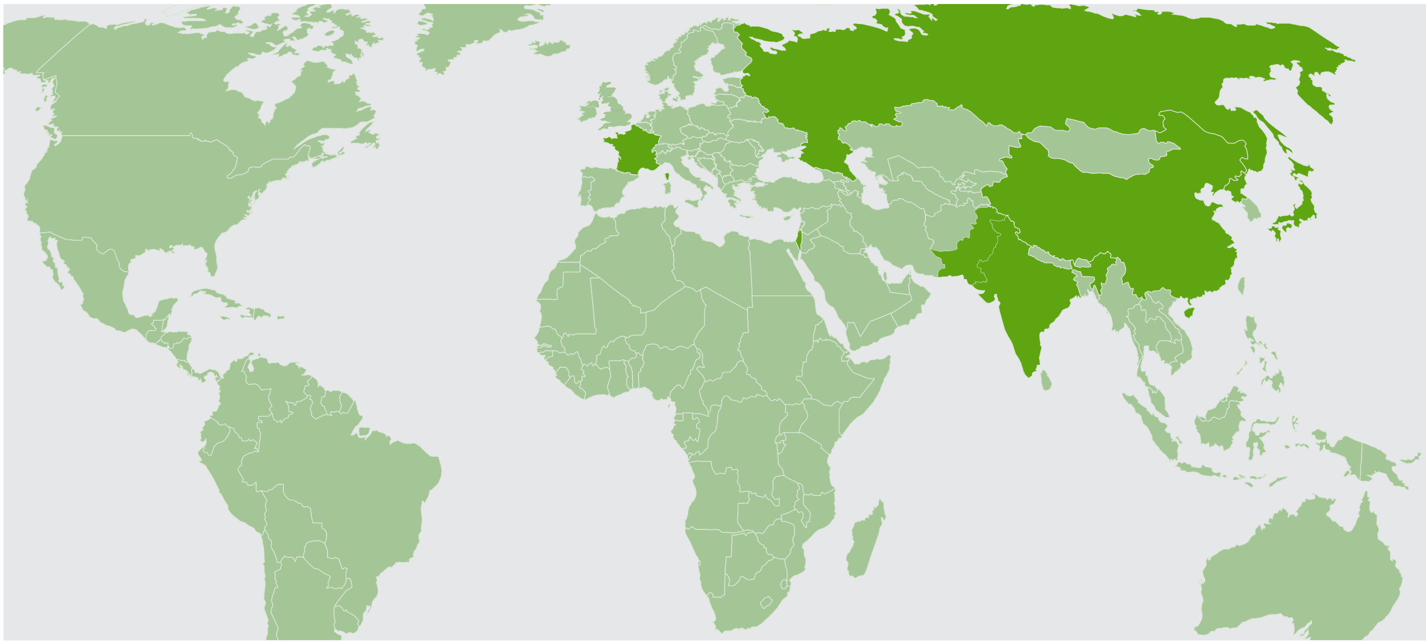

IPFM
INTERNATIONAL PANEL
ON FISSILE MATERIALS

Banning Plutonium Separation

Frank N. von Hippel and Masafumi Takubo

Research Report No. 20
International Panel on Fissile Materials

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About the IPFM

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

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

Both military and civilian stocks of fissile materials must be addressed. The nuclear-weapon states still have enough fissile materials in their weapon stockpiles for tens of thousands of nuclear weapons. And enough civilian 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 about one thousand Hiroshima-type bombs, a design well within the potential capabilities of terrorist groups.

The Panel has been co-chaired since 2015 by Professor Alexander Glaser and Dr. Zia Mian of Princeton University and Professor Tatsujiro Suzuki of Nagasaki University, Japan. It was co-chaired previously by Professor Jose Goldemberg of the University of Sao Paolo, Brazil (2006-2007), Dr. R. Rajaraman (2007-2014) Professor Emeritus, of Jawaharlal Nehru University, New Delhi, India, and Professor Frank von Hippel of Princeton University (2006-2014).

IPFM's members include nuclear experts from seventeen countries: Brazil, Canada, China, France, Germany, India, Iran, Japan, the Netherlands, Norway, Pakistan, South Korea, Russia, South Africa, Sweden, the United Kingdom, and the United States; seven are nuclear-weapon states and ten are non-weapon states.

IPFM research and reports are shared with international organizations, national governments and nongovernmental groups. IPFM meetings and workshops are often in conjunction with international conferences at which IPFM panels and experts make presentations.

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Overview

Kilogram quantities of the artificial element, plutonium, were first produced in nuclear reactors and chemically separated from the spent nuclear fuel almost 80 years ago as part of the United States nuclear weapons program. The first nuclear explosion, in July 1945, was a test of a design powered by 6 kilograms of plutonium. A bomb of that same design was used the following month to destroy the city of Nagasaki. Plutonium has played a key role in almost all nuclear weapons since. It is also being used in a few countries as a power reactor fuel. Today, there are about 550,000 kilograms (about 550 metric tons*) of separated plutonium worldwide. Thousands of additional tons remain unseparated in stored spent fuel.

At the end of the Cold War, in 1990, the global stock of separated, i.e., unirradiated plutonium, totaled a little over 300 tons. More than two thirds was weapons plutonium, of which more than 95% had been produced by the Soviet Union and United States. The United States, Russia (which inherited the Soviet Union's stocks of nuclear weapons and fissile materials), the United Kingdom, France and China had stopped producing plutonium for nuclear weapons. Israel, India, Pakistan and North Korea continued. The quantities the last four countries have produced so far, however, total only about one percent of the Cold War legacy stocks.

In 1993, the UN General Assembly mandated negotiation of a Fissile Material Cutoff Treaty that would ban production of plutonium and other fissile materials for weapon purposes. Substantial negotiations have yet to begin, however.

Meanwhile, the global stock of separated civilian but nuclear-weapon-usable plutonium has grown substantially – increasing from about 100 tons at the end of the Cold War to a total of more than 300 tons as of the end of 2020. In addition, almost 100 tons of US and Soviet/Russian weapons plutonium have been declared excess, increasing the total amount of civilian plus excess weapons plutonium available for non-weapons uses to approximately 400 tons. This growing civilian plutonium stockpile is far larger than the estimated stockpile of about 150 tons of plutonium remaining in weapons and weapon programs as of 2020.

A US National Academy of Sciences study in 1994 found that *all* separated plutonium, civilian as well as military, constitutes a "clear and present danger to national and international security."[1] By the International Atomic Energy Agency's safeguarding assumption that 8 kg of plutonium is sufficient for a simple weapon, the four hundred tons of separated civilian and excess weapons plutonium is enough for 50,000 Nagasaki bombs.

The separation of plutonium for civilian purposes began in the 1960s and 1970s by chemically "reprocessing" spent nuclear power reactor fuel. The purpose was to obtain startup fuel for future liquid-sodium-cooled plutonium "breeder" reactors whose large-scale commercialization was expected to begin in the 1990s. Breeder reactors were to be powered by plutonium while transmuting non-chain-reacting uranium-238 into more chain-reacting plutonium than the reactors consumed. Therefore uranium-238 would be their ultimate fuel. U-238 is 140 times more abundant in natural uranium than the chain-reacting U-235 whose fission provides most of the energy in current-generation power reactors.

Theoretically, breeders could be fueled even by the trace amounts of uranium in ordinary rocks. Average crustal rock contains three grams of U-238 per ton. The fission of those three grams, after conversion into plutonium, would yield as much energy as the combustion of ten tons of coal. The nuclear pioneers therefore argued that it would be possible, in effect, to "burn the rocks." They believed they had created a source of energy that could support human civilization at its current level of energy consumption for millions of years.[2]

* In this report, "tons" refers to metric tons.

Through the 1970s, nuclear power was expected to become the dominant source of energy for an increasingly electrified world and breeder reactors were expected to dominate nuclear power after 2010. These expectations proved to be incorrect. Global nuclear capacity plateaued after 2000 with capacity retirements approximately offsetting new capacity. Breeder reactors have not been commercialized because of their high capital and fuel-cycle costs and low reliability.

Today, nuclear power provides about 10 percent of growing global electrical power production – down from a peak of about 18 percent in 1996. Meanwhile, production of lower-cost electrical power using photovoltaic panels and wind turbines has grown rapidly to approximately equal the level of production by nuclear reactors and is expected to dominate the production of power in the post-fossil-fuel world.[3] Uranium, which accounts for only a few percent of the total cost of power from current reactors, is projected to continue to be available at low cost and could sustain nuclear power at its current level for at least another hundred years.

Globally, only two prototype breeder reactors were operating in 2021– both in Russia. The older had been operating for four decades, fueled by enriched uranium rather than plutonium. Three more prototypes were under construction: two in China and one in India, but appeared to be dual-purpose – to produce plutonium for weapons as well as electrical power.

The world became aware of the potential use of nominally civilian plutonium programs for acquiring nuclear weapons in 1974 when India used some of the plutonium it had separated with the assistance of the US Atoms for Peace Program to launch its nuclear-weapons program. Brazil, Pakistan, South Korea and Taiwan – all with military governments at the time – were discovered to be going down the same track.

The realization that the civilian plutonium programs the US Atomic Energy Commission (AEC) had been promoting worldwide were facilitating nuclear-weapon proliferation became an issue in the 1976 US presidential election. In 1983, after several years of intense public debate and a five-fold increase in the estimated cost of a planned US "demonstration" breeder reactor, Congress ended the US breeder reactor commercialization program. Absent a market for plutonium, US nuclear utilities opted not to reprocess their spent fuel and instead backed legislation for its direct disposal in a deep underground repository to be built by the Department of Energy, which had taken over all the nuclear responsibilities, other than regulation, of the AEC, which was dismantled by Congress in 1974.

The Carter Administration (1977-80) was not able to persuade other countries with on-going civilian plutonium programs to halt them. Germany did so eventually, and, as this report was being completed, the UK announced that its reprocessing operations would end in July 2022. China, France, India, Japan and Russia continue their civilian spent-fuel reprocessing programs.

France and Japan have suspended their breeder demonstration programs but continue with paper studies. France uses its separated plutonium, diluted with depleted uranium, in "mixed-oxide" (MOX) fuel to replace about 10% of the low-enriched-uranium fuel used by its conventional power reactors – even though separating the plutonium and fabricating the MOX fuel costs an order of magnitude more than the low-enriched uranium fuel it replaces. Japan had several thousand tons of spent fuel reprocessed in France and UK and, as of 2022, expected soon to put into operation a large domestic reprocessing plant that had been under construction for three decades. Japan plans to follow France's example and recycle the plutonium in MOX fuel in conventional power reactors.

France's and Japan's nuclear-energy research and development (R&D) establishments justify their uneconomic plutonium recycle programs by arguing that extracting the plutonium from spent fuel will reduce the longevity of the environmental hazards of radioactive waste disposed of deep underground. Official studies in the United States and Sweden have found, however, that, because plutonium oxide is relatively insoluble, is not concentrated in the food chain, and is only weakly absorbed from the human gut, it will not dominate the radiological risk from deep underground spent-fuel repositories.

In addition to its high cost, reprocessing spent fuel has accident risks. Although kept secret for two decades until it was revealed by a Russian émigré, the world's worst nuclear accident prior to the 1986 Chernobyl accident occurred in 1957 in the Soviet Union. A tank of concentrated radioactive waste at the first Soviet military reprocessing plant dried out and exploded. It was necessary to relocate the population from a downwind contaminated area of 1,000 square kilometers – about the same size area as that from which people were relocated after Japan's 2011 Fukushima accident.

