myung Seung Yang et al., "The Status and Prospect of Dupic Fuel Technology," *Nuclear Engineering and Technology*, Vol.38, No.4, 2006, p. 359. DUPIC eventually was abandoned due to lack of interest on the part of South Korea's nuclear power plant operator, Korea Hydro and Nuclear Power Company. Based on a comparison with DUPIC, KAERI apparently convinced the U.S. negotiators that metallization of light water reactor spent fuel would pose no greater proliferation dangers than DUPIC.

[350] Min-Ho Baek et al., "Trade-off study on the power capacity of a prototype SFR [Sodium-cooled Fast Reactor] in Korea," PHYSOR 2012 – Advances in Reactor Physics, Knoxville, Tennessee, 15–20 April 2012.

[351] Won Il Ko and Eun-ha Kwon, "Implications of the new National Energy Basic Plan," *Energy Policy,* Vol. 37, 2009, pp. 3484–88.

[352] KAERI's total budget in 2010 was about $263 million and pyroprocessing and sodium-cooled fast reactor R&D was one of five identified priority areas, Jeong Kong Lee, "Overview of KAERI Activities," 31 March 2011.

[353] Park Seong-won, Pomper and Scheinman, "The Domestic and International Politics of Spent Nuclear Fuel in South Korea," *op. cit.*

[354] *Ibid.*

[355] Ko and Kwon, "Implications of the new National Energy Basic Plan for nuclear waste management in Korea," *op. cit.*

[356] sedac.ciesin.columbia.edu/data/set/grump-v1-population-density/maps/7

[357] Park Seong-won, Pomper and Scheinman, "The Domestic and International Politics of Spent Nuclear Fuel in South Korea," *op. cit.*

[358] *Disposal of Radioactive Waste*, International Atomic Energy Agency, 2011, para. 3.20.

[359] For a discussion of PECOS, see Doo-Seung Hong, "Status and Prospects of Public Engagement Commission on Spent Nuclear Fuel Management," 25 June 2014; and Jungmin Kang, "South Korea in focus: The Politics of Spent Fuel Storage and Disposal," *Bulletin of the Atomic Scientists*, May/June 2011.

[360] "View on issues of public engagement of spent fuel management,14 October 2014 (in Korean).

[361] Jungmin Kang, Seoc-Woo Kim, and Byong-Chul Lee, "Hot potato in South Korea: The spent nuclear fuel storage dilemma," *Bulletin of the Atomic Scientists*, Vol. 71, No. 3, 2015, pp. 76-83.

[362] Frank von Hippel, "South Korean Reprocessing: An Unnecessary Threat to the Nonproliferation Regime," *Arms Control Today*, March 2010.

Chapter 8. Russia

[363] Federal Target Program (FTP) No. 605 "Development of Russia's Nuclear Power Industry in 2007–2010 and further to 2015," fcp.vpk.ru/cgi-bin/cis/fcp.cgi/Fcp/ViewFcp/View/2008/227. This has been replaced by the "Program of the State Atomic Energy Corporation 'Rosatom' activity for the long term period (2009–2015)" (Program 2008), www.government.ru/content/governmentactivity/rfgovernmentdecisions/archive/2008/09/20/9565546.htm; and the FTP "The new generation for nuclear power technologies for the period 2010–2015 and further to 2020" (in the edition from 01.03.2011, No. 135), adopted by the decision of the RF government from 3 February 2010, No. 50 (Program 2010), federalbook.ru/files/TEK/Soderzhanie/Tom%209/III/Programma.pdf.

[364] "Program of creation of infrastructure and spent fuel management for 2011–2020 and until 2030,"

www.rosatom.ru/resources/f4c962804b1b97c38ae09fa6d2e38703/progr_oyt_04_04_2012_yrb.pdf.

[365.] In this chapter, a conversion rate of 31 rubles per dollar is used. Since the spring of 2014, the value of the ruble has dropped by approximately half compared to the dollar.

[366.] The program also includes creation of infrastructure for dealing with the spent fuel of the AMB prototype water-cooled graphite-moderated reactors (Beloyarsk 1 and 2, respectively). AMB-100 operated from 1964 to 1983 and AMB-200 from 1967 to 1988. Half of the fuel in the AMB-200 melted down in 1977 and the reactor had a fire in 1978.

[367.] The numerical suffix on Russian reactor-type designations is the gross electrical power output. The net output is 5 to 10 percent less.

[368.] "The authorization for finishing the reconstruction of the 'wet' spent-fuel storage facility at the MCC has been signed," Nuclear.ru, 18 August 2011, www.nuclear.ru/news/74808/?sphrase_id=50374 (in Russian).

[369.] "Program of creation of infrastructure and spent fuel management for 2011 – 2020 and until 2030," *op. cit.*

[370.] "Certification of the completion of the construction NSF dry storage facility at MCC signed," www.nuclear.ru/news/74817/?sphrase_id=50375 (in Russian).

[371.] "24 containers of the spent fuel to be removed from Leningradskaya NPP during this year," nuclear.ru/news/75027/; "Kursk NPP ready to ship ten containers of spent fuel to MCC," nuclear.ru/news/88854/ (both in Russian).

[372.] M. Baryshnikov, "Main Principles of the Perspective System of SNF Management in Russia," VII International Forum AtomEco 2013, October 2013, Moscow, www.atomeco.org/mediafiles/u/files/Prezentetion_31_10_2013/Baryshnikov.pdf

[373.] *Ibid*; See "In year 2013 the reprocessing of RBMK spent fuel will start at Mayak," www.nuclear.ru/news/74794/?sphrase_id=50376 (in Russian).

[374.] E. Makarov, "Current state of the SNF reprocessing in Russia," www.atomeco.org/mediafiles/u/files/Present12/Makarov.ppt

[375.] E. Makarov, "Current state of the SNF reprocessing in Russia," www.atomeco.org/mediafiles/u/files/Present12/Makarov.ppt

[376.] IAEA, *Communication Received from the Russian Federation Concerning its Policies Regarding the Management of Plutonium,* INFCIRC/549/Add.9/15, 23 May 2014.

[377.] The data in this Table are estimated based on V.I. Kalinkin at al, "Storage of power-reactor spent nuclear fuel," preprint VNIPIET, S.Peterburg, 2009; and the *Third National Report of the Russian Federation in compliance with the obligations of the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management,* Moscow, 2011. Reactor dates and net power from IAEA, Power Reactor Information System.

[378.] V.I. Kalinkin at al, "Storage of power-reactor spent nuclear fuel," *op. cit.*

[379.] E. Makarov, "Current state of the SNF reprocessing in Russia" *op. cit.*

[380.] A*greement between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes and Related Cooperation,* as amended in 2010.

[381.] "BN-800 Fast Reactor to Reach Criticality in April 2014," International Panel on Fissile Materials Blog, 26 December 2013, fissilematerials.org/blog/2013/12/bn-800_fast_reactor_to_re.html.

[382] "The USSR-Russia Fast-neutron Reactor Program" by Gennadi Pshakin in *Fast Breeder Reactor Programs: History and Status*, International Panel on Fissile Materials, 2010.

[383] Government of RF Decision No. 50, 3 February 2010 on the Federal Targeted Program, "The new generation for nuclear power technologies for the period 2010 – 2015 and further to 2020," Resolution of the Government of the Russian Federation, 31 August 2013, No. 762, fcp.economy.gov.ru/cgi-bin/cis/fcp.cgi/Fcp/ViewFcp/View/2011/298/?yover=2013; and federalbook.ru/files/TEK/Soderzhanie/Tom%209/III/Programma.pdf (both in Russian).

[384] Konstantin Pukemov, "Rosatom creates reactors fueled from spent fuel", *Izvestia*, 6 August 2012 (in Russian).

