SCIENCE & GLOBAL SECURITY
2020, VOL. 28, NO. 3, 171–209
https://doi.org/10.1080/08929882.2020.1869474

Global Stocks of Separated Plutonium – Stalled on the Path to Elimination

Frank N. von Hippel and Masafumi Takubo

Program on Science and Global Security, Princeton University, Princeton, New Jersey, USA

ABSTRACT
With the end of the Cold War, Russia, the United States, France, and the United Kingdom declared an end to their production of plutonium for weapons and Russia and the United States declared large quantities excess to their future weapon requirements. The disposal of these excess stocks has stalled, however, and during the next two decades, the relatively small stocks of weapons plutonium in India, North Korea, Pakistan and possibly also China could increase significantly. Meanwhile, despite the failed commercialization of plutonium breeder reactors, the separation of civilian but weapon-usable plutonium from power-reactor fuel continues in France, India, Japan, Russia, and has begun in China. The global stock of separated civilian plutonium now exceeds that of weapons plutonium and could increase further during the next two decades.

Introduction

Plutonium, whether weapon-grade made in dedicated production reactors or extracted from power-reactor spent fuel, can be used by governments – and potentially by sub-state groups – to make nuclear weapons. Limiting the separation of plutonium for both military and civilian purposes and eliminating stocks are therefore critical international-security objectives.

After the end of the Cold War in 1991, the United States, France, Russia, and the United Kingdom announced the end to their production of highly enriched uranium (HEU) and plutonium for weapons.[1] China too halted its production but, given its relatively small stocks and its developing tensions with the United Sates, has refused to commit to a permanent halt.[2]

In 2000, following major reductions in their Cold War stockpiles of nuclear warheads, Russia and the United States each declared 34 tons of plutonium excess to their weapons needs in their Plutonium Management and Disposition Agreement (PMDA).[3] Their original disposition choice focused on use of the plutonium in "mixed-oxide" (MOX) plutonium-

CONTACT Frank N. von Hippel fvhippel@princeton.edu Program on Science and Global Security, Princeton University, Princeton, NJ, USA.

uranium fuel for light-water reactors (LWRs) except for about eight tons of impure weapon-grade plutonium that the United States decided to dispose with nuclear waste. The United States and its allies were to pay for the construction of Russia's MOX fuel fabrication facility.

Both MOX fuel plants grew in cost, however, and the U.S. Congress refused to escalate its commitment to the Russian plant. In 2010, therefore, it was agreed that Russia could use its excess weapons plutonium to fuel its prototype BN-800 breeder reactor and, in 2016, the Obama Administration decided unilaterally to pursue disposal of its 34 tons by dilution and burial.[4] Due to the U.S. unilateral change of plans and because of U.S. sanctions on Russia following Russia's seizure of Crimea from Ukraine, Russia suspended its adherence to the PMDA.[5] Neither country has yet begun disposal, although the United States continues with its plan for dilution and burial.

As far as is publicly known, the four nuclear-armed states that are not parties to the Nonproliferation Treaty: India, Israel, North Korea and Pakistan, are continuing to produce plutonium for weapons. On the scale of Russian and United States plutonium production during the Cold War, the increments from these smaller weapons programs are miniscule, however, and the global stockpile of separated weapons plutonium has remained roughly constant (Figure 1).

Stocks of separated *civilian* plutonium have grown greatly since the end of the Cold War, however. This plutonium, although not optimal for nuclear weapons, is weapon-usable.[6]

Programs to separate plutonium from power-reactor spent fuel were launched in the 1960s and 1970s to provide startup fuel for liquid-sodium-cooled plutonium "breeder" reactors that were expected to become the dominant source of electrical power after 2000. France and the United Kingdom took advantage of the expertise that they had developed in their weapons programs and became suppliers of spent-fuel "reprocessing" services to other countries. The Soviet Union developed its own civilian reprocessing program and took back for reprocessing the spent fuel it supplied to its satellite countries.[7]

Sodium-cooled breeder reactors were unable to compete economically with the water-cooled reactors that still dominate the global power-reactor fleet today, however, and only a few prototypes were built. Also, the growth of global nuclear capacity slowed and then stopped after the Chernobyl and Fukushima accidents, relieving the concern that had motivated the development of breeder reactors: that uranium demand.