The United Kingdom is now confronted with the question of how to dispose of the world's largest stock of separated civilian plutonium, about 140 tons, including about 22 tons separated for Japan that is marooned in the UK. Unlike the governments of France and Japan, the UK has not forced its nuclear utilities to use the separated plutonium in MOX fuel. An alternative being considered is to process the plutonium into a stable waste form for deep underground disposal.

The cost of cleaning up the UK's plutonium production and separation site is estimated to be the equivalent of more than one hundred billion dollars. The cost and risk of storing spent fuel in air-cooled casks, pending the future availability of deep repositories, are small in comparison.

Japan is the only non-nuclear-armed state that reprocesses today but there is concern that its example might be emulated by other non-weapon states. In recent years, South Korea has pressed the US to rewrite their agreement on peaceful nuclear cooperation to give it the same right to reprocess as Japan. In 2011, the US temporarily deflected this demand with a ten-year joint "feasibility study", but the discussion may soon resume.

Plutonium-239, the main isotope produced by neutron capture in U-238, has a half-life of 24,000 years. It will outlive the states that produced it. That has already happened once, in 1991, when the Soviet Union disintegrated, resulting in global efforts to help Russia secure its huge stocks of inherited weapon-usable materials.

This report recommends the following initiatives to accelerate the end of spent-fuel reprocessing and to dispose of already separated plutonium that has no near-term use plan:

1. Broaden the proposed Fissile Material Cutoff Treaty to include a ban on the separation of plutonium for any purpose, civilian as well as military, and place all unirradiated civilian plutonium and demilitarized weapons plutonium under IAEA safeguards.

2. Launch an international research program to achieve a consensus on the environmental hazards of direct deep disposal of spent fuel relative to reprocessing and deep disposal of reprocessing wastes, and multinational cooperation on disposal of excess plutonium.

Background

Origin of civilian plutonium separation: The breeder-reactor dream

Separation of plutonium for breeder reactor research and development (R & D) by chemically "reprocessing" spent conventional power reactor fuel began in the 1960s and 1970s. At the time, it was believed that global nuclear power capacity would continue to grow exponentially (Figure 1) and that global uranium resources recoverable at prices affordable for conventional nuclear power reactors would be rapidly depleted.[4]

In fact, as is shown in Figure 1, after the 1986 Chernobyl accident, global nuclear capacity plateaued and, as shown in Figure 2, the price of uranium in constant dollars has varied by about a factor of two above and below its long-term average of about $100/kgU (2018$) but has not trended upwards. The 2020 edition of the biennial report, *Uranium Resources, Production and Demand*, published jointly by the OECD Nuclear Energy Agency and the International Atomic Energy Agency concluded that:

> Sufficient uranium resources exist to support continued use of nuclear power and significant growth in nuclear capacity for low-carbon electricity generation and other uses (e.g., heat, hydrogen production) in the long term. Identified recoverable resources, including reasonably assured resources and inferred resources (at a cost <USD 260/kgU…) are sufficient for over 135 years, considering uranium requirements as of 1 January 2019.[5]

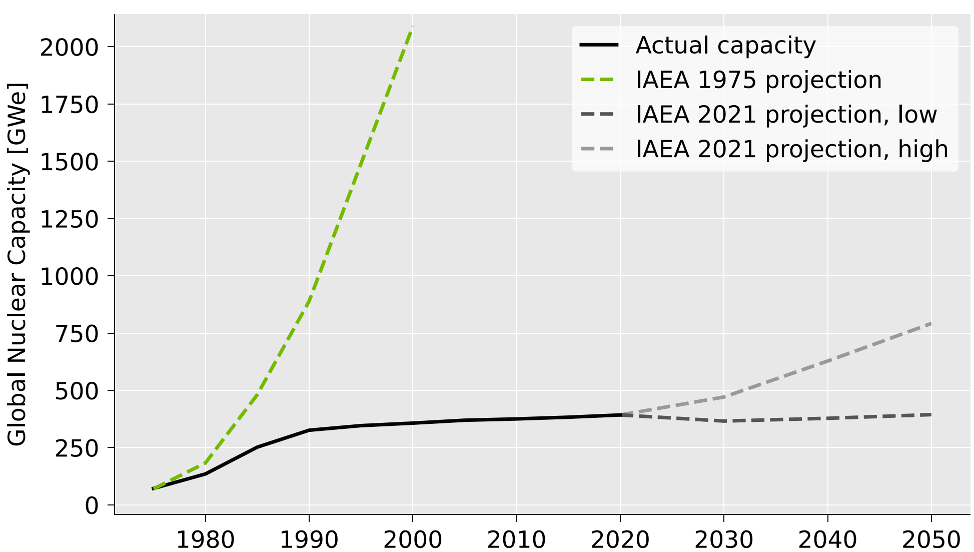


Figure 1. International Atomic Energy Agency (IAEA) 1975 projection of world nuclear capacity and what actually happened. Source: IAEA data.[6]

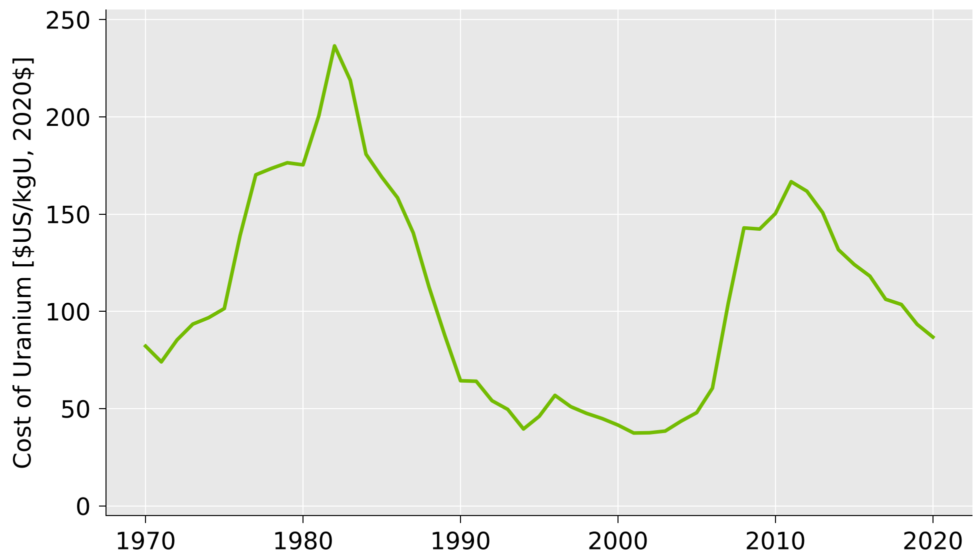


Figure 2. Uranium price history in constant dollars. Source: US Department of Commerce and US Energy Information Administration data.[7]

During the 1960s and 1970s, however – driven by high projections for nuclear power growth and low projections for resources of uranium at acceptable costs – the leading industrialized states of the time launched major efforts to develop plutonium "breeder" reactors that would use uranium much more efficiently. Enrico Fermi's mistaken 1945 prediction, "The country which first develops a breeder reactor will have a great competitive advantage in atomic energy," continued to influence thinking in the nuclear-power community for decades.[8]

Conventional "light"-water-cooled power reactors (LWRs) are fueled primarily by chain-reacting uranium-235 in low-enriched uranium. The percentage of uranium-235 in such LEU is increased from 0.7 percent in natural uranium up to three to five percent. LWRs fission only a very small amount of the non-chain-reacting U-238 that makes up the remaining 95+ percent of LEU in the fuel. The development of plutonium "breeder" reactors was therefore launched in the hope of turning the 99.3 percent U-238 in natural uranium into chain-reacting plutonium. Breeders would be fueled initially by plutonium extracted mostly from spent LWR fuel. Thereafter, they would be sustained by plutonium produced in the breeder reactor cores and in uranium "blankets" placed around the cores to capture neutrons that leak out.

In order to produce more plutonium than it consumes, the chain reaction in a plutonium breeder reactor must be mediated by "fast" neutrons that have lost little of the energy with which they were produced in fissions. Fast neutrons increase the average number of neutrons produced per plutonium fission. The extra neutrons are required to make the reactors net plutonium producers.

Since collisions with the single proton nuclei of hydrogen in water deprive neutrons of large fractions of their energy, fast-neutron reactors require a coolant with heavier nuclei.[9] A number of alternatives have been explored, but all prototype breeder reactors that have operated have used liquid sodium, which has a melting point of about 100 °C.[10]

France, Germany, Japan, Russia and the United Kingdom all built prototype sodium-cooled breeder reactors, and China, India and Russia are currently doing so (Table 1).

Sodium burns in air or water, however. Elaborate and time-consuming arrangements therefore are required to exclude air when refueling breeder reactors and it is necessary to clean out the sodium completely before they can be opened for repairs.

There are also advantages from using sodium as a coolant. Sodium has a high boiling temperature (882 ºC), making pressurization unnecessary to achieve the temperature of about 300 ºC required to generate the high-pressure steam used to drive turbogenerators. A thick pressure vessel around the reactor is therefore not required. Also, because the heat-conducting properties of liquid sodium are superior to those of water, sodium-cooled reactor cores can be made more compact.

These advantages made liquid-metal-cooled reactors attractive to US and Soviet submarine designers. In the US, in 1957, Admiral Rickover, the "father" of the US nuclear-submarine program, installed a sodium-cooled reactor in his second nuclear submarine.

The following year, however, Rickover had the reactor torn out and replaced by a water-cooled reactor.[11] His verdict, that sodium-cooled reactors are "expensive to build, complex to operate, susceptible to prolonged shutdown as a result of even minor malfunctions, and difficult and time-consuming to repair,"[12] proved prescient. The median cumulative "capacity factor" of the nine experimental and prototype breeder reactors that have been built and used to generate electric power for the grid has been about 20 percent. This capacity factor (the IAEA calls it the "load factor") is a reactor's lifetime electrical-energy output divided by the theoretical output had the reactor operated at full power all the time. LWRs have a median capacity factor of approximately 80 percent.[13]

Grid-connected breeder reactors (country)	Power (MWe)	Online	Lifetime capacity factor (percent)
Demonstration Fast Reactor (UK)	11	1962-77	35
Fermi I (US)	61	1966-72	0.9
Phénix (France)	130	1973-2010	40
Prototype Fast Reactor (UK)	234	1976-1994	18
BN-600	560	1980-	76 (through 2020)
Clinch River Breeder Reactor (US)	350	Cancelled 1983	Not completed
Superphénix (France)	1200	1986-1998	3
SNR (Germany)	300	Cancelled 1991	Completed but not operated
Monju (Japan)	246	1995-2017	0
BN-800 (Russia)	789	2015-	71 (through 2020)
China Experimental Fast Reactor	20	2011-	0.002 (through 2016)
Prototype Fast Breeder Reactor (India)	470	Construction start 2004	Not applicable
Demonstration Fast Reactor I (China)	642	Construction start 2017	Not applicable
Demonstration Fast Reactor II (China)	642	Construction start 2020	Not applicable
BREST-300 (Russia)	300	Construction start 2021	Not applicable

Table 1. Over 60 years, nine grid-connected experimental and prototype breeder reactors have operated. Three are still operating. Two were canceled before completion or operation. Four are under construction (three for suspect reasons). Source: IAEA, Power Reactor Information System, 2021.