[385] Based on BN-800 NPP, Atomenergoprojekt, 2011, p. 10, atomproekt.com/activitycategories/generation/projects_with_reactors_bn/ (in Russian).

[386] "The experimental-demonstration BREST-300 reactor will be located at SCC site," www.nuclear.ru/news/73028/?sphrase_id=50379 (in Russian).

[387] "Liquid metal facility 'SPRUT' is launched at the IPPE," www.atominfo.ru/news8/h0984.htm (in Russian).

[388] B. Nigmatulin, "Russia's Nuclear Power: Reality, challenges and illusions," *ProAtom*, 4 February 2012, http:/www.proatom.ru/modules.php?name=News&file=article&sid (in Russian).

[389] IPPE is responsible for working out the technical specifications for the reactor, the general designer of the reactor is VNIPIET, and EDO "Gidropress" is responsible for construction. See "Rosatom is a global technological leader," Rosatom Department for Communications, 7 June 2012.

[390] The positive conclusion for construction of SVBR-100 is received from of the State General Expertise. nuclear.ru/news/89628/ (in Russian).

[391] "SVBR-100: Lead-bismuth's big spurt," nuclear.ru/opinions/65471/?sphrase_id=27550= (in Russian).

[392] "The total cost of the project for construction of SVBR-100 increased up to 36 Bln Rubbles," nuclear.ru/news/93666/ (in Russian).

[393] O. Saraev, "RF could built the serial fast neutron unit in 2019," www.atominfo.ru/news/air8059.htm (in Russian).

[394] "OKBM is planning to complete the technical project of BN-1200 reactor in 2014," ria.ru/atomtec_news/20140204/993001614.html (in Russian).

[395] NIW, "Russia," *Nuclear Intelligence Weekly*, 25 July 2014; "The procedure of environmental impact related with construction of the unit No. 5 at the Beloyarskaya NPP is begun," www.nuclear.ru/news/72504/ (in Russian).

[396] "Fast reactor starts clean nuclear energy era in Russia," rt.com/news/168768-russian-fast-breeder-reactor/; and www.nuclear.ru/rus/press/nuclearenergy/2131779/ (both in Russian).

[397] "MCC: The last batch of irradiated uranium rods is shipped for reprocessing," 6 March 2012, nuclear.ru/news/74858/?sphrase_id=33156 (in Russian).

[398] "Commission has began work on acceptance of the MOX production plant into operation," nuclear.ru/news/94368/ (in Russian). Gary Peach, " MOX Fuel Plant Ready for Launch," *Nuclear Intelligence Weekly,* 1 December 2014.

[399] "The modernization of the MOX fuel production complex at the NIIAR is completed," www.nuclear.ru/news/67592/?sphrase_id=50386 (in Russian).

[400] "Breakthrough in future," *Strana-Rosatom*, Vol. 07, No. 52, March 2012, pp. 8–9 (in Russian).

[401] "Test of assemblies with dense fuel will begin at Beloyarsk in September," 29 March 2013, www.nuclear.ru/news/67495/?sphrase_id=50387 (in Russian).

[402] The FTP "The new generation for nuclear power technologies for the period 2010 – 2015 and further to 2020", (in the edition from 01.03.2011, No. 135), adopted by the decision of the RF government from February 3, 2010 No. 50, See Program 2010). federalbook.ru/files/TEK/Soderzhanie/Tom%209/III/Programma.pdf (in Russian).

[403] "The approval of state expertise for the ODC project on recycling of SNF is obtained," 17 September 2013; nuclear.ru/news/75138/?sphrase_id=33141 (in Russian).

[404] P. Gavrilov, "Technological perspectives of nuclear fuel cycle closure," presentation at the International conference "AtomEco-2011", Moscow, 31 October – 1 November, 2011.

[405] "The test of the ODC equipment is starting at the MCC," www.nuclear.ru/news/74866/?sphrase_id=50388 (in Russian).

[406] This would be a second attempt to complete an RT-2 reprocessing plant at this site. Construction of the first design, with a capacity of 1500 tons per year was begun in 1976 but was halted in 1990 for lack of funding. The only portion completed was the spent fuel intake pool that is currently being used for interim storage. See Thomas B. Cochran, Robert S. Norris, and Oleg A. Bukharin, *Making the Russian Bomb: From Stalin to Yeltsin*, Westview Press, 1995, pp. 153 – 156.

[407] "Approval of the ODC project for reprocessing of spent nuclear fuel by Russia's Glavgosekspertizy is obtained," www.nuclear.ru/news/75138/?sphrase_id=50393; "MCC starts debugging of the technology at the ODC with the usage of real fuel," www.nuclear.ru/news/75131/?sphrase_id=50394 (both in Russian).

[408] "NIIAR: Construction of a new radiochemical complex will begin in December of 2013," www.nuclear.ru/news/67507/?sphrase_id=50395 (in Russian).

[409] Program 2010, federalbook.ru/files/TEK/Soderzhanie/Tom%209/III/Programma.pdf (in Russian). According to Program 2010, design decisions for a full-scale pyrochemical reprocessing unit are to be made during the period 2015 – 2020.

[410] "Breakthrough in future," *Strana-Rosatom*, Vol. 07, No. 52, March 2012, pp. 8 – 9 (in Russian).

[411] "250 mln rubles wired to the SCC in the frame of creation of complex for nitride fuel production," www.nuclear.ru/news/66384/?sphrase_id=50396 (in Russian).

[412] V. Asmolov, "VVER LWR should be ready for MOX usage," presentation at the eighth international conference "Safety, efficiency and economy of nuclear power," Moscow, 23 – 25 May, 2012. mntk.rosenergoatom.ru/mediafiles/u/files/SbornikTezisovMNTK2012.pdf

[413] The general designer of the VVER-TOI is Atomenergoproect, but Gidropress, the Design Branch of Rosenergoatom, and the Kurchatov Institute are also involved, "The serial project of VVER-TOI will be presented to the world market in 2013," 23 January 2012. See www.nuclear.ru/news/72035/?sphrase_id=50400 (in Russian).

[414] O. Saraev, "Perspective of the development and implementation of the closed fuel cycle," presentation at conference on "Safety, efficiency and economy of nuclear power," Moscow, 23 – 25 May 2012.

[415] Another way to deal with plutonium that has been proposed is multiple recycling of plutonium in light water reactors. Yu. Fedorov, "The possibility of solving of spent nuclear fuel management with the use of multiple recycling of the REMIX-type fuel in light water reactors," presentation at the Atom-Eko conference, Moscow, 16 – 17 October, 2012.

[416] E. Kudryavtsev, A. Khaperskaya, and V. Smirnov, "Development of the Spent Fuel Management Infrastructure in the Russian Federation," *IAEA International Conference on Management of Spent Fuel from Nuclear Power Reactors*, International Atomic Energy Agency, Vienna, Austria31 May to 4 June 2010.

[417] The hearing on creation of underground laboratory for HLW was held in Zheleznogorsk. www.nuclear.ru/rus/press/oyatrao/2127238/ (in Russian).

Chapter 9. United Kingdom

[418] M. Forwood *The legacy of reprocessing in the United Kingdom*, IPFM Research Report No. 5, International Panel on Fissile Materials, 2008, p. 3.

[419] Forwood, *op. cit.*, p. 3

[420] The United Kingdom produced a total of 4 tons of weapon-grade plutonium, *Global Fissile Material Report 2010: Balancing the Books, Production and Stocks*, International Panel on Fissile Materials, 2010, Chapter 5.

[421] For a history, authored by BNFL, of the justifications for reprocessing Magnox fuel, see Radioactive Waste Management Advisory Committee collections, collections.europarchive.org/tna/20080727101330/defra.gov.uk/rwmac/

[422] W. Patterson, "Fast breeder reactors in the United Kingdom," in *Fast breeder reactors: history and status,* International Panel on Fissile Materials, 2010, pp. 73–88.