Despite the economic failure of breeder reactors, however, France decided to continue separating civilian plutonium and to "recycle" it in MOX fuel in some of its light-water reactors. France also offered MOX fuel

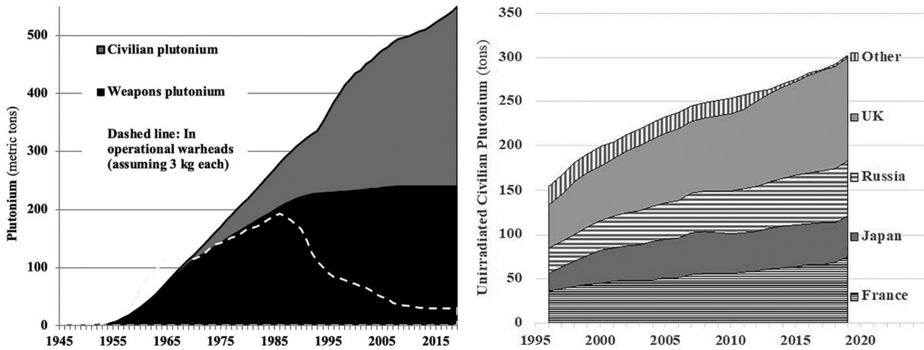

Figure 1. Growing stocks of unirradiated plutonium (left). The global stock of civilian plutonium is mostly in France, Japan, Russia and the United Kingdom (right). Not shown are the stocks of China and India, which are relatively small.

fabrication services to its foreign reprocessing customers (Belgium, France, Germany, Italy, Japan, the Netherlands and Switzerland). Given the poor economics of plutonium recycle, however, of these foreign customers, only the Netherlands renewed its reprocessing contract. Belgium, Germany and Switzerland abandoned MOX fuel use. Italy abandoned nuclear power altogether after the Chernobyl accident. Japan decided to build its own reprocessing and MOX fuel fabrication plants. The United Kingdom built a MOX fuel fabrication plant for its foreign customers' plutonium but was unable to get it to operate properly and abandoned it.

Russia built the only two currently operating prototype breeder reactors. Both India and China have prototypes under construction.[8]

In 1997, nine countries (Belgium, China, France, Germany, Japan, Russia, Switzerland, the United Kingdom and the United States) agreed on Plutonium Management Guidelines, and noted "the importance of balancing supply and demand, including demand for reasonable working stocks for nuclear operations, as soon as practical."[9] Of these nine countries, the United States had abandoned civilian reprocessing in 1972; Belgium, Germany and Switzerland have ended their plutonium programs and eliminated their stocks of separated plutonium; and the United Kingdom is now in the process of ending its reprocessing operations. France, India, Japan and Russia continue to separate plutonium from spent power reactor fuel, however, and China is building a "demonstration" reprocessing plant and has been negotiating with France to buy a large civilian reprocessing plant. Two decades after the agreement on the Plutonium Management Guidelines, the global stock of separated civilian plutonium has doubled.

The growing global stock of unirradiated plutonium is shown at the left in Figure 1. Growth of the global stock of *weapons* plutonium slowed dramatically after the end of the Cold War because Russia and the United States ended their production.[10] The global stock of separated plutonium continued to grow, however, mostly because of continued separation of civilian plutonium from power-reactor fuel. Prior to the U.S. weapons stockpile peaking in the middle 1960s, virtually all available U.S. plutonium was quickly fabricated into warheads. On this basis, a comparison of declassified historical data on U.S. plutonium and weapons stocks shows that U.S. warheads contained average of about 3 kg of plutonium each during that period. The right side of Figure 1 shows that the global stock of civilian plutonium is mostly in France, Japan, Russia and the United Kingdom, which, in accordance with the Plutonium Management Guidelines, began in 1997 to submit annual public reports to the IAEA of those stocks, starting with the data for 1996.[11] Not shown are the stocks of China and India, which are relatively small.

The purpose of this paper is to explain what happened and to project possible futures for global plutonium stocks to 2040, two decades hence. We limit our projections to 2040 since, even then, depending on future policy choices, the uncertainty ranges are very large. Mid-range projections are not meaningful because, depending upon policy decisions, the high or low national projections will be more plausible.

Much larger quantities of plutonium are accumulating in unreprocessed spent power reactor fuel – on the order of 2000 tons as of the end of 2013.[12] In the long term – a century or so in the future – that plutonium too is of concern but it is diluted by one hundred times as much uranium and mixed with highly radioactive fission products, making it much less accessible for weapons purposes in the near term.

The discussion in the remainder of the paper is organized into the following three areas:

- Stocks of plutonium in and remaining available for nuclear warheads;
- Disposition plans for the weapon-grade plutonium that Russia and the United States declared excess for weapons purposes at the end of the Cold War;
- Civilian stocks of plutonium.