To date, the capital costs of breeder reactors have been higher than those of LWRs. If the capital costs per kilowatt of generating capacity were the same, however, the median capital charge per kilowatt hour for a sodium-cooled reactor operating with a 20-percent capacity factor would be four times higher than that of an LWR operating with an 80-percent capacity factor. Given that the capital charge is the largest part of the cost of power from a new nuclear power plant, the economic failure of breeder reactors in most countries is easily understood.[14]

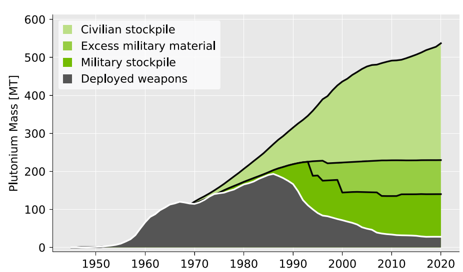
Although no country has succeeded in commercializing breeder reactors, Russia, India and China have persisted with research, development and demonstration (RD&D) efforts.

Russia owned the world's only two prototype sodium-cooled breeder reactors operating in 2021: the BN-600 and BN-800, connected to the grid in 1980 and 2015 respectively. (The suffix of a Russian power reactor indicates its approximate generating capacity in megawatts.)

After fifteen sodium fires during the BN-600's first fourteen years of operation[15], both the BN-600 and BN-800 have been operating relatively well with capacity factors almost as high as those of Russian LWRs in 2020. Construction of a follow-on BN-1200 reactor has been delayed until at least the 2030s, however, because its capital cost is expected to make it noncompetitive with LWRs.[16]

Few breeder reactors but continued civilian plutonium separation

Figure 3 shows the history of the buildup of the global stock of unirradiated plutonium and of the reported stocks of civilian plutonium during the past quarter century.



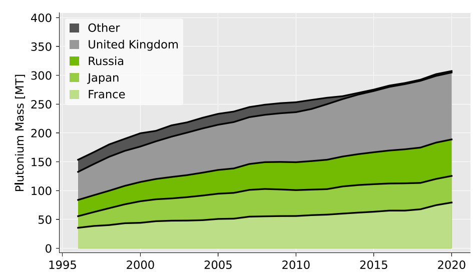


Figure 3. Growing stocks of separated civilian plutonium. Left. Global stocks of separated plutonium. Production of plutonium for weapons slowed dramatically with the end of the Cold War while Russian and US nuclear-warhead stockpiles plummeted, creating a plutonium-disposal problem.[17] Despite the failure of breeder-reactor commercialization, however, the rate of civilian plutonium separation increased! Right. Civilian stocks of plutonium are currently dominated by four countries: France, Japan, Russia and the UK.[18] "Others" represent other European states that had reprocessing contracts with France and UK that were not renewed. Not shown are the relatively small stocks in China and India, for which estimates are shown in Table 2 (IPFM).

Country	Separated civilian plutonium plus weapons plutonium declared excess (tons)
China	0.04 (end of 2016)
France	79.4
India	4-13 (estimated)
Japan	46.1
Russia	100.3
UK	116.1
US	49.4
Total	**~400**

Table 2. Declarations or estimates of national stocks of separated civilian and excess weapons plutonium (mostly as of the end of 2020, except where noted). The declarations are from the national INFCIRC/549 statements to the IAEA: Communication[s] Received from Certain Member States Concerning Their Policies Regarding the Management of Plutonium.

State	Facility name or location (status)	Operation	Design Capacity (tons of heavy metal in spent fuel per year)
Belgium	Eurochemic	1966-74	60
China	Jiuquan pilot plant	2010-	50
	Jinta I	2025-?	200
	Jinta II	2030-?	200
France	Marcoule	1958-97	960
	UP2, La Hague	1966-	1000
	UP3, La Hague	1994-	1000
Germany	WAK, Karlsruhe	1971-1990	35
India	PREFRE I (Tarapur)	1977-	100
	PREFRE II (Tarapur)	2011-	100
	Kalpakkam	1998-	100
Italy	ITREC-Trisaia	1966-74	5
	EUREX	1970-83	35
Japan	Tokai (shutdown)	1977-2006	100
	Rokkasho	2006	800
Russia	RT-1 (Ozersk)	1977-	400
	EDC (Zheleznogorsk)	2018-	250
UK	B-205	1964-2022 (planned)	1500
	THORP	1994-2018	1200
US	West Valley, New York	1966-72	300
	Barnwell, South Carolina	Not completed (cancelled, 1983)	1500

Table 3. Civilian Reprocessing Plants. Of the 21 plants listed here, nine are operating, nine are shut down and in decommissioning or planned for shutdown, two are under construction and one was never completed. Of the ten countries involved, five (China, France, India, Japan, Russia) are still committed to reprocessing.[19]

Five countries: China, France, India, Japan and Russia still have spent fuel reprocessing programs (Table 3). China, India and Russia also still have active breeder-reactor research, development and demonstration programs. The relatively small stocks of separated non-weapon-grade plutonium accumulated thus far by China and India can be credibly justified by the needs of their breeder demonstration programs.

Russia, however, has stockpiled vastly more separated plutonium than it can foreseeably use. For forty years, after civilian reprocessing began in the Soviet Union/Russia in 1977,[20] it separated reactor-grade plutonium for fueling future breeder reactors while using almost none because its prototype breeder reactors were fueled with enriched uranium instead of plutonium. As a result, as of the end of 2020, Russia had accumulated a stock of 60 tons of separated civilian plutonium – about 7,500 "significant quantities" by the IAEA's metric of 8 kilograms for a Nagasaki-type bomb. In addition, Russia has declared excess for weapons purposes about 40 tons of separated weapon-grade plutonium.

Despite the shutdowns of their prototype breeders, France (Figure 4) and Japan have continued their programs of separating plutonium from the spent fuel discharged by their LWRs. In the absence of breeder reactors requiring plutonium fuel, France pioneered the "recycling" of plutonium in plutonium-uranium MOX fuel in some of its own and its foreign customers' LWRs. Japan has been recycling, albeit slowly, plutonium that was separated from its spent fuel by France and fabricated there into MOX. Japan also plans to recycle plutonium separated at home when its spent-fuel reprocessing and MOX-fuel-fabrication plants finally become operational.

France's and Japan's plutonium-recycle programs continue even though the programs can reduce their national fuel uses of low-enriched uranium (LEU) by only about 10 percent at a cost an order of magnitude larger than the avoided cost of LEU fuel.[21]

France and Japan have not been using as much plutonium as they have been separating, however. As a result, as of the end of 2020, France's stock of unirradiated civilian plutonium had grown to 79.4 tons and Japan's was 46.1 tons.

In 2018, under US pressure, Japan's Atomic Energy Commission declared that "Japan will reduce the size of its plutonium stockpile".[22] At the time, Japan's stock was 46.6 tons.[23] At the end of 2020, it was 46.1 tons.[24] After Japan's Rokkasho Reprocessing Plant begins operating, Japan might have to pay the UK to take ownership of Japan's stock of separated plutonium in the UK to offset the increase of Japan's stock of separated plutonium at home. It would be difficult for Japan's Government to explain to its public, however, why it is forcing Japan's nuclear utilities to pay for the disposal of their separated plutonium in the UK while simultaneously forcing them to pay for the separation of more plutonium in Japan.

Japan's average rate of usage of plutonium during 2016-21 was less than 0.5 tons per year.[25] Nevertheless, Japan plans to complete construction of its decades-delayed $24 billion domestic reprocessing plant in 2022[26] and put it into operation soon thereafter, ramping up over six years to its design capacity of 800 tons of spent fuel per year at which point it will be recovering about 7 tons of plutonium per year.[27]

Figure 4. France's reprocessing complex at La Hague on the English Channel. Since almost all foreign nuclear utilities declined to renew their reprocessing contracts, the 5,000 workers at La Hague have been supported almost entirely by France's nuclear utility, Électricité de France (Source: Wikipedia).[28]

In May 2022, the United Kingdom announced that it would shut down its last operating reprocessing plant in July 2022.[29] As of the end of 2020, however, the UK had accumulated 140 tons of separated civilian plutonium, including 24 tons of foreign plutonium (22 tons Japanese) marooned in the UK as a result of the failure of the UK's MOX fuel fabrication facility.[30]

After a half century and combined expenditures totaling more than $100 billion worldwide,[31] no plutonium breeder or MOX-fueled light-water reactor (LWR) has yet produced power at a cost competitive with that from LWRs fueled with low-enriched uranium and with the plutonium in the spent fuel left unseparated for ultimate disposal in a deep repository.

Civilian plutonium-separation programs are therefore "zombies,"[32] dead economically but nevertheless carrying on as "the living dead." Why do they continue?

Partial explanations for this institutional inertia will be discussed below. It becomes even more striking in a context where the future of nuclear power itself has been dimming. Given more stringent regulation following three major accidents at Three Mile Island in the US in 1979, Chernobyl in the Soviet Union in 1986 and Fukushima in 2011 and the loss of expert construction workers due to fewer nuclear power plants being constructed, the cost of electric power from new nuclear power plants has increased while the costs of generating electric power using wind turbines, photovoltaic panels and burning natural gas have all plummeted. Global generation of nuclear electric power has plateaued and, due to the growth in power production from other sources, the nuclear share of global electric power production has declined from a peak of 17.5 percent in 1996 to about 10 percent in 2019.[33]

In 2020, the IAEA – historically optimistic about the future of nuclear power – projected that, in 2050, nuclear power will provide 8.5% ±2.7% of global electric power with new capacity brought on line between 2020 and 2050 averaging 8 to 18 GWe/yr.[34] That projection is far below earlier projections (see e.g. Figure 1) but may still be high since additions of new nuclear capacity have averaged only about 4.5 GWe/yr since 1990.[35] Also, the IAEA's projection requires the average retirement age of nuclear power plants to increase from 42 years in 2015-19[36] to about 60 years in 2050.

Excess Cold War weapons plutonium

With the end of the Cold War, the combined Russian and US stock of operational nuclear warheads was downsized from a high of about 70,000 in the mid-1980s to about 8,000 in 2020.[37] In 2000, each agreed to declare 34 tons weapon-grade plutonium excess to its military needs.[38] In 2010, Russia decided it would use its 34 tons in MOX fuel for its newest prototype breeder reactor, the BN-800.[39] Russia's 34 tons plus an estimated six additional tons of weapon-grade plutonium that Russia committed not to use for weapons in the 1994 Russia-US Plutonium-Production Shutdown Agreement,[40] plus Russia's separated civilian plutonium total about 100 tons available for starting breeder reactors. This would be enough to start six 1-GWe (1000-MWe) breeder reactors and refuel them for their first five years of operation,[41] after which the recycle of the plutonium recovered from their spent fuel and uranium blankets would be expected to take over. Currently, however, Russia is operating only one plutonium-fueled breeder. Nevertheless, it continues to separate plutonium from LWR fuel and plans to increase its rate of separation.