[423] Forwood, *op. cit.*, p.6.

[424] J. Parker, *Windscale Inquiry Report*, Her Majesty's Stationery Office, 1978.

[425] "21 Today. Sellafield's THORP reprocessing plant — A Lame Duck and Loser," Cumbrians Opposed to a Radioactive Environment, 26 March 2015, www.no2nuclearpower.org.uk/wp/wp-content/uploads/2015/03/Briefing-THORP-21.pdf.

[426] Forwood, *op. cit.*, p. 9

[427] G. MacKerron, *Evaluation of nuclear decommissioning and waste management,* Report commissioned by the UK Secretary of State for Energy and Climate Change, March 2012, pp. 47–48.

[428] The *economic and commercial justification for THORP,* British Nuclear Fuels, July 1993, p. 2.

[429] M. Sadnicki, F. Barker and G. MacKerron, *THORP: the case for contract re-negotiation*, Friends of the Earth, 1999, p. xv.

[430] Forwood, *op. cit.* p. 10.

[431] WISE, *Nuclear Monitor*, No. 690, 26 June 2009, pp. 1–3.

[432] *Consultation on the management of foreign origin nuclear fuels held in the UK,* UK Department of Energy and Climate Change, 2014, www.gov.uk/government/uploads/system/uploads/attachment_data/file/285882/overseas_fuels_consultation.pdf

[433] Patterson, *op. cit.*, pp. 73–76.

[434] The definitive paper t hat argued this came from D. Finon, "Fast breeder reactors: the end of a myth," *Energy Policy,* Vol. 10, No. 4, 1982, pp. 305–321.

[435] For an overview of the technical problems of fast breeders that have led to poor performance, see F. von Hippel, "Overview: the rise and fall of plutonium breeder reactors," in *Fast breeder reactors: history and status*, International Panel on Fissile Materials, 2010.

[436] Royal Commission on Environmental Pollution, *Nuclear power and the environment*, 6th report, Her Majesty's Stationery Office, London, 1976.

[437] C. M. Buckley, G. MacKerron, and A. J. Surrey, "The International Uranium Market," *Energy Policy,* Vol. 8, No. 2, June 1980, pp. 84–104.

[438] Patterson, *op. cit.* p. 87.

[439] See also the discussion of this issue in M. Schneider and Y. Marignac, *Spent nuclear fuel reprocessing in France*, International Panel on Fissile Materials, 2008, Chapter VI.

[440] Matthew Bunn, "The economics of MOX fabrication" in *Nuclear reprocessing: has it a future?* Oxford Research Group, Current Decisions Report No. 22, 1999, pp. 42-45.

[441] IAEA, *Communication Received from the United Kingdom of Great Britain and Northern Ireland Concerning its Policies Regarding the Management of Plutonium*, INFCIRC/549/Add.8/17, International Atomic Energy Agency, 15 August 2014.

[442] There was an early conviction that all AGRs might use MOX, followed by the view that only the two newest among the AGRs might be suitable, followed by a final view that none of the AGRs were candidates for MOX use. See *BNFL National Stakeholder Dialogue plutonium working group final draft Report,* The Environment Council, November 2002 for the evolution of this argument.

[443] Rob Broomby, "Hinkley firm denies fuel claim," *BBC News*, 6 November 2013, www.bbc.co.uk/news/science-environment-24834932.

[444] T. Morris and N. Malhotra, *BNFL and the restructuring of the nuclear industry:1997–2009*, Oxford Centre for Corporate Reputation, January 2011, pp. 19–26.

[445] Forwood, *op. cit.* p. 13.

[446] IAEA, *Communication Received from the United Kingdom of Great Britain and Northern Ireland Concerning its Policies Regarding the Management of Plutonium,* INFCIRC/549/Add.8/17, International Atomic Energy Agency, 15 August 2014.

[447] *Management of the UK's plutonium stocks: a consultation on the long-term management of UK owned civil separated plutonium,* UK Department of Energy and Climate Change, 7 February 2011.

[448] UK National Audit Office, *Department of Energy: Monitoring and control of British Nuclear Fuels plc* 295, Her Majesty's Stationery Office, 5 April 1989, pp. 14–18.

[449] National Audit Office, *op. cit.* p. 16.

[450] *Our energy future — creating a low carbon economy*, UK Department of Trade and Industry, Cm 7561, February 2003, pp. 61– 62.

[451] OSPAR Commission *Radioactive substances* 2014, 7 October 2014, www.ospar.org/content/content.asp?menu=00220306000000_000000_000000.

[452] British Energy *Annual Report and Accounts 1997/98* p. 4 and the same company answering questions from the UK House of Commons Select Committee on Environment Food and Rural Affairs, November 2001, following its *Memorandum submitted by British Energy* to that committee.

[453] UK Department of Trade and Industry, *Managing the Nuclear Legacy*, 2002 pp. 45–46

[454] Morris and Malhotra, *op. cit.*, pp. 28 –29.

[455] Department of Trade and Industry, 2003, *op. cit.* Chapter 3, pp. 25– 36.

[456] *BNFL confirms Magnox station lifetimes,* 23 May 2000, www.uea.ac.uk/~e680/energy/energy_links/nuclear/bnfl_closure.htm.

[457] *UK Strategy for Radioactive Discharges 2001– 2020*, Department for Environment, Food and Rural Affairs, 2002.

[458] NDA, Oxide Fuels: Preferred Option, Nuclear Decommissioning Authority, June 2012, p. 6.

[459] NDA, Oxide Fuels: Credible Options, Nuclear Decommissioning Authority, November 2011, p. 2.

[460] NDA, Oxide Fuels: Credible Options, 2011, p. 17.

[461] NDA, Oxide Fuels: Credible Options, 2011, Figure 1 p. 8.

[462] See Broomby, op. cit. 2013.

[463] It was, for example, suggested by President Bill Clinton's Science Advisor, Jack Gibbons, to his UK counterpart, William Waldegrave, in a telephone conversation in November 1993 even before THORP became operational and contaminated in 1994; Frank von Hippel, personal communication.

[464] NDA, *Oxide Fuels: Preferred Option*

[465] Royal Society, *Fuel Cycle Stewardship in a Nuclear Renaissance*, 2011, p. 66. The report also takes for granted that separated plutonium should be fabricated into MOX.

[466] *Towards a Low Carbon Pathway for the UK*, Smith School of Enterprise and the Environment, Oxford University, 2012.

[467] *Consultation on the management of overseas origin nuclear fuels held in the UK,* Department of Energy and Climate Change (DECC), 3 March 2014.

[468] These dates are contained in *The Magnox Operating Programme (MOP9)*, Nuclear Decommissioning Authority, 2012, www.nda.gov.uk/publication/the-magnox-operating-programme-mop9-july-2012/

[469] Personal communication from Martin Forwood, 16 April 2015, based on Freedom of Information response from the NDA, 11 November 2014.

[470] Frank von Hippel and Gordon MacKerron, *Alternatives to MOX: Direct-disposal options for stockpiles of separated plutonium*, International Panel on Fissile Materials, 2015.

[471] *Progress on Approaches to the Management of Separated Plutonium – Position Paper,* Nuclear Decommissioning Authority, January 2014. p. 6. In fact, both EDF and Horizon, the two most active potential developers of nuclear reactors in the United Kingdom, have publicly declared their strong opposition to MOX use, Rob Broomby, *op. cit.*

[472] NDA, Progress on Approaches to the Management of Separated Plutonium, op. cit. p. 7

[473] NDA, *Ibid*, pp. 9–10.