Weapon stocks

The definition of weapon-grade plutonium used here is plutonium that contains 90% or more plutonium-239. That is close to the definition used in the U.S.-Russian Plutonium Management and Disposition Agreement.[13]

The Soviet Union and the United States produced about 95% of the current global stock of weapons plutonium during their Cold War. After the 1994 agreement between Russia and the United States to end their production of plutonium for weapons, the rate of growth of the global stock

Table 1. Declared or estimated national stocks of weapons plutonium in 2019 and projected ranges for 2040. The numbers for 2019 are based on national declarations in the case of the United Kingdom and United States and updates of estimates by the International Panel on Fissile Materials in the case of the other countries.[146] Numbers have been rounded because of uncertainties.

	Stocks of plutonium available for weapons (metric tons)	
Country	2019[147]	Range in 2040
China	2.3–3.5	2.3–8.5
France	5–7	5–7
India	0.45–0.75	0.8–6
Israel	0.8–1.1	0.8–1.5
North Korea	0.04	0.04–1
Pakistan	0.27–0.47	0.8–1.5
Russia	80–96	80–96
United Kingdom	3.2	3.2
United States	38.4	38.4
Total	∼130–150	∼130–170

slowed dramatically (Figure 1). Production in India, Israel, North Korea and Pakistan continued, however. Non-governmental estimates for the sizes of the stocks remaining available for weapons as of the end of 2019 are shown in Table 1, as are the projected ranges for 2040 discussed below.

The approximately 100 tons of plutonium that Russia and the United States have together declared excess for weapons purposes are not included in Table 1. Plans for that plutonium is discussed in the next section.

Of the five nuclear-weapon states that are parties to the Nonproliferation Treaty (NPT), only China has increased the number of its warheads since the end of the Cold War. Options for China to produce additional weapon-grade plutonium if it continues its buildup are discussed below.

Although Russia and the United States could each declare more weapons plutonium excess, no changes are projected here for their stocks, or for those of France or the United Kingdom out to 2040.

Nuclear-weapon production in the four nuclear-armed states that are not parties to the NPT: Israel, India, Pakistan and North Korea, has been driven by regional security concerns that were not mitigated by the end of the Cold War. As far as is publicly known, their production of weapon-grade plutonium has continued. Potential increases in weapons plutonium stocks therefore are discussed for five countries: China, India, Israel, North Korea and Pakistan.

China. China is estimated to have produced between 2.3 and 3.5 tons of weapon-grade plutonium before it halted production in 1988.[14] Assuming 3 to 6 kilograms per warhead, that would be enough for about 400 to 1000 warheads. China is estimated to have about 350 warheads – approximately double its estimated number at the end of the Cold War, with calls from hardliners for further increases.[15]

If China wished to produce more weapon-grade plutonium, it could use some of its existing power reactors or build a new production reactor. Technically, it would be easiest to use its two Canadian-supplied 2000-MWt (thermal) pressurized heavy-water reactors (HWRs) at the Qinshan nuclear power plant, southwest of Shanghai. The natural-uranium fuel in these reactors is in water channels similar to those in graphite-moderated reactors designed to produce weapon-grade plutonium. Fuel can be inserted into and discharged from such channels without shutting down the reactor. If discharged after a fission-energy release of 1 MWt-day per kg of natural uranium fuel (corresponding to the fission of approximately one of the 7 grams of uranium-235 in a kilogram of natural uranium) the plutonium in the fuel would be weapon-grade.[16] Under China's agreement for peaceful nuclear cooperation with Canada, however, the Qinshan nuclear power plant is one of three nuclear facilities in China subject to IAEA safeguards and China must have Canada's agreement before it can reprocess the HWR fuel.[17]

It would be more difficult technically for China to produce weapon-grade plutonium in light-water power reactors (LWRs) because the fuel would have to be discharged after about nine months instead of the 4.5 years typical today. That would require shutting down the LWRs for at least a week to open up their pressure vessels and retrieve the lightly irradiated fuel. Also, since the fuel would contain about one sixth as much plutonium per ton as fully irradiated spent fuel, six times as much fuel would have to be reprocessed to recover a given amount of plutonium.[18]

It is unlikely that China would separate plutonium for weapons purposes using the large reprocessing plant that France's Orano hopes to sell to the China National Nuclear Corporation (CNNC). France has reportedly requested that the plant be placed under IAEA safeguards.[19] To be effective, the safeguards would have to follow the separated plutonium through fabrication to the reactors that use it.