The US, in addition to committing that it will dispose 34 tons of excess weapon-grade plutonium in parallel with Russia, has announced that it will dispose an additional 16 tons for a total of approximately 50 tons of separated plutonium.[42]

Use of enriched uranium to fuel breeder prototypes

Ironically, the Soviet Union demonstrated decades ago that the easiest way to provide initial cores for "breeder" reactors is to use enriched uranium. The first two Soviet prototype breeder reactors, the BN-350 (1973-1999) and BN-600 (1980-) have been fueled throughout their lives with uranium in annular core zones enriched to 17, 21 and 26% U-235 (listed from the center to the outside of their cores). [43] The third and most recent prototype, the BN-800 (2015-) was started with a mostly enriched uranium core but is shifting to plutonium fuel as Russia's MOX fuel fabrication capacity expands.[44] Russia also has contracted to supply enriched uranium fuel for the first seven years of operation of China's first prototype breeder reactor.[45]

It would have saved the huge expense associated with reprocessing, and avoided the problem of excess stocks of separated civilian plutonium, had countries pursuing breeder-reactor research and development fueled their prototypes with enriched uranium.

How plutonium separation ended in the United States and United Kingdom

Given that plutonium separation continues in China, France, India, Japan and Russia, it is worth understanding why and how it ended in the United States and United Kingdom. As will be seen below, both countries decided to accept the verdict of the market, although the United Kingdom took decades to do so.

United States

The end of reprocessing in the US was triggered by an early crisis in the global nonproliferation regime. The Treaty on the Nonproliferation of Nuclear Weapons, for which the US had been a leading advocate, had come into force in 1970. Four years later, however, India conducted a nuclear weapon test using plutonium that had been separated with US assistance for India's plutonium breeder development program. This forced the US leadership to confront the fact that the US Atomic Energy Commission's (AEC's) worldwide promotion of plutonium breeder reactors was undermining the new nonproliferation regime.

The Ford Administration (1973-77) successfully blocked the export of reprocessing technology by France and Germany to Brazil, Pakistan, South Korea and Taiwan. The Carter Administration, which followed (1977-81), carried out a review of the economics of the AEC's proposed programs to commercialize breeder reactors and recycle plutonium in LWRs. It concluded that breeders and plutonium-fueled LWRs would not be able to compete economically with LWRs fueled with low-enriched uranium "once-through" with direct disposal of the spent fuel in a deep repository. In 1977, President Carter therefore froze licensing of the construction of the government-funded 350-MWe Clinch River Demonstration Breeder Reactor and of the privately funded already-under-construction Barnwell Spent-Fuel Reprocessing Plant, in South Carolina.

The Reagan Administration (1981-9) reversed President Carter's actions. But the Reagan Administration also believed in leaving civilian technology choices to the market. It therefore made clear it would not subsidize reprocessing or oppose a decision of Congress to end government funding for the US breeder reactor demonstration program.

US nuclear utilities had been led to expect that the cost for reprocessing their spent fuel would be offset by payments for the recovered plutonium for use in the startup cores of breeder reactors.[46] With the end of the US breeder-commercialization program and the poor economics of plutonium fuel in LWRs, however, there would be no market for civilian plutonium. The utilities therefore decided that the least costly disposal path for their spent fuel would be direct emplacement in a deep repository.

Congress quickly passed the 1982 Nuclear Waste Policy Act, which instructed the US Department of Energy to site and build a national repository for spent fuel and other radioactive waste. The nuclear utilities would pay 0.1 cents per nuclear kilowatt hour to the government for disposal of their spent fuel. The government would pay for the additional space required for spent naval-reactor fuel and the reprocessing waste from past US weapons-plutonium production.

Environmental critiques and local political opposition to the repository site chosen by Congress 100 kilometers northwest of Las Vegas, Nevada indefinitely delayed completion of the US repository, however. The US Government is therefore paying for dry casks to store the utilities' spent fuel on their reactor sites. This is becoming a problem at sites where all the reactors have been decommissioned (see e.g., Figure 5). Two companies have proposed consolidated dry-cask storage sites in the desert on either side of the Texas-New Mexico border. One has received a federal license and the other is expected to, but there is opposition in both states.[47]

Figure 5. Casks are all that remain on the site of the US 560-MWe Connecticut Yankee nuclear power plant, which operated on the east bank of the Connecticut River from 1968 to 1996. The forty casks on the left contain more than 90 percent of the spent fuel discharged by the reactor over its lifetime.[48] The casks on the right (increased from two to five subsequent to this photo) contain the radioactive internals of the reactor. All the casks await the licensing of a national deep underground repository or central interim surface storage site. Photo: courtesy Connecticut Yankee.

United Kingdom

The end of civilian reprocessing in the UK has been long and drawn out. The UK ended its breeder development program with the shutdown of the Dounreay Prototype Fast Reactor in 1994. But it continued to separate and accumulate civilian plutonium with no planned use for another three decades. Between 1994 and 2018, two reprocessing plants operated on the Sellafield site in northwest England. The older plant, B-205, was built to reprocess the uranium-metal fuel discharged by the UK's first-generation gas-cooled power reactors, which were originally developed to produce weapons plutonium as well as power. The reactors could have been shifted to a more storable ceramic fuel after the UK's needs for weapon-grade plutonium were satisfied in approximately 1995, but were not. The last of these first-generation reactors, called Magnox reactors due to the easily-dissolved magnesium alloy used to clad their uranium-metal fuel, was shut down in 2015. The reprocessing of the backlog of Magnox spent fuel is to be completed in 2022, after which B-205 is to be decommissioned.[49]

The newest reprocessing plant on the Sellafield site, the Thermal Oxide Reprocessing Plant (THORP), was built by the government-owned company, British Nuclear Fuels Limited (BNFL) to provide reprocessing services to European and Japanese utilities that desired startup plutonium fuel for planned breeder reactors. Construction on THORP started in 1979 and it began operating in 1994 with cost-plus contracts to reprocess a total of 5,000 tons of spent fuel from nuclear utilities in Germany, Italy, Japan, Netherlands, Spain, Sweden and Switzerland. To provide the additional 2,000 tons of "baseload" contracts required to pay for the construction of the plant, the UK government required its two electric power companies – set up in the process of privatizing the UK power generation industry – to have their fuel reprocessed as well. This requirement was imposed even though both companies operated second-generation Advanced Gas-cooled Reactors (AGRs) using uranium-oxide fuel inside stainless-steel cladding that could be stored long term and there was no anticipated use for the separated plutonium.[50] In 2004, the year the baseload contracts were originally to have been completed, BNFL went bankrupt and the site was taken over by the UK Nuclear Decommissioning Authority. The baseload contracts were completed eight years later in 2012.[51]

Virtually none of THORP's foreign reprocessing contracts were renewed.[52] To sustain THORP, UK nuclear utilities were forced to sign post-baseload reprocessing contracts for an additional 2500 tons of AGR fuel – still with no foreseeable use for the plutonium.

In 2009, the utilities operating the UK's fourteen 600-MWe AGRs and its one LWR were bought by Électricité de France (EDF).[53] At home, EDF is required to support France's government-owned reprocessing and MOX fuel fabrication plants. France's government felt no obligation to support reprocessing in the UK, however, and EDF declined to renew its UK subsidiary's reprocessing contracts. In 2018, therefore, after fulfilling its existing contracts, THORP shut down. In the future, UK AGR spent nuclear fuel is to be stored at Sellafield.[54] Pending availability of deep repositories, surface spent fuel storage has become standard practice in all European countries other than France and the Netherlands.[55]

The examples of the US and UK demonstrate that, in the absence of government mandates, the "invisible hand" of the market will phase out reprocessing, leaving governments to deal with the problem of disposing of the separated plutonium, reprocessing waste, and contaminated reprocessing plants. In 2018, the UK National Auditing Office estimated the remaining cost of cleaning up the Sellafield plutonium site at £91 billion (~ $120 billion), not including the cost of disposing of the reprocessing waste and separated plutonium.[56]

Plutonium separation and nuclear-weapon proliferation

The persistence of plutonium separation is not just a curious case of economic irrationality; it also threatens international security. The world learned that in 1974 when India used some of the plutonium it had separated for its breeder reactor program in the "peaceful nuclear explosion experiment" that launched its nuclear-weapon program.[57]

Seventeen years later, when the Soviet Union collapsed, there was worldwide concern about the security of its huge stocks of highly enriched uranium and unirradiated plutonium. The US bought 500 tons of excess Soviet weapon-grade uranium – enough for 20,000 nuclear weapons –after Russia blended it down to 5-percent enrichment for sale to fuel US nuclear power reactors. There was no commercial market for plutonium fuel, however. The US Departments of Energy[58] and Defense[59] therefore invested between one and two billion dollars to upgrade the security of Russia's excess weapon materials. Small quantities of stolen Soviet/Russian fissile material have been intercepted.[60] It is not known outside Russia whether larger quantities were stolen.

Both "weapon-grade" plutonium (containing more than 90% Pu-239) and "reactor-grade" plutonium extracted from spent power-reactor fuel, which contains about 50% Pu-239, are "direct-use" nuclear-weapon materials. Reactor-grade plutonium in a first-generation Nagasaki-type weapon design – arguably within the reach of terrorists[61] – would explode with a yield between the equivalent of 500 tons and about 20,000 tons of chemical explosives.[62] In modern nuclear-weapon designs, reactor-grade plutonium could reliably produce the same yield as weapon-grade plutonium.[63]

Civilian plutonium separation and use have greatly increased the number of locations where separated plutonium can be found. In an age of instability, this creates significant risks of nuclear-weapon proliferation and terrorism.

There is no offsetting benefit to justify those risks.

Why reprocessing continues

Direct disposal of spent fuel is less costly than recycling the plutonium. Reprocessing of spent nuclear fuel therefore continues only where governments require it.

There appear to be three main factors in addition to institutional inertia underlying national decisions to continue reprocessing:[64]

- Weapon-program connections,
- Pressures from local and regional governments and their elected representatives to keep the jobs and tax benefits associated with huge reprocessing facilities, and
- The myth that deeply buried reprocessing waste is less hazardous than deeply-buried spent fuel.

As discussed below, these factors contribute with different weights in different countries.

Weapon-program connections

With the notable exception of Japan, all countries that still reprocess spent fuel originally began by separating plutonium for weapons. In the case of China and India, this connection appears to be still operative.

China

China's pilot civilian reprocessing plant is located at the Jiuquan Atomic Energy Complex, adjacent to a shutdown military reprocessing plant just south of the Gobi Desert.[65] The workforce will soon move to a larger twin-line, 400-ton per year "demonstration" reprocessing plant being built nearby.[66]

These facilities are owned by the China National Nuclear Corporation (CNNC). Until 1988, CNNC was the Ministry of Nuclear Industry, originally established to produce plutonium and highly enriched uranium for China's nuclear weapons. In a 2016 self-description, CNNC described itself as "a leading element of national strategic nuclear forces and nuclear energy development, [undertaking] missions to ensure national security and facilitate domestic economic development."[67]

Based on this self-description, if tasked by China's government, CNNC would be expected to produce additional plutonium to facilitate an expansion of China's nuclear-weapon stockpile. It appears that CNNC may now have been so tasked.

The best independent estimate of China's stockpile of weapon-grade plutonium is 2.3-3.5 tons[68] – enough, allowing for working stocks, for at least 500 warheads. This is consistent with the US 2020 intelligence estimate that China was expected to have about 200 warheads on intercontinental ballistic missiles by 2025 and had enough fissile material to double that number.[69]

In the summer of 2021, however, China was discovered to be building about 300 ICBM silos in its northern and western desert areas.[70] Half of China's current 20 silo-based ICBMs are believed to carry one warhead and the other half are believed to carry five. China's newest ICBM, the DF-41, is believed to be able to carry up to three warheads.[71] If China puts missiles carrying three warheads into each of the new silos, it would, almost certainly require additional plutonium.