[474] *Managing the Nuclear Legacy,* UK Department of Trade and Industry, 2002, Figure 1, p. 18

[475] NDA, *Annual Report and Accounts 2013/2014*, Nuclear Decommissioning Authority, p. 13.

[476] NDA, *Annual Report and Accounts 2013/2014*, p. 11 and p. 14. Putting the 2002 liabilities on the same price basis as those for 2013/4 puts the 2002 figure for Sellafield liabilities at £39.3 billion, using data from the UK office for National Statistics for the retail price index. At first sight this suggests that the liability estimate has more or less doubled between 2002 and 2014 (£39.3 billion against £79.1 billion). However, because the Nuclear Decommissioning Authority has spent over £10 billion on Sellafield since 2005, this number should be added to the £79.1 billion in 2014 to allow a more direct comparison between the 2002 and 2014 estimates.

[477] NDA, A*nnual Report and Accounts 2013/2014*, p. 14.

Chapter 10. Transmutation

[478] Jungmin Kang and Frank von Hippel, "Limited Proliferation-Resistance Benefits from Recycling Unseparated Transuranics and Lanthanides from Light-Water Reactor Spent Fuel," *Science and Global Security,* Vol. 13, 2005, pp. 169–181.

[479] From J. Boulton, ed., *Management of Radioactive Fuel Wastes: The Canadian Disposal Program,* Atomic Energy of Canada Research Company, AECL-6314, 1978, Figure 6, adapted by Canadian Nuclear FAQ, www.nuclearfaq.ca, a public-domain website. For the analogous figure for light water reactor

fuel see *Implications of Partitioning and Transmutation in Radioactive Waste Management*, International Atomic Energy Agency, 2004, figure 1.

[480] Even taking into account the plutonium that would have been produced in the low-enriched uranium fuel that otherwise would have been used. See *Plutonium Fuel: An Assessment,* Nuclear Energy Agency, OECD, 1989.

[481] See, for example, Shwageraus, E., P. Hejzlar, and M. S. Kazimi, "A Combined Nonfertile and UO_2 PWR Fuel Assembly for Actinide Waste Minimization," *Nuclear Technology,* Vol. 149, 2005, pp. 281–303.

[482] *Nuclear Wastes: Technologies for Separations and Transmutation,* National Academy Press, 1996, Figure 4–2 and Table 4–3.

[483] *Ibid.,* p. 66.

[484] "Planning Act No. 2006–739 of 28 June 2006 Concerning Sustainable Management of Radioactive Materials and Waste," www.andra.fr/download/andra-international-en/document/editions/305cva.pdf

[485] ASTRID: Advanced Sodium Technological Reactor for Industrial Demonstration.

[486] World Nuclear Association, "Fast Neutron Reactors," 16 March 2015, www.world-nuclear.org/info/Current-and-Future-Generation/Fast-Neutron-Reactors/.

[487] MYRRHA: Multipurpose Hybrid Research Reactor for High-tech Applications.

[488] myrrha.sckcen.be/en/MYRRHA/Applications and Friederike Frieß, Physics Department, Technische Universität Darmstadt, personal communication, August 2014.

[489] www.enecho.meti.go.jp/committee/council/basic_problem_committee/033/pdf/33-4.pdf (in Japanese).

[490] Jong-Bae Choi, Ministry of Education, Science and Technology, "Status of Fast Reactor and Pyroprocess Technology Development in the Republic of Korea," *Proceedings of an International Conference Fast Reactors and Related Fuel Cycles: Challenges and Opportunities, Kyoto, Japan, 7–11 December 2009*, International Atomic Energy Agency, 2012, p. 119.

[491] P.G. Schedrovitsky et al., "The Programme for Fast Reactor Development in the Russian Federation," *Proceedings of an International Conference Fast Reactors and Related Fuel Cycles*, International Atomic Energy Agency, 2009, pp. 139-147.

[492] P.B. Lyons, "Meeting tomorrow's energy needs," *Proceedings of an International Conference Fast Reactors and Related Fuel Cycles*, International Atomic Energy Agency, 2009, pp. 63–67.

[493] Assuming a 1/3 efficiency in conversion of heat into electric power, a capacity factor of 80 percent and a fuel energy release of 43 MWt-days/kgU. 10.89 kg of plutonium plus americium in a ton of spent fuel based on *Plutonium Fuel*, OECD Nuclear Energy Agency, 1989, Table 9.

[494] 330 GWe of light water reactor capacity from the Power Reactor Information System (PRIS) Database, International Atomic Energy Agency. One kilogram of fission of the transuranics in spent fuel when loaded into a fast reactor yields one GWt-day of heat. Seventy four tons would release about 200 GWt-years. Assuming a heat-to-electrical-energy conversion ratio of 40 percent for fast reactors and a 74 percent capacity factor (the lifetime capacity factor of Russia's BN-600, IAEA-Power Reactor Information System) gives 110 GWe.

[495] *Nuclear Wastes: Technologies for Separations and Transmutation, op. cit.*, pp. 211–212.

[496] Sodium burns in both air and water. Also, a loss of coolant flow without control rod insertion would result in sodium boiling that would for most core configurations increase the reactivity of the core resulting in a small nuclear explosion – the "Bethe-Tait" accident. Attempts to put an upper bound on the energy that might be released in such an accident that is low enough not to require an unacceptably costly containment vessel have proven controversial and, in the case of Germany's

SNR-300 demonstration breeder reactor, resulted in a decision not to operate it after it had been completed at a cost of about $6 billion (2014$). See W. Marth, *The SNR 300 Fast Breeder in the Ups and Downs of its History*, Kernforschungszentrum [Nuclear Research Center] Karlsruhe, 1994.

[497.] The U.S. Nuclear Regulatory Commission has estimated that a near-worst-case release from a spent-pool fire at the Peach Bottom Nuclear Power Plant would on average result in the long-term evacuation of an area of 9,400 square miles (24,000 square kilometers) and the long-term displacement of 4.1 million people. It also estimates the probability of such an event being caused by an earthquake as very low, however: once in ten million reactor years. See Table 33, in "Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a U.S. Mark I Boiling Water Reactor," NUREG 2161, U.S.Nuclear Regulatory Commission, October 2013, Table 33.

[498.] See chapter 8, "Sweden and Finland," in *Managing Spent Fuel from Nuclear Power Reactors,* International Panel on Fissile Materials, 2011.

[499.] They also may feel some responsibility to help dispose of the radioactive waste generated by the nuclear power plants that support their communities economically.

[500.] UNSCEAR, *Sources and Effects of Ionizing Radiation,* United Nations Scientific Committee on the Effects of Atomic Radiation, United Nations, 2000, Annex B, Table 31.

[501.] BEIR, *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2*, National Academy Press, 2006, Table 13-1.

[502.] See for example, the discussion in Allan Hedin, *Spent nuclear fuel — how dangerous is it?* Swedish Nuclear Fuel and Waste Management Co (SKB), Technical Report TR-97-13, 1997.

[503.] See chapter 13, "Geological Disposal," in *Managing Spent Fuel from Nuclear Power Reactors* International Panel on Fissile Materials, 2011.

[504.] See, for example, *Long-term safety for the final repository for spent nuclear fuel at Forsmark: Main report of the SR-Site project,* Volume III, Swedish Nuclear Fuel and Waste Management Co (SKB), TR-11-01, 2011, www.skb.se/upload/publications/pdf/TR-11-01_vol3.pdf, Figure 13-18. Radium-226 has a half-life of 1600 years. The half-lives of the other radioisotopes shown as contributing to the dose between 100 thousand and a million years after burial are, in order of importance: iodine-129, (16 million-year half-life fission product), neptunium-237 (2 million year half-life transuranic made by neutron capture on uranium-235), selenium-79 (65,000-year half-life fission product), lead-210 (22-year half-life decay product of uranium-238), nickel-59 (76,000-year half-life activation product of nickel-58 in steel), actinium-227 (22-year half-life decay product of uranium-235), and niobium-94 (24,000-year half-life activation product of niobium-93 in steel).