The most unobtrusive way for China to increase its stock of weapon-grade plutonium would be by reprocessing the irradiated uranium "blankets" around the cores of the two 600 Megawatt electric (MWe) fast-neutron breeder reactors (CFR-600s) that CNNC has under construction, using the "demonstration" reprocessing plant it also currently has under construction. The plutonium produced in the blankets would be weapon-grade. Scaling from calculations for India's 500-MWe Prototype Fast Breeder Reactor, a CFR-600 operating at a 75% capacity factor could produce about 0.17 tons of weapon-grade plutonium per year.[20] China's first CFR-600 is currently scheduled to be operational in 2023 and the second in 2026. By 2040, the two reactors could increase China's stock of weapon-grade plutonium by up to 5 tons.

China's first CFR-600 is expected to be fueled with Russian HEU during its first seven years.[21] Russia probably is providing China with design assistance for its breeder program as well. Russia could require as part of this arrangement that the CFR-600s and the plutonium they produce be placed under IAEA safeguards.

The most effective way to persuade China not to make more plutonium for weapons, however, would be to deal with the concerns about the adequacy of its deterrent that have provoked its nuclear-weapon buildup.[22] China's breeder reactor and reprocessing programs are discussed at greater detail in the section on civilian plutonium below.

India. As of the end of 2019, India had produced an estimated 0.4 to 0.7 tons of weapon-grade plutonium.[23] Virtually all of this plutonium was produced by two reactors.[24] The first, CIRUS (Canada India Reactor United States), was named to give credit to Canada for supplying the reactor and the United States for supplying its initial inventory of heavy water. CIRUS was a high-powered research reactor with a thermal power of 40 megawatts (MWt). It began operating in 1963 and produced the plutonium for India's 1974 nuclear test. CIRUS was shut down at the end of 2010 as part of a 2005 deal between India and the United States that laid the basis for the lifting in 2008 of the Nuclear Suppliers Group embargo on cooperation with India's nuclear-energy program imposed following India's 1974 nuclear test.

India's second plutonium-production reactor, Dhruva (100-MWt), went into operation in 1985 and, at a capacity factor of 65%, would produce about 0.018 tons of weapon-grade plutonium per year.[25] If Dhruva operated through 2040 at this rate, it would add 0.4 tons of weapon-grade plutonium to India's stock.

India has been building a 500-MWe Prototype Fast Breeder Reactor (PFBR) since 2004. Completion of the reactor has been delayed repeatedly and its estimated cost has doubled.[26] In September 2020, it was announced that operations had slipped by another year to October 2022.[27] India's Department of Atomic Energy envisions building two follow-on 500-MWe Commercial Fast Breeder Reactors (CFBRs) on the same site.[28]

In its 2005 agreement on peaceful nuclear cooperation with the United States, India refused to place under IAEA safeguards either its breeder program or the reprocessing program that is separating plutonium for initial breeder reactor cores from the spent fuel of unsafeguarded heavy-water reactors.[29] This has raised concerns that India might be planning to use its breeders to produce plutonium for its nuclear-weapons program.[30] Glaser and Ramana estimated that, operating at a 75% capacity factor, the PFBR could produce about 0.14 tons of weapon-grade plutonium per year in its blanket.[31] If the reactor has technical problems such as those many sodium-cooled reactors have had, and operates on average at only half the assumed 75% capacity factor, half as much plutonium would be produced. Assuming that the PFBR goes into operation in 2022 and that the two planned but not-yet-under-construction CFBRs go into operation in 2030, the three reactors could increase India's stock of weapons plutonium by 2.5 to 5 tons by 2040. Thus India could produce up to an additional 5.4 tons of weapon-grade plutonium by 2040.[32]

Israel. Israel's plutonium production reactor at Dimona in the Negev Desert was provided by France as a research reactor based on the design of France's EL-3 research reactor with an initial power of 26 MWt. The Dimona reactor went into operation in 1963.[33] Israel upgraded its power, however, and estimates of the reactor's final power range from 40 to 140 MWt, resulting in great uncertainty of estimates of Israel's stock of weapon-grade plutonium. In 2010, a mid-range estimate was a production rate of 18 kg weapon-grade plutonium per year.[34] In 2019, the cumulative production was estimated as 0.8–1.05 tons.[35]

The Dimona reactor will be 75 years old in 2040. A recent review concluded, however, that, with refurbishment, the operation of this pool-type reactor could be extended to 80 years or more.[36] Israel may have enough plutonium for its weapons needs but is believed to use the Dimona reactor to produce tritium to "boost" the power of its fission weapons. Since tritium has a radioactive halflife of 12 years, unless Israel develops an alternative source of tritium, it will have to operate the reactor indefinitely. At 0.018 tons of plutonium per year, Israel's stock of weapon-grade plutonium would increase by 0.4 tons by 2040.