The plutonium produced in the uranium blankets around the cores of the two 600-MWe breeder reactors CNNC is building on a peninsula near Xiapu will be weapon-grade. This plutonium could be used either in reactor fuel or in warheads. Scaling from an estimate made by Glaser and Ramana for India's 500-MWe reactor, a Chinese 600-MWe breeder reactor could produce about 170 kilograms of weapon-grade plutonium annually, enough for perhaps 400 warheads over a decade.[72]

It is concerning in this connection that China has stopped submitting to the IAEA the annual public reports on its civilian stock of unirradiated plutonium it committed to when it joined in the 1996 Guidelines for the Management of Plutonium. Its last report was of its stocks as of the end of 2016. As of the end of September 2021, the other eight countries that are parties to the Guidelines had reported their stocks as of the end of 2020.[73] This raises the question of whether China still considers its stocks of reactor-grade plutonium strictly civilian. The purpose of China's LWR spent fuel reprocessing program is to provide startup plutonium for its breeder reactors but, if those reactors are to produce plutonium for China's weapons, the LWR plutonium becomes part of China's nuclear-weapon-production program. As discussed below, this complication has already existed in India's breeder program for two decades.

India

In 1964, India's Department of Atomic Energy (DAE) started operating a small reprocessing plant at its Bhabha Atomic Research Center (BARC) near Mumbai to separate weapon-grade plutonium from the irradiated fuel of its first research reactor for India's nuclear-weapon and breeder R&D programs.[74] DAE subsequently built three small reprocessing plants to separate reactor-grade plutonium from the spent fuel of some of India's heavy-water power reactors to provide the initial cores for its Prototype Fast Breeder reactor.[75]

India has refused to put either its breeder program or the associated reprocessing program under IAEA safeguards. In its 2005 agreement with the United States, which paved the way for the end of the international embargo on nuclear technology and uranium that was imposed on India following its 1974 nuclear test, India's government justified its refusal of safeguards on its reactor-grade plutonium by characterizing its breeder program as "strategic," which suggested a weapons connection.[76]

Thus, there are grounds to suspect that both China's and India's reprocessing and breeder programs are dual purpose – to produce weapon-grade plutonium for their national nuclear-weapon programs as well as electric power.

Japan

Japan is currently the only state without nuclear weapons that maintains a commitment to reprocessing. In 1977, after the 1973 Arab oil embargo and petroleum price increase that disrupted the world economy, Japan's prime minister was understood by the Carter Administration to have stated that Japan's breeder program was a matter of "life and death" for Japan.[77] Japan's Ministry of International Trade and Industry (predecessor of the current Ministry of Economics, Trade and Industry [METI]), and Japan's Science and Technology Agency – then in charge of nuclear power policy – must have understood that dependence on imported uranium, which is cheap and can be stockpiled at relatively modest cost, is very different from dependence on imported oil. Nevertheless, a commitment to Japan's plutonium program became embedded within both METI and Japan's dominant Liberal Democratic Party, backed by the stubbornness of Japan's nuclear-energy R&D community.

It is possible that Japan maintains both its plutonium-separation and uranium enrichment programs in part to have a nuclear-weapon option in case the "nuclear umbrella" the US has offered to protect Japan from attack comes to seem inadequate as Japan's ultimate security guarantee. ("Nuclear umbrella" is a shorthand for the US commitment to use nuclear weapons, if necessary, to defend its allies.)

In 2018, Nobuo Tanaka, a former senior nuclear-policy official in METI and its predecessor ministry, argued

> "Nuclear power is necessary for security and national defense reasons. Although Japan, which experienced Hiroshima and Nagasaki, has no intention whatsoever of acquiring nuclear weapons, discarding nuclear capability in this day and age, when nuclear missiles of North Korea fly over us, would mean that country would take Japan lightly."[78]

Some members of Japan's defense establishment also appear to believe that, if Japan did not have its own plutonium separation and uranium enrichment programs, the US too might take Japan's security concerns lightly.

It is, in fact, a standard argument in the US government's nuclear-weapon policy debates that certain US nuclear-weapon systems cannot be eliminated and that the US cannot adopt a no-nuclear-first-use policy because Japan might react by deciding to acquire its own nuclear deterrent.[79] Yukio Sato, a former Permanent Representative of Japan to the UN, and an opponent to the US adopting a no-first-use policy, stated in his book, *An Extended Umbrella*, published in 2017, "It is not bad there is concern that Japan might go nuclear since that is the main reason the US offers its nuclear umbrella to Japan."[80]

Japan could credibly threaten to acquire nuclear weapons. It has enough unirradiated reactor-grade plutonium in country to build more than one thousand nuclear warheads.[81] It also has modern US-made fighter-bombers and has developed solid-fuel space launchers comparable to the US Minuteman intercontinental ballistic missile.[82] This does not mean, however, that Japan needs the huge Rokkasho Reprocessing Plant, designed to separate up to eight tons of plutonium per year, to establish the credibility of its ability to acquire nuclear weapons. Its Tokai pilot reprocessing plant – now shut down – was more than adequate for that purpose.

Jobs and subsidies to host regions

Regional and community governments hosting reprocessing plants in remote, low-income areas are given large subsidies for accepting the facilities. These subsidies, property taxes on the plants, and jobs at the plants become essential to local economies. Local and regional political representatives therefore become fierce defenders of the facilities in the central government policy-making process. These political dynamics are familiar for military bases, nuclear-weapon laboratories and space-program facilities in the United States. In principle, governments could repurpose the funds to support more useful work, but those benefiting from the current expenditures know who they are while those with skills matched to alternative jobs are much more difficult to mobilize.

France

The reprocessing plant at La Hague is on a remote peninsula jutting out into the English Channel. As its operator, Orano (formerly AREVA) claims, it is "the leading employer in the Cotentin Peninsula."[83]

The cost of reprocessing has become a major burden on Électricité de France (EDF), however, and reprocessing is no longer a significant source of foreign exchange for France. With the exception of one small power reactor in the Netherlands, none of Orano's former foreign customers renewed their reprocessing and MOX-fuel-fabrication contracts. EDF therefore has to provide almost 100% support for the 5,000 workers at the Orano's reprocessing plant.[84] Another 725 workers are at Orano's Melox MOX fuel fabrication plant.[85] In addition, 29,000 workers are operating EDF's 56 nuclear power reactors.[86]

Japan

Japan Nuclear Fuel Limited and its related companies have about 7,500 full-time employees,[87] mostly at the Rokkasho Reprocessing Plant on the northern tip of Japan's main island in one of Japan's poorest regions, Aomori Prefecture. Government and utility payments associated with the reprocessing plant provide a significant fraction of the support for the prefectural and village governments.[88]

The political leadership of Aomori Prefecture mobilizes whenever any question is raised about the future of the complex. Indeed, after the Fukushima accident, when the Democratic Party of Japan (DPJ), which controlled the government at the time, was advocating a phaseout of nuclear power, opposition from Aomori was so fierce that the DPJ adopted the nonsensical policy of phasing out nuclear power but not phasing out reprocessing![89]

In 2005, Japan's Atomic Energy Commission claimed that opposition to prolonged on-site storage of spent fuel from the communities hosting Japan's nuclear power reactors required reprocessing to proceed. Otherwise, the JAEC warned, the host communities would force the shutdown of nuclear power in Japan.[90]

After 25 years delay in the operation of the Rokkasho Reprocessing Plant, however, most of the host communities have accepted the idea of extended storage of spent fuel at the power plants. Community concerns about the delay in removal of the spent fuel appear to be outweighed by the benefits provided by the nuclear power plants in jobs, subsidies and local tax revenue.

Figure 6. Central square in Russia's plutonium city, Zheleznogorsk, in central Siberia, 2010. Photo: Tatiana Bulyonkova, 3 June 2010, flickr.com.[91]

Russia

During the Cold War, the Soviet Union built three isolated towns with populations of about 100,000 each to produce plutonium for nuclear weapons. Each was originally known by its postbox number in a nearby large city. Ozersk in the Urals was originally known as Chelyabinsk-40 and, later as Chelyabinsk-65. Seversk and Zheleznogorsk, both in central Siberia were originally known as Tomsk-7 and Krasnoyarsk-26 respectively (Figure 6).[92]

Unlike their counterparts in the United States, these cities are still “closed,” surrounded by double fences with access controlled by internal troops now under President Putin’s direct command.[93]

Figure 7. Russia’s spent-fuel-storage and civilian reprocessing site outside Zheleznogorsk is surrounded by a triple security fence. Spent-fuel transport casks – white dashes at this scale – can be seen at the top on railroad cars along the tracks coming in from the north. The spent fuel storage buildings are interconnected into two sets, each set with its own pool for a total of 8,600 tons of spent fuel in pools and 37,800 tons in dry storage – enough in total for about 70 years of the annual discharges from Russia’s reactors in 2013. The building at the right is the new pilot reprocessing plant that has been reported at this site. Source; Google Earth image, 13 July 2021.[94]

Since the dramatic post-Cold War downsizing of Russia’s nuclear-warhead stocks, the plutonium-production reactors and military reprocessing plants in these three cities have all been shut down. The Mayak complex outside Ozersk is still responsible for tritium production for Russian weapons,[95] and Seversk hosts one of Russia’s four uranium enrichment plants which produce low-enriched uranium to fuel Russian and foreign nuclear power reactors. Additional missions are required to support the cities, however. This may be one reason an experimental molten-lead-cooled breeder reactor is being built in Seversk.

At Mayak, civilian plutonium separation continues and there are plans to increase the rate of reprocessing despite the fact that Russia's stockpile of separated plutonium already exceeds any foreseeable need.

Zheleznogorsk has become the destination of most of Russia's spent power-reactor fuel. Rosatom maintains that all of this spent fuel will be reprocessed and has built a pilot reprocessing plant in Zheleznogorsk (Figure 7).

Before the collapse of the Soviet Union, Zheleznogorsk was to be the home of RT-2, a large reprocessing plant with a design throughput of 1500 tons of spent LWR fuel per year. Construction on RT-2 began in 1976 but was stopped in 1990 due to a lack of funds and opposition from the nearby large city of Krasnoyarsk, 50 kilometers up the Yenisei River.[96]

RT-2's two intake pools, which were completed before construction of the reprocessing plant was abandoned, have been dense-racked to hold a combined 8,600 tons of LWR spent fuel. They probably also serve as the intake pools for a complex of buildings holding spent fuel in air-cooled casks. The design capacity of this dry-cask storage reportedly is 11,275 tons of LWR fuel plus 26,510 tons of spent fuel from graphite-moderated, water-cooled (Chernobyl-type) reactors.[97]

United Kingdom

Although reprocessing is ending at the United Kingdom's Sellafield reprocessing complex on the northwest coast of England, the site still has a massive workforce of 11,000 people.[98] Most of this workforce is employed in decommissioning and cleanup operations with a century-long timetable.[99] In 2020, discussions with neighboring Cumbria County communities increased the likelihood that one of these communities may host the national deep radioactive-waste repository.[100] But resistance there and at other proposed sites is strong.[101] If a site is found, Sellafield could be given the task of mixing the 140 tons of plutonium stored there with other materials to create stable waste forms for disposal in the repository.

The myth that reprocessing waste is less dangerous than spent fuel

Following the failure of their plutonium breeder-reactor commercialization programs, the fast-neutron-reactor establishments in both France and Japan began to argue that separating plutonium from spent fuel and fissioning it should nevertheless continue in order to reduce the longevity of the hazard from spent fuel.