[505.] Bernd Granbow, "Mobile fission and activation products in nuclear waste disposal," *Journal of Contaminant Hydrology,* Vol. 104, 2008, pp. 180–186.

[506.] Long-term safety for the final repository for spent nuclear fuel at Forsmark, op. cit., Vol. 3, pp. 746–752.

[507.] "AREVA Signs A Series Of Strategic Agreements With Its Chinese Partners," Areva press release, 25 April 2013; and Ayesha Rascoe, "Areva sees nuclear waste recycling planning [in the U.S.] by 2015," *Reuters*, 6 June 2011, www.reuters.com/article/2011/06/06/us-areva-nuclear-usa-idUSTRE7555OO 20110606.

[508.] www.areva.com/EN/operations-3028/the-advantages-of-recycling.html, accessed 31 May 2014.

[509.] www.enecho.meti.go.jp/committee/council/basic_problem_committee/033/pdf/33-4.pdf (in Japanese).

[510.] Mycle Schneider and Yves Marignac, *Spent fuel reprocessing in France*, International Panel on Fissile Materials, 2008.

[511.] Roald A. Wigeland, Theodore H. Bauer, Robert N. Hill, and John A. Stillman, "Repository Impact of

Limited Actinide Recycle," *Proceedings of GLOBAL 2005*, Tsukuba, Japan, 9–13 October 2005, Paper No. 496.

[512] J. Choi et al., "Experimental assessment of non-treated bentonite as the buffer material of a radioactive waste repository," *Journal of environmental science and health. Part A, Toxic/hazardous substances & environmental engineering.* Vol. 36, No. 5, 2001, pp. 689–714

[513] Calculated by Jungmin Kang for the case of LEU and MOX fuel with a burnup of 53 MWt-days/kgHM.

[514] As of the end of 2011, the United States had an estimated 67,600 tons of spent power-reactor fuel, *Fuel Cycle Potential Waste Inventory for Disposition*, Rev. 5, U.S.Department of Energy, 2012, Table 3–4.

[515] *Nuclear Wastes: Technologies for Separations and Transmutation*, pp. 82–83.

[516] *Ibid.* p. 3. With regard to "additional operational risk," the only clear statement in the report refers to proliferation risk associated with the processing of plutonium in a fuel cycle involving transmutation (p. 108). The radiological risks of fuel cycles were found to be small with or without transmutation (p.111). The financial costs of reprocessing were found to be large (p. 117).

[517] "Avis no. 2013-AV-0187 de l'Authorité de sûreté nucléaire du 4 July 2013 sur la transmutation des elements radioactifs à vie longue" ["Opinion No. 2013-AV-0187 of the Nuclear Safety Authority of 4 July 2013 on transmutation of long-lived radioactive elements"] and "Avis IRSN n° 2012 – 00363, Objet: Plan national de gestion des matières et des déchets radioactifs… Etudes relatives aux perspectives industrielles de séparation et de transmutation des éléments radioactifs à vie longue Examen du rapport d'étape du CEA, d'octobre 2010, relatif aux évaluations technicoéconomiques des options de séparation-transmutation" ["IRSN review No. 2012-00363 of National management of radioactive materials and waste: Studies on industrial prospects of separation and transmutation of long-lived radioactive elements, review of the interim report of the CEA, in October 2010, on technical assessments economic options for partitioning and transmutation."]

[518] "If our aim isn't to utilize resources [with breeder reactors], then it would be better to dispose of the waste directly without reprocessing it,» Osamu Tochiyama, chair of METI's technical working group on waste disposal and Director of the Radioactive Waste Disposal Safety Research Center at the Nuclear Safety Research Association, quoted in Daisuke Yamada, "As I See It: Gov›t needs to look at options on handling, disposal of radioactive waste," *Mainichi*, 1 May 2014.

[519] UNSCEAR, *Sources and Effects of Ionizing Radiation,* 2000, Vol. 1, Annex C, Table 44; see also "Carbon-14 and the environment," Institut de Radioprotection et de Sûréte Nucléaire, www.irsn.fr/EN/Research/publications-documentation/radionuclides-sheets/environment/Pages/carbon14-environment.aspx

[520] BEIR, *Health Risks from Exposure to Low Levels of Ionizing Radiation,* Table 12–13.

[521] Thomas Cochran, Robert Norris and Oleg Bukharin, *Making the Russian Bomb: From Stalin to Yeltsin*, Westview Press, 1995, pp. 109-113.

[522] "Levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami" in UNSCEAR, *Sources, Effects and Risks of Ionizing Radiation,* Vol. 1, United Nations Scientific Committee on the Effects of Atomic Radiation, United Nations, 2013, p. 37.

[523] "Risks of explosion associated with "red oils" in reprocessing plants," Institut de Radioprotection et de Sûreté Nucléaire Technical Note, June 2008, www.irsn.fr/EN/publications/technical-publications/Documents/IRSN_Technical-Note_Red-Oils_062008.pdf. Other references give a detonation temperature of 130 °C or even lower. See Randall N. Robinson, David M. Gutowski, and William Yeniscavich, *Control of Red Oil Explosions in Defense Nuclear Facilities*, Technical Report, Defense Nuclear Facilities Safety Board, 2003; and Velayuthan Sreekantan Smitha et al., "Reactive Thermal Hazards of Tributyl Phosphate with Nitric Acid," *Industrial & Engineering Chemistry Research*, Vol. 51, No. 21, 2012, pp. 7205–10.

[524] In the period 1990–94, 24,000 workers at reprocessing plants received an average of 3 mSv/yr while 76,000 workers in uranium mines and mills received an average of 4 mSv/yr. UNSCEAR, *Sources and Effects of Ionizing Radiation*, 2000, Vol. 1, Annex E, Table 12.

[525] Edwin Lyman and Harold Feiveson, "The Proliferation Risks of Plutonium Mines," *Science and Global Security,* Vol. 7, 1998, pp. 119–128.

[526] Glenn Seaborg, speech at the 1995 meeting of the American Nuclear Society, San Francisco, quoted in "Burying Spent Fuel is Not the Best Approach to Nonproliferation, Seaborg Tells ANS," *Spent Fuel,* Vol. 2, 6 November1995, p. 2.

[527] As part of the Atoms for Peace Program, Canada and the United States provided India with the CIRUS research reactor that India used to produce much of its weapons plutonium. The United States also trained Indian engineers in reprocessing. This cooperation was terminated after India conducted what it described as a "peaceful nuclear explosion" in 1974. Three decades later, in 2005, the G.W. Bush Administration joined with the Indian government, in a campaign to persuade the Nuclear Suppliers Group to end this embargo. This effort achieved its goal in 2008. See IAEA, "Statement [by the Nuclear Suppliers Group] on Civil Nuclear Cooperation with India," International Atomic Energy Agency, INFCIRC/734 (Corrected), 19 September 2008.

Chapter 11. Economics

[528] NEA, *The economics of the back end of the fuel cycle,* Nuclear Energy Agency, OECD, 2013, p. 124.

[529] The reason why there is only one round of recycling in current conditions is that a large fraction of the plutonium in spent MOX fuel cannot be easily fissioned in a light water reactor. This is much less of a problem with fast neutron reactors.

[530] NEA, *The economics of the back end of the fuel cycle*, p. 125.

[531] *The future of the nuclear fuel cycle: An interdisciplinary MIT study,* Massachusetts Institute of Technology, 2010 and NEA, *The economics of the back end of the fuel cycle* are recent examples.

[532] Thus far, nuclear power has been different from other technologies in not achieving reductions of capital costs with experience. See A. Grubler, "The costs of the French nuclear scale-up: A case of negative learning by doing," *Energy Policy,* Vol. 38, 2010; and N. Hultman, J. Koomey, and D. Kammen, "What history can teach us about the future costs of U.S. nuclear power," *Environmental Science & Technology,* Vol. 40, No. 7, April 2007.

[533] The step is not actually necessary because fast-neutron reactors could be started up with enriched uranium. For example, Russia and China have fueled their experimental and demonstration reactors with highly enriched uranium (HEU) fuel because of their lack of facilities to fabricate MOX fuel, and South Korea plans to use low enriched uranium (LEU) fuel because of U.S. proliferation concerns. See "Cooperation deal to develop advanced reactor," *World Nuclear News*, 27 August 2014, www.world-nuclear-news.org/NN-Cooperation-deal-to-develop-advanced-reactor-2708141.html.

[534] J. Surrey, ed., *The British electricity experiment*, Earthscan, London, 1996.

[535] *Meeting the energy challenge: A White Paper on Energy*, UK Department of Trade and Industry, 2007, p. 204, paras. 116–118.

[536] NEA, *Uranium 2014: Resources, production and demand,* Nuclear Energy Agency, OECD, 2014. In 2013, uranium was produced in 21 countries (p. 11).

[537] Russia does reprocess some spent fuel it provided to other countries but it does not return the separated plutonium or radioactive waste. In effect, therefore, it is offering a spent fuel disposal service, which it has chosen to implement through reprocessing.

[538] N. Stern, *The Stern review on the economics of climate change,* Her Majesty's Treasury, 2006, Chapter 2.

[539] NEA, *The economics of the back end of the fuel cycle*, 2013, *op. cit.*

[540] The studies referred to in Table 1 of this paper are, in order of the columns in Table 1: G. De Roo and J. Parsons, "A methodology for calculating the levelized cost of electricity in nuclear power systems with fuel recycling," *Energy Economics,* Vol. 33, 2011, pp. 826–839; Matthew Bunn et al. "The economics of reprocessing vs. direct disposal of spent nuclear fuel," *Nuclear Technology*, Vol. 150, June 2005, p. 209; G. Rothwell et al., "Option values for the long-term use of MOX," Working Paper for the International Atomic Energy Agency (2011); NEA, *The economics of the nuclear fuel cycle,* Nuclear Energy Agency, OECD, 1994; NEA, *Advanced nuclear fuel cycles and radioactive waste management,* Nuclear Energy Agency, OECD, 2006.

[541] The inconsistencies in the results presented in NEA, The economics of the back end of the fuel cycle, 2013, derive from the fact that the 6.7 and 7.3US$/MWh figures come from a single "reference" case, while the 20 percent figure is averaged across a wide range of scenarios.

[542] Rob Broomby, "Hinkley firm denies fuel claim," *BBC*, 6 November 2013, www.bbc.co.uk/news/science-environment-24834932

[543] G. Rothwell et al., "Sustainability of light water reactor fuel cycles," *Energy Policy*, 74, 2014, S16–S23.

[544] *Ibid*, p. S22.

[545] J-M. Charpin, B. Dessus and R. Pellat, Economic forecast study of the nuclear power option, Report to Prime Minister, July 2000, fissilematerials.org/library/cha00.pdf (Translated from French).

[546] Charpin, Dessus and Pellat, *op. cit.* Appendix I contains a scenario for no reprocessing (S7). We derive a scenario for 100 percent reprocessing from a linear combination of this scenario and scenario S6, which is for 70 percent reprocessing.

[547] Reported in T. Katsuta and T. Suzuki, *Japan's spent fuel and plutonium management challenges,* International Panel on Fissile Materials, 2006.

[548] Katsuta and Suzuki, *Japan's spent fuel and plutonium management challenges*, Table 2.5, p. 11. The JAEC then qualified these results by introducing a "cost for policy change" involving the unrealistic assumption that, in the absence of reprocessing, nuclear plants would have to be closed and replaced by fossil fueled power plants when their spent fuel pools filled up. This turned a cost advantage for once-through into a small advantage for twice-through. This does not undermine the basic cost analysis showing advantage to the once-through cycle if sufficient spent fuel storage capacity is available.

[549] "Estimation of Nuclear Fuel Cycle Cost," Japan Atomic Energy Commission, Technical Subcommittee on Nuclear Power, Nuclear Fuel Cycle, 10 November 2011, Slides 31–32, www.aec.go.jp/jicst/NC/about/kettei/seimei/111110_1_e.pdf.

[550] "Is France to Blame for [China National Nuclear Corporation's] Back-End Problems?" *Nuclear Intelligence Weekly,* 19 December 2011; see also Chapter 2.

[551] M. V. Ramana and J. Y. Suchitra, "Costing plutonium: economics of reprocessing in India," *International Journal of Global Energy Issues*, Vol. 27, No. 4, 2007, pp. 454– 471.

[552] Charpin, Dessus and Pellat, op. cit.

[553] "Estimation of Nuclear Fuel Cycle Cost," Japan Atomic Energy Commission, Technical Subcommittee on Nuclear Power, Nuclear Fuel Cycle, etc, 10 Nov. 2011, www.aec.go.jp/jicst/NC/about/kettei/seimei/111110_1_e.pdf, Slide 28 for a 0 percent discount rate, assuming 7.5 kg of LEU spent fuel reprocessed per kg of MOX fuel produced.

[554] BCG, *Economic assessment of used fuel management in the United States*, Boston Consulting Group, 2006.

[555] Reproduced directly from NEA, *The economics of the back end of the fuel cycle*, 2013, p. 106, Table 3.9.

[556] NEA, *The economics of the back end of the fuel cycle*, 2013. Only the results for the once-through and twice-through cycles are discussed here.

[557] These variations are explained at some length together with the quantitative results, in NEA, *The economics of the back end of the fuel cycle*, 2013, Chapter 3, pp. 63–108.

[558] NEA, *The economics of the back end of the fuel cycle*, 2013, pp. 14 and 69.

[559] NEA, *The economics of the back end of the fuel cycle*, 2013, Table 3.10, p. 107.

[560] NEA, *The economics of the back end of the fuel cycle*, 2013,Table 3.5.

[561] As shown in NEA, The economics of the back end of the fuel cycle, 2013, Figures 3.23, 3.24, 3.25 and 3.26, pp. 90–93.

[562] NEA, *The economics of the back end of the fuel cycle,* 2013, p. 8.

[563] In NEA, *The economics of the back end of the fuel cycle, 2013*, Table 3.5, p. 88, there are six cases out of the 24 in which the cost advantage to the once-through cycle is greater than 30 percent.

[564] NEA, *The economics of the back end of the fuel cycle,* 2013, p. 16.

[565] *Plutonium Fuel: An Assessment*, Nuclear Energy Agency, OECD, 1989. While reprocessed uranium could be used as part of the feedstock for MOX, in practice, the costs of doing so are higher than if depleted uranium is used, and at present, reprocessed uranium is stored more or less universally.

[566] In some cases, for example, France, it is assumed that some of the spent MOX fuel will be stored over long periods, and then reprocessed for use in a fast reactor cycle. However, this is far from certain and would mean a transition to a fast-neutron reactor fuel cycle. Given that studies of the fast reactor fuel cycle suggest that its cost will be higher than for the twice-through cycle, the assumption here is that ultimately the spent MOX will be treated as waste.

[567] NEA, *The economics of the back end of the fuel cycle* uses three of these four issues (the exception is MOX fabrication costs) in its own sensitivity testing, (p. 94).

[568] Data in this paragraph derived from inspection of NEA, *The economics of the back end of the fuel cycle*, Figs 3.23 to 3.26, pp. 90–93.