This argument provided the rationale for the promulgation of France's 2006 Planning Act on Radioactive Materials and Wastes, which requires

> "the reduction of the quantity and toxicity of radioactive waste shall be sought notably by processing spent fuel and by processing and conditioning radioactive waste."[102]

The supposed hazards associated with burying plutonium also provided a rationale in Japan to maintain the requirement that spent fuel be reprocessed. Japan's Designated Radioactive Final Disposal Act of 2000 allows only waste from reprocessing and MOX fuel production to be emplaced in the planned national repository. Spent fuel is excluded.[103]

In the early days of nuclear power in Japan, there was not much resistance from Japan's nuclear utilities to the imposition of the reprocessing requirement. At the time, they expected a relatively quick transition to breeder reactors. After it became clear that breeders would not be commercialized for the foreseeable future, however, they found themselves entrapped. In March 1993, in a meeting in Tokyo, the fuel-cycle managers of Japan's three largest nuclear utilities were asked whether, if they had the choice to make the decision again, would they choose reprocessing. One answered, "No, but we are trapped now," and the other two nodded their agreement.[104]

In 2016, out of fear that some of Japan's nuclear utilities might go bankrupt after the Fukushima accident, an additional law established the Nuclear Reprocessing Organization of Japan to collect funds for reprocessing. The law requires nuclear utilities to pay NuRO for the "steady implementation of reprocessing" of their spent fuel and fabrication of the recovered plutonium into MOX fuel. The annual payments are based on the nuclear kilowatt-hours each utility generated during the previous year.[105]

The need to eliminate plutonium also provides a new false rationale for fast-neutron reactors because fast neutrons are required to fission effectively the even-numbered isotopes of plutonium: Pu-238, Pu-240 and Pu-242. Because of its high fraction of even-numbered isotopes, the plutonium in spent MOX fuel is not a good fuel for LWRs. France has therefore put off reprocessing its spent MOX fuel until a future when fast-neutron reactors might or might not be built.[106]

France's 2006 law required that a fast-neutron reactor or an accelerator-driven reactor be in operation by 2020. In 2012, France's Atomic Energy Commission (CEA, renamed in 2010 the Commission of Atomic Energy and Alternative Energies but without a change in acronym) proposed construction of a fast-neutron reactor that it named ASTRID for Advanced Sodium Technological Reactor for Industrial Demonstration. CEA was unable to obtain full funding for the project, however, and, in 2016, announced that, instead of putting ASTRID into operation in 2020 as the law required, it would only begin to work on a detailed design in 2020.[107] In 2019, the project was cancelled.[108]

Japan's prototype breeder reactor, Monju, was commissioned in August 1995, but was shut down by a sodium fire four months later. Despite efforts by Japan's Atomic Energy Agency (JAEA) to get it back into operating order, the reactor did not operate again. In 2015, after many safety infractions, Japan's Nuclear Regulation Authority declared JAEA "unfit" to operate the reactor safely.[109] In December the following year, Japan's government decided to decommission Monju. A Council on Fast Reactor Development that had been established earlier in that year tried to justify continuation of R&D on fast reactors and reprocessing, despite the demise of Monju by citing cooperation with France's ASTRID project. After ASTRID was cancelled, the justification became cooperation with the US Idaho National Laboratory on its proposed Versatile Test Reactor (VTR), whose fate is now up in the air due to lack of Congressional support.[110] The most recently, the proposed partnership is with Bill Gates' TerraPower, which plans to build a prototype sodium-cooled Natrium reactor in Wyoming with up to $2 billion project support from the US Department of Energy.[111]

Government-commissioned studies in the US and Sweden have found, however, that the claimed safety benefits from separating and fissioning the plutonium are not significant. The radiation doses to humans on the surface above a failed deep underground spent-fuel repository would *not* be dominated by plutonium or other transuranic elements.

In the US, the Department of Energy commissioned the National Academies to study the technologies, costs and environmental and health benefits of separating and fissioning ("transmuting") the plutonium and the other transuranic elements in spent fuel. The study, published in 1996, concluded

> "Taken alone, none of the dose reductions seem large enough to warrant the expense and additional operational risk of transmutation."[112]

In Sweden, the Nuclear Fuel Management Company (SKB), which is responsible for the design and construction of the national deep-underground spent fuel repository, carried out an assessment of the doses from plutonium and other radioisotopes to a hypothetical subsistence farmer on the surface above the repository for a hypothetical case in which the spent fuel would not be packaged in durable casks surrounded by clay.

It will be seen in Figure 8 that plutonium and the other long-lived transuranic elements do not dominate the calculated doses. This is in part because the oxides of these elements are relatively insoluble in oxygen-depleted deep ground water.[113] Furthermore, the plutonium oxide that does reach the surface is not easily absorbed by plants or through the walls of the human gut.

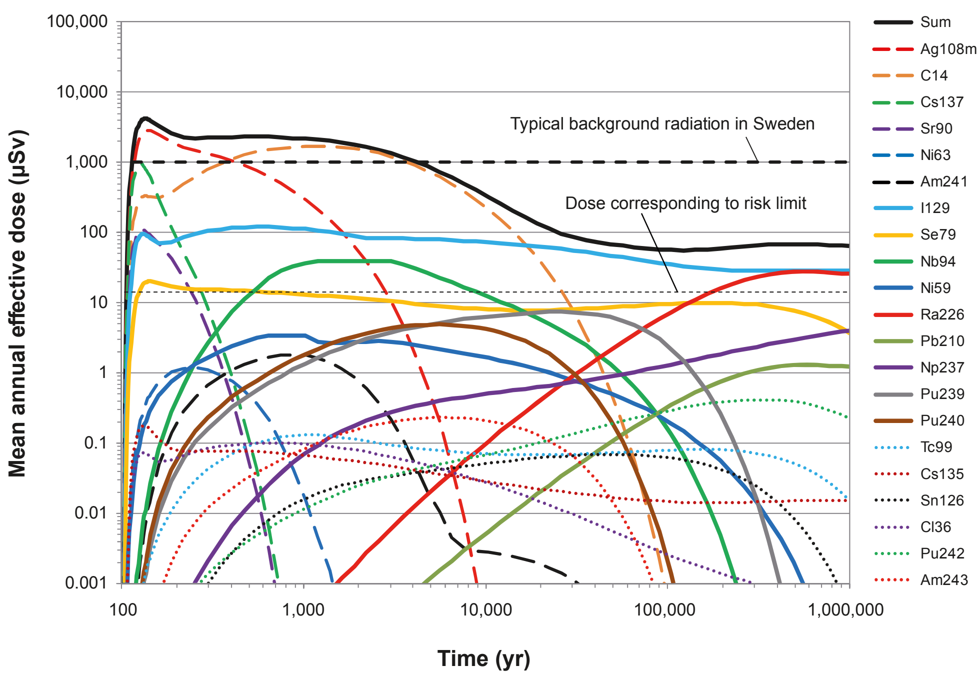


Figure 8. Contributors to the radiation doses above a failed deep repository. Calculations by the Swedish Nuclear Fuel Management Company (SKB) of the contributions, as a function of time after repository closure, of different radioisotopes in spent fuel to the radiation dose received by hypothetical subsistence farmers and their families drinking water and eating produce grown above a hypothetical deep repository where spent fuel has been buried without casks or surrounding layer of bentonite clay. The contributions of the long-lived transuranic elements: Neptunium-237, Plutonium-239, Pu-240 and Americium-241 are visible. The dominant contributors in different eras, however, are: from 400 to 20,000 years, carbon-14 produced by neutron absorption in trace nitrogen-14 in the fuel; from 20,000 to 400,000 years, iodine-129, a long-lived fission product; and thereafter out to one million years, I-129 and radium-226, the latter a decay product of the mined uranium-238 that constitutes more than 90% of the mass of the fuel. Source: SKB.[114]

This finding is consistent with the fact that, even though about 3 tons of plutonium-239 was delivered to the earth's surface in radioactive "fallout" from atmospheric nuclear testing from 1945 through 1980, plutonium was estimated to make only a small contribution to the projected cumulative radiation dose from the fallout and that contribution was dominated by inhalation rather than ingestion.[115] The section on recommendations discusses the possibility that the UN Scientific Committee on the Effects of Atomic Radiation, the organization that conducted the fallout study, might carry out a study on the environmental hazards from deep underground spent fuel repositories.

Ironically, the radioisotopes that SKB found would dominate the doses to hypothetical subsistence farmers living above a failed repository are costly to capture and immobilize during reprocessing and are dumped into the atmosphere and ocean by France's reprocessing plant at La Hague.

Specifically, La Hague releases into the atmosphere in the form of carbon-dioxide a large fraction of the 5,700-year half-life carbon-14 in the spent fuel it reprocesses, and dumps into the English Channel virtually all of the volatile 16-million-year half-life fission-product, iodine-129.[116] Japan's Rokkasho Reprocessing Plant, which was designed by France's AREVA, has the same arrangements.

Accident risks from reprocessing

In addition to reprocessing failing to reduce the risks from spent fuel, it brings with it risks of accidents much more consequential than repository leakage. Indeed, the world's worst nuclear accident before Chernobyl occurred in the Urals in 1957 at the Soviet Union's first military reprocessing plant, the Mayak Production Association, outside the nuclear city now known as Ozersk.

The water in a tank of concentrated liquid radioactive waste evaporated and the dried-out reprocessing chemicals heated up and exploded. As a result, it was necessary to relocate the population from a contaminated downwind area of 1,000 square kilometers, about the same size as the Fukushima accident relocation area.[117] Fortunately, the plume did not blow toward either Chelyabinsk or Ekaterinburg, major nearby cities with populations of more than one million each (Figure 9).

The accident is little known because the Soviet Union was able to keep it secret for two decades until Zhores A. Medvedev, an émigré scientist, revealed it.[118] The US and UK intelligence services had made no efforts to inform their publics about what they knew – perhaps wishing not to arouse concerns about the safety of their own governments' military reprocessing plants.[119]

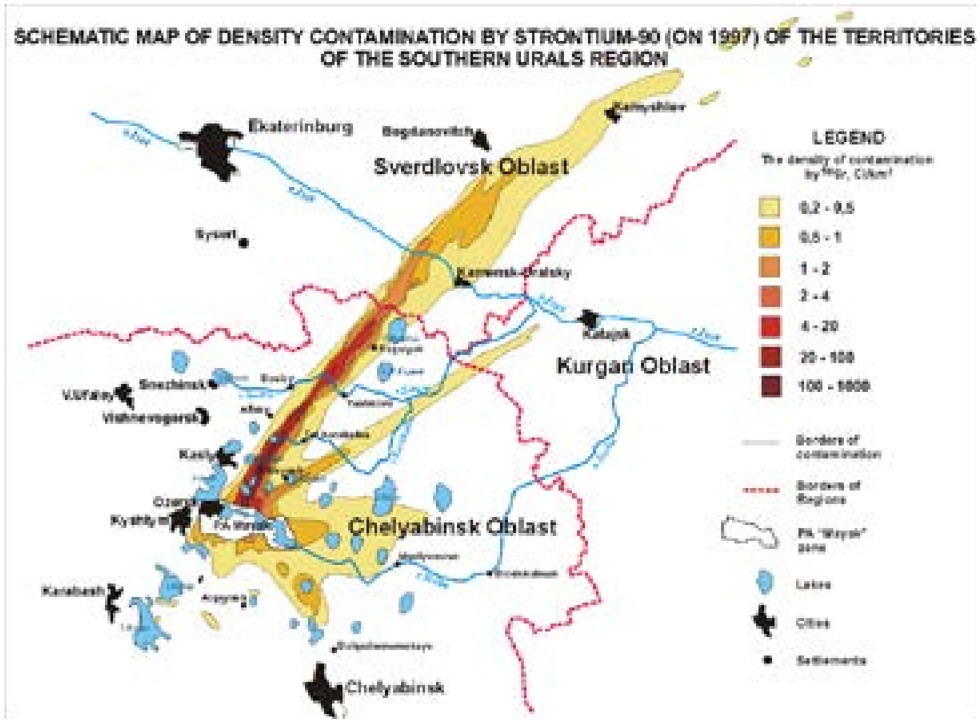


Figure 9. The "Urals Trace," strontium-90 contamination from the 1957 explosion in a tank of dried-out reprocessing waste at the Mayak Production Association outside Ozersk, Source: Urals Research Center for Radiation Medicine, University of Utah and Pacific Northwest National Laboratory.[120]