[569] NEA, *The economics of the back end of the fuel cycle*, Section 4.6.1, p. 120.

[570] NEA, *The economics of the back end of the fuel cycle*, Section 4.6.1, p. 120.

[571] Mycle Schneider and Yves Marignac, *Spent Nuclear Fuel Reprocessing in France,* International Panel on Fissile Materials, 2008, chapter VI.

[572] NEA, *The economics of the back end of the fuel cycle*, p. 75.

[573] NEA, *The economics of the back end of the fuel cycle,* Section 2.1.2, p. 30.

[574] NEA, *The economics of the back end of the fuel cycle*, Figure 3.2.

[575] NEA, *The economics of the back end of the fuel cycle*, p. 99. This result is calculated for a 400 TWh/yr system at 0 percent discount rate. The uranium price would need to rise to \$270–\$300/KgU if the discount rate were 3 percent. See NEA, *The economics of the back end of the fuel cycle,* 2013, footnote on p. 142. Other assumptions in this analysis include a 20 percent fast-reactor capital cost premium over LWRs (the latter assumed to cost \$4,500/kWe, p. 77) and the claim that the cost of reprocessing fast reactor fuel and fabricating MOX fuel for fast reactors would be the same as the corresponding costs for thermal reactor fuel (p.77). Overall, the NEA assumptions about fast reactor costs may be considered somewhat optimistic.

[576] *Uranium 2014: Resources, Production and Demand*, OECD Nuclear Energy Agency and International Atomic Energy Agency, 2014, p. 130.

[577] Gavin M. Mudd, "The future of yellowcake: A global assessment of uranium resources and mining," *Science of the Total Environment*, Vol. 472, 2014, pp. 590–607.

[578] K. Deffeyes and I. MacGregor, "World uranium resources," *Scientific American*, Vol. 242, January 1980, pp. 66–76.

[579] *Energy, electricity and nuclear power estimates for the period up to 2050*, International Atomic Energy Agency, 2014, Table 3.

[580] Power Reactor Information System (PRIS) Database, International Atomic Energy Agency, 12 April 2015, www.iaea.org/PRIS/WorldStatistics/WorldTrendinElectricalProduction.aspx.

[581] NEA, *The economics of the back end of the fuel cycle*, p. 81.

[582] NEA, *The economics of the back end of the fuel cycle*, p. 81.

[583] NEA, *The economics of the back end of the fuel cycle*, p. 81.

[584] BCG, Economic assessment of used fuel management in the United States, 2006, p. iv.

[585] In a 7 June 2013 press release, Areva stated that "AREVA will also contribute its technical expertise to the ongoing construction of a Japanese MOX fuel fabrication plant, whose technology is based on AREVA's MELOX plant in France," www.areva.com/EN/news-9857/areva-signs-series-of-strategic-agreements-with-japanese-partners.html.

[586] Cost from Japan Nuclear Fuel Limited (JNFL), which is responsible for the construction and operation of the Rokkasho reprocessing and MOX fuel fabrication plants, October 2012, www.jnfl.co.jp/jnfl/establishment.html (in Japanese). As mentioned earlier it has been reported that Areva, which designed the Rokkasho Reprocessing Plant, is asking €20 billion ($26 billion) for a reprocessing plant with the same capacity in China.

[587] "Estimation of Nuclear Fuel Cycle Cost," Japan Atomic Energy Commission, Technical Subcommittee on Nuclear Power, Nuclear Fuel Cycle, etc, 10 Nov. 2011, www.aec.go.jp/jicst/NC/about/kettei/seimei/111110_1_e.pdf, slide 30.

[588] *Ibid.,* slides 31 and 32.

[589] Derived from NEA, *The economics of the back end of the fuel cycle*, figure 3.27, p. 94.

Chapter 12. Radiological Risk

[590] Gordon R. Thompson, *Radiological Risk at Nuclear Fuel Reprocessing Plants*, Institute for Resource and Security Studies, 2014. Posted at clarku.academia.edu/GordonThompson

[591] J.P. Mercier, F. Bonneval, and M. Weber, "Application of Probabilistic Approach to UP3-A Reprocessing Plant," Paper #6.1, *Proceedings of the CSNI Specialist Meeting on Safety and Risk Assessment in Fuel Cycle Facilities, 7-9 October 1991, Tokyo, Japan,* Nuclear Energy Agency, OECD, 1991.

[592] Robert Alvarez, Jan Beyea, Klaus Janberg, Jungmin Kang, Ed Lyman, Allison Macfarlane, Gordon Thompson, and Frank von Hippel, "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States", *Science and Global Security*, Vol. 11, 2003, pp 1-51; National Research Council, *Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report*, National Academies Press, 2006.

[593] At Rokkasho, the plutonium is immediately mixed with uranium in roughly equal proportions.

[594] Gordon R. Thompson, *Radiological Risk at Nuclear Fuel Reprocessing Plants, op. cit.*

[595] The *Safety of the Nuclear Fuel Cycle,* OECD Nuclear Energy Agency, 2005, Chapter 9.

[596] See, for example, Steve Fetter and Frank von Hippel, "The Hazard from Plutonium Dispersal by Nuclear-warhead Accidents", *Science and Global Security*, Vol. 2, 1990, pp. 21–41.

[597] "Unreprocessed radioactive waste in Tokai could explode if safeties fail," *The Asahi Shimbun*, 3 December 2013.

[598] *The Safety of the Nuclear Fuel Cycle, op. cit*, Chapter 12.

[599] www.liveinternet.ru/users/bubaraba/post2786190/. There are many maps of the East Urals Trace available on the web.

[600] IAEA, *The Radiological Accident in the Reprocessing Plant at Tomsk*, International Atomic Energy Agency, 1998.

[601] John G. Kemeny (chair) and eleven other commissioners, *Report of the President's Commission on the Accident at Three Mile Island*, U.S.Government Printing Office, October 1979; Alexander Shlyakhter and Richard Wilson, "Chernobyl: the inevitable results of secrecy," *Public Understanding of Science,* Vol. 1, July 1992, pp. 251–259; and National Diet of Japan, *The official report of The Fukushima Nuclear Accident Independent Investigation Commission*, Executive summary, National Diet of Japan, 2012.

[602] Satoshi Segawa and Kunio Fujita (JNFL), "The Need to Study of Bounding Accident in Reprocessing Plant," in: *Safety Assessment of Fuel Cycle Facilities — Regulatory Approaches and Industry Perspectives, OECD/NEA Workshop, Toronto, Canada, 27-29 September 2011*, NEA/CSNI/R(2012)4, OECD Nuclear Energy Agency, July 2013, pp. 453–471.

[603] Segawa and Fujita assumed an airborne release fraction of 10^{-4} vs. the value of $2x10^{-3}$ suggested in the Nuclear Fuel Cycle Facility Accident Analysis Handbook, NUREG/CR-6410, U.S. Nuclear Regulatory Commission, 1998, case of boiling liquid aqueous solution.

[604] Martin Stott and Peter Taylor, *The Nuclear Controversy: A guide to the issues of the Windscale Inquiry*, Town and Country Planning Association, and the Political Ecology Research Group, 1980, Chapter 4.

[605] Jan Beyea, Yves Lenoir, Gene Rochlin, and Gordon Thompson (group chair), "Potential Accidents and Their Effects," Chapter 3 in *Report of the Gorleben International Review*, March 1979.

[606] Ernst Albrecht, Minister-President of Lower Saxony, "Declaration of the state government of Lower Saxony concerning the proposed nuclear fuel center at Gorleben" (English translation), May 1979.

[607] *The storage of liquid high level waste at BNFL, Sellafield: Addendum to February 2000 Report*, UK Nuclear Installations Inspectorate, August 2001; and preceding UK Nuclear Installations Inspectorate reports.

[608] Gordon R. Thompson, "Comments on the US Nuclear Regulatory Commission's Waste Confidence Generic Environmental Impact Statement, Draft Report for Comment (September 2013)," Declaration on behalf of a group of environmental organizations, 19 December 2013.

[609] A. Stohl, P. Seibert, G. Wotawa, D. Arnold, J.F. Burkhart, S. Eckhardt, C. Tapia, A. Vargas, and T.J. Yasunari, "Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: determination of the source term, atmospheric dispersion, and deposition," *Atmospheric Chemistry and Physics*, Vol. 12, 2012, pp. 2313–2343.

[610] J. Lelieveld, D. Kunkel, and M.G. Lawrence, "Global risk of radioactive fallout after major nuclear reactor accidents," *Atmospheric Chemistry and Physics,* Vol. 12, 2012, pp. 4245–4258.

[611] Andrew Barto et al., *Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a US Mark I Boiling Water Reactor,* U.S.Nuclear Regulatory Commission, NUREG-2161, October 2013, Table 33.

[612] *Examen de la methode d'analyse cout-benefice pour la surete, Rapport DSR No. 157, Annex du Chapitre 4, Evaluation Economique des Consequences d'Accidents Graves et Enseignements*, Institut de Radioprotection et de Sûreté Nucléaire, 5 July 2007; assuming US$1.40 per Euro.

[613] National Research Council Committee on Inherently Safer Chemical Processes, *The Use and Storage of Methyl Isocyanate (MIC) at Bayer CropScience*, National Academies Press, 2012.

[614] Deutsche Gesellschaft fur Wiederaufarbeitung von Kernbrennstoffen, "Brief Description of the Wackersdorf Reprocessing Facility," August 1983, English translation of the German original, published by Oak Ridge National Laboratory, Tennessee, 1986.

[615] *The Storage of liquid high level waste at BNFL, Sellafield, op. cit.*

[616] Office of Nuclear Regulation, "The Storage of Liquid High Level Waste at Sellafield: Revised Regulatory Strategy," document TRIM: 2011/295603, 2011.

[617] *Radiological Risk at Nuclear Fuel Reprocessing Plants*, Appendix A, Tables 9–3 and 9–4, adjusted for a fuel age of seven years. It is reported that La Hague is allowed to receive spent fuel that has cooled for a period as short as one year.

[618] *Radiological Risk at Nuclear Fuel Reprocessing Plants*, Appendix A, Table 10–2.

Contributors

Anatoli Diakov, a Professor of Physics at the Moscow Institute of Physics and Technology, was the founding Director of the Moscow Center for Arms Control, Energy and Environmental Studies. He has written papers on nuclear arms reductions, the history of Russia's plutonium production, disposition options for excess plutonium, Russia's plutonium production, disposition options for excess plutonium, and the feasibility of converting Russia's icebreaker reactors from HEU to LEU as well as on many other topics relating to nuclear arms control and disarmament. He is a member of IPFM. He was a lead author of the chapter on Russia.

Klaus Janberg has worked in France, the United States and Germany from 1969 to 1976 on different fast neutron breeder reactor projects. From September 1976 till October 1980, he was department head of the German reprocessing company DWK and in charge of negotiating the UP3 contract with COGEMA for the German utilities. In parallel, he was in charge of developing away-from-reactor spent-fuel storage sites in Ahaus and Gorleben, Germany. From 1980 to 2000, he was General Manager with the engineering company GNS, which developed the CASTOR dry storage casks. He was the lead author of the chapter on Germany.

Jungmin Kang is a visiting professor at Korea Advanced Institute of Science and Technology. He works on a range of issues including the nexus between nuclear security and safety, verifying DPRK's plutonium production, radioactive-waste management, spent-fuel storage, and the proliferation-resistance of closed fuel cycles. He is editor of *Assessment of the Nuclear Programs of Iran and North Korea* (2013). He is a member of IPFM. He was a contributor to the chapter on South Korea.

Gordon MacKerron retired as the Director of SPRU, the Science and Technology Policy Research Unit of the University of Sussex in 2014. He previously directed the Sussex Energy Group within SPRU from 2005 until 2008. He is an economist by training, and has worked mostly on the economic and policy issues of energy, especially nuclear power, and on contemporary energy policy issues more broadly, including climate change and security of supply. He was the founding chair of the UK government's independent Committee on Radioactive Waste Management (2003 – 2007) and is a member of IPFM. He was the lead author of the chapters on the United Kingdom and Economics.

M.V. Ramana is a physicist with Princeton University's Nuclear Futures Laboratory and Program on Science and Global Security. He works on the future of nuclear energy in the context of climate change and nuclear disarmament, and is the author of *The Power of Promise: Examining Nuclear Power in India* (2012). He is a member of IPFM. He was the lead author of the chapter on India and co-editor of the report.

Mycle Schneider is an independent international consultant on energy and nuclear policy based in Paris. He is the Lead Author and Publisher of the annual World Nuclear Industry Status Report. He is a Board Member and Spokesperson of the International Energy Advisory Council and has given evidence or held briefings at national Parliaments in 14 countries. He has given lectures or had teaching appointments at 20 universities and engineering schools in 10 countries. Over the past three decades, he has provided information and consulting services to several governments and European institutions as well as numerous NGOs and think tanks. He is a member of IPFM. He was a lead author of the chapter on France.

Masafumi Takubo is an independent nuclear policy analyst based in Tokyo. He manages the nuclear information website Kakujoho [Nuclear Information], which he established in 2004. He was affiliated with the Japan Congress Against A-and H-Bombs (GENSUIKIN), a leading grass-roots organization for over thirty years, including as the Senior Researcher in the International Division and as a consultant. Takubo has written widely on Japanese nuclear policy, including on spent-nuclear fuel reprocessing. He is a member of IPFM. He was a lead author of the chapter on Japan.

Gordon Thompson is Executive Director of the Institute for Resource and Security Studies, and a Senior Research Scientist at Clark University. He works on a range of technical and policy issues related to human security and the sustainability of our civilization. Among those issues are the various risks associated with nuclear technologies, including the radiological, nuclear-proliferation, and program risks associated with reprocessing. He was lead author of the chapter on radiological risk.

Frank von Hippel, a senior research physicist and Professor of Public and International Affairs emeritus at Princeton University's Program on Science and Global Security, was a founding co-chair of the International Panel on Fissile Materials and a founding co-Director of Princeton's Program on Science and Global Security. He has worked on fissile material policy issues for the past 40 years. He was a lead author of the chapters on South Korea, Japan and Transmutation and co-editor of the report.

Hui Zhang is a Senior Research Associate at the Project on Managing the Atom in the Belfer Center for Science and International Affairs at Harvard University's John F. Kennedy School of Government. His research areas include verification techniques of nuclear arms control, fissile material control, the prevention of nuclear terrorism, China's nuclear policy, nuclear safeguards and non-proliferation, policy relating to reprocessing and the nuclear fuel cycle. He was a lead author of the chapter on China.

Yun Zhou is a special consultant at Ux Consulting Company and a research scholar at the Center for International and Security Studies at the University of Maryland. She was a research fellow at Harvard University's Belfer Center for Science and International Affairs from 2009 to 2014. Her current research interests include the international security and safety implications of a global nuclear expansion and alternative nuclear technologies. She received her Ph.D. in nuclear engineering from the University of California, Berkeley and her B.S. in engineering physics from Tsinghua University, China. She was a lead author of the chapter on China.

A report published by
The International Panel on Fissile Materials (IPFM)
www.fissilematerials.org

Program on Science and Global Security
Princeton University
221 Nassau Street, 2nd Floor
Princeton, NJ 08542, USA

July 2015

Kræнk Visuell