A number of smaller contamination events have occurred as a result of "red oil" explosions within reprocessing plants. Red oil is created by radiolytic reactions between the nitric acid and organic solvents used in the standard PUREX plutonium separation process. In 1993, red oil exploded in a process tank at Russia's Seversk military reprocessing plant with an estimated energy release equivalent to 100 kilograms of chemical explosives. Fortunately, the tank did not contain much radioactivity.[121]

Another potential explosion hazard in high-level-waste tanks is from the accumulation of hydrogen produced by ionizing radiation from fission product decays splitting the H_2O water molecules in the waste. Ramana, Nayyar and Schoeppner considered the potential consequences of a hydrogen explosion in a high-level-waste tank at the Kalpakkam reprocessing plant on India's southeast coast. They calculated 47,000 extra cancer deaths if the wind blew the radioactivity toward Chennai, a city of nine million to the north of the plant.[122]

By comparison, storing spent fuel in air-cooled dry-casks and burying it later in a deep repository is both low cost and low risk.

Recommendations

Based on the above discussions, this report makes two recommendations:

1. Broaden the proposed Fissile Material Cutoff Treaty to include a ban on the separation of plutonium for any purpose, civilian as well as military. In the meantime, strengthen implementation of the 1997 Guidelines for the Management of Plutonium and place all unirradiated civilian and demilitarized weapons plutonium under IAEA safeguards.

2. Launch international scientific studies on the environmental hazards of the direct disposal in a deep repository of spent fuel vs. reprocessing wastes and engage in multinational cooperation on direct disposal of separated plutonium.

A ban on the separation of plutonium for any purpose

The dangers from the growing global stock of economically negative-value but weapon-usable separated plutonium suggest the desirability of broadening the scope of the proposed international Fissile Material Cutoff Treaty (FMCT), which, in its current formulation, would ban only the separation of plutonium and production of highly enriched uranium for weapons purposes.

Negotiation of an FMCT was called for by a UN General Assembly resolution in 1993. For more than a decade, however, the Geneva-based Conference on Disarmament debated proposals to link negotiations on the FMCT to negotiations of other arms-control treaties.

Since 2009, the required consensus for proceeding with the negotiations has been blocked by Pakistan – apparently out of concern about the potential weapons use of the large stock of reactor-grade plutonium India has separated for its breeder program.[123] India has fed this concern by designating its plutonium breeder reactor program as "strategic" and refusing to place it under IAEA safeguards.

India intends to use the reactor-grade plutonium extracted from the spent fuel of its heavy-water power reactors to fuel its Prototype Fast Breeder Reactor, but may well intend to use the PFBR to produce weapon-grade plutonium as well as electric power.

China's breeder program is likely dual purpose as well.

Given that negotiation of an FMCT is already stalled, it could be argued that broadening the ban to include plutonium separation for any purpose will make it even more difficult to start negotiations. On the other hand, India and China have already complicated the situation by mixing their civilian and military plutonium programs. In this context banning civilian and military plutonium separation could be a step toward dealing with Pakistan's concerns by halting plutonium production in India's breeder program. France's and Japan's nuclear utilities might welcome the broadening, given the economic burdens their governments have imposed on them by insisting that they continue to pay for reprocessing.

Negotiations such as are proposed here may not seem possible in the foreseeable future but it also is hard to foresee when negotiations on a traditional FMCT will become possible. Given that situation, a complete ban is a simpler and more rational objective for any negotiation.

Broadening the FMCT into a ban on the production of all weapon-usable fissile materials would parallel the evolution of the Comprehensive Nuclear Test Ban Treaty (CTBT).

Article 5 in the 1970 Nonproliferation Treaty allows for "peaceful nuclear explosions." This came about because, in the late 1960s, when the NPT was being negotiated, US and Soviet nuclear-weapon-design laboratories were promoting peaceful nuclear explosions as a low-cost method to create harbors and canals, break up underground rock to free natural gas, create cavities for storing oil and gas, and for other applications.[124]

By the 1990's, when the Comprehensive Test Ban Treaty (CTBT) was finally negotiated, however, the environmental impacts of peaceful nuclear explosions were seen as outweighing the benefits. Radioactive fallout from surface explosions would require long-term evacuation from adjacent areas and natural gas released from fractured rock by underground explosions would be made unusable by contamination with radioactive tritium. It therefore was agreed that the basic obligation in the CTBT should be expanded to "not to carry out any nuclear weapon test explosion *or any other nuclear explosion*" (emphasis added).

A provision was included in Article 8 of the CTBT that makes it possible to revisit the issue of peaceful nuclear explosions at any CTBT Review Conference. Any state party can request an amendment to the CTBT that would allow "underground nuclear explosions for peaceful purposes." The bar to such an amendment is set very high, however. It can only be considered if there is a consensus among the parties.

Another IPFM report has argued that all reactor fuel uses of weapon-usable highly enriched uranium (HEU) can be converted to low-enriched uranium and that therefore *all* production of HEU could be banned.[125] Adding a ban on the separation of plutonium for any purpose would similarly bar the door to economically pointless "civilian" plutonium programs that could morph into weapons programs.

As with the CTBT, an article could be included in the FMCT that would allow any country to propose an amendment allowing reprocessing if there were a consensus among the parties that the benefits would exceed the risks.

Ending civilian reprocessing would greatly reduce the cost of verifying an FMCT. When they were both operating, two facilities, Japan's pilot and commercial reprocessing plants, accounted for 20% of the IAEA's global safeguards budget.[126] Not including the B-205 plant, which the UK is in the process of shutting down, the nuclear-armed states have a total of 9 operating non-military reprocessing plants plus the two under construction in China (Table 3). Although not as costly as reprocessing plants, MOX-fuel-fabrication plants also are costly to safeguard. Extra safeguards are also required during periods when unirradiated MOX fuel is present at reactors using MOX fuel.

Strengthen implementation of the 1997 Guidelines for the Management of Plutonium

In the meantime, the nine countries subscribing to the 1997 agreed Guidelines for the Management of Plutonium should meet to discuss implementation of their commitments relating to the Guidelines' requirement to "take into account…the importance of balancing supply and demand, including demand for reasonable working stocks for nuclear operations, as soon as practical."[127]

The nine parties to the Guidelines now include only four countries with ongoing civilian plutonium programs (China, France, Japan, and Russia). In addition, they include the United Kingdom, which planned to end its reprocessing in July 2022, and the United States, which, although it ceased civilian reprocessing in 1972, has declared large stocks of weapons plutonium excess to its weapons needs. The final three country members are Belgium, Germany, and Switzerland. The first two once had both pilot reprocessing and MOX plants and all three had reprocessing contracts with France and the UK. They did not renew those contracts, however, and have disposed of almost all of their separated plutonium in MOX fuel. Plutonium scrap from closed MOX plants in Belgium and Germany has been shipped for storage to France's reprocessing plant at La Hague.[128] Among the countries that reprocess for civilian purposes today, only India is missing.

The continued participation of countries that no longer have plutonium stocks may be objected to by some of the other countries. The remaining countries could meet, however, to discuss their plutonium programs, their definitions of "reasonable working stocks" and how they plan to reduce to those levels and publicly report those plans to the IAEA.

As discussed above, there is no foreseeable civilian demand for separated plutonium in Russia that would consume its existing stocks. Also, French and Japanese nuclear utilities now appear to see the separation of plutonium for recycle in LWR MOX fuel as a costly extravagance that they would be happy to end if their governments allowed (despite the fact that Japan's utilities now pretend to support reprocessing wholeheartedly).

Placement under IAEA safeguards of material declared excess to weapon needs

In its final document, the 2000 Nonproliferation Treaty Review Conference reported agreement on the need for

> "[a]rrangements by all nuclear-weapon States to place, as soon as practicable, fissile material designated by each of them as no longer required for military purposes under IAEA or other relevant international verification and arrangements for the disposition of such material for peaceful purposes, to ensure that such material remains permanently outside of military programmes."[129]

That same year, in their Plutonium Management and Disposition Agreement (PMDA), Russia and the US agreed to each eliminate at least 34 tons of excess Cold War weapons plutonium and committed to IAEA verification of its disposition.[130] In 2016, US committed that an additional six tons of US excess separated plutonium would be disposed under IAEA safeguards.[131]

Also in 2016, however, President Putin suspended Russia's participation in the PMDA. In his explanatory statement, he complained about the Obama Administration's unilateral decision to change the disposal method for the US excess 34 tons from use in MOX fuel in power reactors to dilution and burial. He also cited the US imposition of sanctions on Russia following Russia's seizure of Crimea from Ukraine.[132] Subsequently, Russia decided to fuel its BN-800 prototype breeder reactor with civilian plutonium and to leave its excess weapons plutonium in storage.[133] This leaves open the possibility of Russia returning to the PMDA, including IAEA verification.

Unfortunately, the process of converting excess weapon-grade plutonium into unclassified form so that the IAEA can monitor its storage has been subject to prolonged delays. In the United States, most of the excess material is still in the classified form of nuclear-warhead "pits" and, because of limited space for adding plutonium operations in existing facilities, the timeline for extracting the plutonium and converting it into oxide form for dilution and disposal stretches to 2050.[134] Even though Russia has extracted most of its excess weapons plutonium from pits and converted it into 2-kilogram metal spheres for storage, it considers the isotopic makeup of its excess weapon-grade plutonium classified and will not expose it to IAEA safeguards until after it has been blended with reactor-grade plutonium.

The nuclear-armed states should be encouraged to declare more plutonium excess for weapons use. Russia and the US each have much larger stocks of weapon-grade plutonium than can be justified by their current warhead stocks – about 88 and 38 tons respectively to support an estimated 4,000 operational warheads each.[135] The US stock of 38 tons of plutonium reserved for weapons may seem reasonable by the IAEA's criterion of 8 kg per warhead but the fact that the US had more than 30,000 warheads deployed during 1965-67, despite producing only 90 tons (90,000 kg) of weapon-grade plutonium during the entire Cold War, suggests that the IAEA's standard is generous for advanced nuclear-weapon states.[136] Russia's estimated stock of about 88 tons of plutonium reserved for weapons is even more excessive.

International studies and cooperation on safe plutonium disposal

Spent fuel vs. reprocessing wastes

Civilian programs to separate plutonium create grave risks of nuclear-weapon proliferation, nuclear terrorism and accidents. In the absence of an economic justification, advocates of reprocessing claim that separating and fissioning the plutonium would reduce the environmental hazard from future deep-underground radioactive-waste repositories. Major national studies in the US and Sweden have found, however, that the claimed environmental benefits are not significant.

An independent international study of the environmental hazards from deep underground spent fuel repositories would be justified by the same reasoning as that which created the UN Scientific Commission on the Effects of Atomic Radiation in 1955. UNSCEAR was established in response to concerns about the hazards from global radioactive fallout from atmospheric nuclear testing and obfuscation of those hazards by the governments doing the testing.[137]

UNSCEAR reports were (and still are) written to assess the hazards to humans from both natural and artificial radiation and radioactivity. These studies are done by international teams of experts who review published analyses and produce comprehensive reports, including detailed analyses.[138] Such reports helped force Russia, the United Kingdom and the United States to end their atmospheric nuclear testing with their 1963 Partial Nuclear Test Ban Treaty.[139]

UNSCEAR would be the best existing international organization to do a study of the hazards of spent fuel repositories. It could assess the literature relating to the solubility and migration of radionuclides through cracks and pores of rock and build on its existing expertise relating to their movement through the food chain and within the human body and the resulting doses per unit intake. It has already estimated the doses from all other parts of the nuclear fuel cycle.[140] It has not done so for repositories for spent fuel or reprocessing waste only because no operating or closed repositories exist. It could, however, review the theoretical studies that have been done for hypothetical scenarios for repository leakage and assess the factors that would influence the radiation doses to the populations living above repositories from plutonium and other transuranic elements compared to the fission products and other radionuclides in spent fuel.

If UNSCEAR were to conclude, as the US and Swedish national studies cited above already have, that there is no significant environmental benefit from plutonium separation, pressure might increase on the remaining countries that reprocess to reconsider their policies for the sake of international security.

Direct disposal of existing separated plutonium

Objectively, all separated non-weapons plutonium is waste because, even ignoring the cost of reprocessing, it costs more to fabricate into fuel than the equivalent amount of low-enriched uranium fuel.

The US, having abandoned as too costly its project to dispose of its excess plutonium in MOX fuel for conventional power reactors, has a program to dispose of it by dilution and deep burial in the Department of Energy's deep underground repository for plutonium-contaminated waste in New Mexico, the so-called Waste Isolation Pilot Plant (WIPP). As of the end of 2020, the US had disposed of 4.5 tons of plutonium in WIPP – mostly in plutonium-contaminated wastes.[141] As of April 2022, the path had been cleared for disposal of 13.1 tons of diluted excess plutonium in WIPP (about a ton of which is included in the 4.5 tons already emplaced) and an Environmental Impact Statement process was under way with expected completion in FY2023 to assess the feasibility of disposing an additional 34 tons there.[142]

The United Kingdom is testing a technology for immobilization of some or all of its excess plutonium in low-solubility ceramic for deep burial.[143] France has accumulated unusable, unirradiated MOX fuel containing at least 20 tons of plutonium.[144] Japan, in addition to its approximately 22 tons of plutonium stranded in the United Kingdom, has more than eight tons of unirradiated plutonium on its own soil with no obvious path forward.[145] These four countries could profitably share information and perspectives on their different approaches to plutonium disposal – hopefully to be joined eventually by Russia and perhaps other nuclear-armed states. An acknowledgement by the world's nuclear-energy establishments that separated plutonium is a disposal problem, not a resource, would be a huge step forward.

Conclusions

The governments of China, France, India, Japan and Russia have continued to reprocess spent power reactor fuel for various noneconomic reasons.

China's and India's reprocessing and breeder programs appear to be motivated in part by the need for more weapon-grade plutonium for their still growing nuclear arsenals.

In the cases of France, Japan and Russia, the persistence of civilian reprocessing appears to reflect the fact that, to use William Walker's word, reprocessing has become "embedded" in the political systems of those countries.[146] Some of the elements of embeddedness include the local economic importance of large reprocessing plants in rural areas and the reluctance of bureaucracies to admit major programmatic errors. The "zombie" civilian plutonium programs have become pointless, however, and the weapons potential of their growing stocks of unused separated plutonium, if stolen, constitute what the 1994 US National Academies study on disposition of excess plutonium described as "a clear and present danger."[147] The time for an international consensus to end further separation of plutonium is therefore long overdue.

Despite a 70-year history, $100 billion spent on efforts to commercialize sodium-cooled plutonium breeder reactors worldwide, and the accumulation of 300 tons of separated civilian plutonium, there are only two prototype breeder reactors operating today, both in Russia, only one of which is plutonium fueled. Rosatom has put off the construction of a third because it is not convinced that it would be economically competitive with light water reactors.

France and Japan are recycling their separated plutonium into MOX light-water reactor fuel. The governments of both countries acknowledge that, including the cost of reprocessing, MOX fuel costs an order of magnitude more than the low-enriched uranium fuel that otherwise would be used. Both governments argue, however – despite the conclusions of the expert studies that have been done – that plutonium separation and fissioning in fast-neutron reactors reduces the long-term hazard from spent fuel.

If plutonium were not a nuclear-weapon material, the continuing commitments to plutonium separation in these countries could be accepted as a self-inflicted economic inefficiency, similar to military bases that have outlived their usefulness but have become embedded as economic supports to nearby communities.

But plutonium, whether military or civilian, can be used to make nuclear weapons and every few kilograms contain the potential for destroying a city. From this perspective, the 200 tons (200,000 kg) of civilian plutonium that have been separated and added to the previously existing 100 tons since the end of the Cold War must be recognized as an international security threat. So must the additional 100 tons of plutonium that have been declared excess to the weapon requirements of Russia and the United States during the same period. The nonuse of all this material, enough to make 50,000 Nagasaki bombs, despite its designation for non-weapons use, elevates the economic pointlessness of separating more civilian plutonium into a threat to international security.

This situation must be confronted and dealt with. Our specific recommendations are for:

1. A ban on the separation of additional plutonium for *any* purpose through broadening of the scope of the proposed Fissile Materials Cutoff Treaty to include separation for civilian purposes, and placement of all unirradiated civilian and excess weapons plutonium in the nuclear weapon states under IAEA safeguards.

2. An international study on the environmental hazards of direct disposal of spent in deep repositories relative to disposal of reprocessing wastes and multinational cooperation on direct disposal of existing separated plutonium.

Ban on plutonium separation

In 1993, the UN General Assembly put on the international nuclear arms-control agenda a ban on the separation of plutonium and production of highly enriched uranium for weapons. Negotiations on an FMCT would provide an opportunity for discussing a complete ban on reprocessing and HEU production. As with the Comprehensive Test Ban Treaty, an article could be included that would allow any country to propose an amendment allowing an exemption if there were a consensus among the parties that the benefits would exceed the risks.

The 2000 NPT Review Conference report recommended, there should be in addition, "[a] rrangements by all nuclear-weapon states to place, as soon as practicable, fissile material designated by each of them as no longer required for military purposes under IAEA or other relevant international verification and arrangements." Putting all non-weapons plutonium under civilian control and IAEA safeguards would reduce the inequities between the civilian nuclear energy programs of the weapons and non-weapon states. Russia and the US also should be encouraged to declare more of their stocks of weapons plutonium excess for weapons use.

International study on repository hazard and cooperation on safe plutonium disposal

Taking advantage of the public's fears of the dangers from deeply buried radioactive waste and ignoring the conclusions of government-commissioned studies in the United States and Sweden, advocates of sodium-cooled fast-neutron reactors and reprocessing have created a myth that the longevity of the hazard from spent fuel can be reduced from millions to hundreds of years by separating out plutonium and other transuranic elements and fissioning them in fast-neutron reactors.

An international review of this claim would be useful. The UN Scientific Committee on the Effects of Atomic Radiation – originally established to determine the true health impacts of the global radioactive fallout from atmospheric nuclear testing – would be the best existing body to take on the task.

Multinational cooperation on studies of the options for direct disposal of civil and excess weapons plutonium also would be useful. After the failure of its attempt to dispose of its plutonium in power reactor fuel, the US is implementing dilution and direct disposal. The UK is researching immobilization and then disposal. They could share information on their approaches with each other, hopefully to be joined at some point by France and Japan and eventually by the other countries with stocks of excess plutonium. An acknowledgement by all the world's nuclear-energy establishments that separated plutonium is a disposal problem, not an economic resource, would be a huge step forward.

Endnotes

[1] *Management and Disposition of Excess Weapons Plutonium*, National Academy Press, 1994, p. 1.

[2] Alvin Weinberg, "Energy as the ultimate raw material, or problems of burning the sea and burning the rocks," *Physics Today*, November 1959, pp. 18-25.

[3] *Energy Technology Perspectives 2020*, OECD International Energy Agency.

[4] In 1975, the IAEA projected that global nuclear capacity would be 2089 GWe in the year 2000 with capacity being added at an average rate of 120 GWe/year between 1990 and 2000 and warned that "the total presently known and estimated resources [of 3.5 million tons of uranium] at < 30$/lb U3O8 ($114 in 2019$) will be exhausted by about 2000," R.B. Fitts and H. Fujii, "Fuel Cycle Demand, Supply and Cost Trends," *IAEA Bulletin* 18(1), 1975, pp. 20-24. At the end of 2021, global nuclear generating capacity was 394 GWe, including 24 GWe of capacity in Japan that had not operated since the Fukushima accident, and the average rate of growth since 2001 had been about 2 GWe/yr (0.8 GWe/yr excluding the idle Japanese capacity), *Power Reactor Information System*, IAEA. In 2000, the OECD Nuclear Energy Agency estimated global uranium resources at 10.5 million tons at a recovery cost less than $130/kgU, *Forty Years of Uranium Resources, Production and Demand in Perspective*, OECD Nuclear Energy Agency, 2006, Figs. 6.1-6.3.

[5] *Uranium Resources, Production and Demand*, OECD Nuclear Energy Agency, *2020*, p. 14.

[6] R.B. Fitts and H. Fujii, "Fuel Cycle Demand, Supply and Cost Trends", *IAEA Bulletin* 18(1), 1975; *Energy, Electricity and Nuclear Power Estimates for the Period up to 2050*, IAEA, 2021; and *Power Reactor Information System*, IAEA, 2021.

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[11] Edward Lundquist, "Liquid sodium reactor powered USS Seawolf was part of first nuclear task force," *Defense Media Network*, 30 March 2014.

[12] Richard G. Hewlett and Francis Duncan, *Nuclear Navy: 1946–1962*, University of Chicago Press, 1974, p. 274.

[13] *Power Reactor Information System (PRIS)*, IAEA.

[14] For a more detailed discussion of the history of efforts to commercialize breeder reactors, see *Fast Breeder Reactor Programs: History and Status*, IPFM, 2010.

[15] Ilia Pakhomov, *"BN-600 and BN-800 Operating Experience,"* Gen IV International Forum, 19 December 2018.

[16] "Russia defers BN-1200 until after 2035," *Nuclear Engineering International Magazine*, 2 January 2020; Anatoli Diakov and Pavel Podvig, "Construction of Russia's BN-1200 fast-neutron reactor delayed until 2030s," 20 August 2019.

[17] Weapons stocks from *Global Fissile Material Report 2010: Balancing the Books: Production and Stocks*, IPFM, with updates by Moritz Kütt, Zia Mian and Pavel Podvig in *SIPRI Yearbook: Armaments, Disarmament and International Security*, Stockholm International Peace Research Institute. Numbers of warheads from the "Nuclear Notebook," https://thebulletin.org/nuclear-notebook/.

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