North Korea. Thus far, the Democratic People's Republic of Korea (DPRK) has produced all its plutonium using the approximately 20-MWt graphite-moderated, CO_2-cooled Yongbyon reactor, whose design is based on the published designs of the United Kingdom's Magnox first-generation plutonium and power-production reactors. Operating at continuous full power, this reactor could produce about 6.7 kg of weapon-grade plutonium per year.[37] The reactor has been shut down for a significant fraction of the time since it began operating in 1985, however, and North Korea used some of the plutonium it produced in its six nuclear tests. Albright estimated that, as of the end of 2016, the DPRK had a stock of 23–37 kg of plutonium,[38] which would have been reduced by a few kg by the 2017 test. As of the end of August 2020, there had been no indication of additional reprocessing at the Yongbyon site since July 2016.[39] Assuming a 50% capacity factor, the reactor could produce an additional 0.080 tons of plutonium by 2040. Because of the low power density in its core compared with the U.K. Magnox reactors on which its design is based, radiation swelling and cracking of the graphite would not be an age-limiting factor.

The DPRK also has built an Experimental Light Water Reactor (ELWR) with a thermal rating of approximately 100 MWt. The amount of low-enriched uranium (LEU) in the ELWR core is reportedly about 4 tons.[40] After 200 full-power days, the ELWR core would contain about 16 kilograms of weapon-grade plutonium.[41] Assuming 300 full-power days per year, it could produce up to an additional 0.5 tons of weapon-grade plutonium by 2040. In total, therefore, the two DPRK reactors could produce up to an additional 0.6 tons of weapon-grade plutonium by 2040.

Pakistan. After India's 1974 nuclear explosion, the United States succeeded in persuading France to cancel the sale of a reprocessing plant to Pakistan. At the time, Pakistan had in any case only one power reactor, a 100-MWe heavy-water reactor provided by Canada, Kanupp-1, which was under IAEA safeguards. Pakistan's first nuclear weapons were made using HEU produced with gas centrifuges.

In 1986–87, however, Pakistan began to build heavy-water-moderated plutonium production reactors similar to India's CIRUS reactor. Four of these reactors were brought into operation in 1998, 2010, 2013 and 2015 about 35 km south of the city of Khushab. The thermal power of each of the first three reactors is estimated at about 40 MWt, the same as CIRUS, with Khushab-4 estimated to have approximately twice that power, for a total of about 200 MWt.[42] Assuming the reactors produce 0.8 grams of weapon-grade plutonium per MWt-day[43] and operate 40–80% of the time, their combined output of weapon-grade plutonium would be 0.023–0.047 tons per year. As of the end of 2019, their cumulative output has been estimated as 0.3–0.5 tons of plutonium.[44] They could produce an additional 0.5–1 tons of weapon-grade plutonium by 2040.

There has been some question as to whether Pakistan's nuclear program has been limited by its ability to mine and import natural uranium.[45] The reported ore grade in its uranium mines is lower than that of most commercial uranium mines, but paying, for example, twice the commercial-market cost for uranium, would be a tolerable burden on a nuclear-weapon program.[46]

Additonal countries? It is possible that, during the next two decades, one or more additional countries might decide to separate plutonium for weapons.

The most recent proliferation crisis has focused on Iran, which, in addition to building a uranium-enrichment capacity, almost completed a research reactor near Arak in Markazi Province quite similar to India's CIRUS reactor. In the 2015 Joint Comprehensive Plan of Action (JCPOA) agreement limiting Iran's nuclear program, however, Iran agreed to work with international partners to redesign the core of the Arak reactor to reduce its power by half and use low-enriched rather than natural uranium fuel. This would reduce its production of plutonium by an order of magnitude.[47] Iran also stated that it did not "intend … to engage in any spent fuel reprocessing" and agreed that the spent fuel of the Arak reactor would be "shipped out of Iran for the lifetime of the reactor."[48]

As is discussed in the section on civilian plutonium programs below, the Korea Atomic Energy Research Institute has been campaigning for South Korea to have the same "right" to reprocess as Japan. One motivation for this campaign may be a long-standing interest in South Korea in having a nuclear-weapon option like Japan's.

Table 1 summarizes the above estimates. It will be seen, that, because the Russian and U.S. stocks dominate and are not expected to change much, fractionally, the global total quantity of weapon-grade plutonium is not expected to change greatly by 2040. China, India, North Korea and Pakistan could all potentially increase their national stocks of weapons plutonium by significant factors, however. North Korea and Pakistan would be building up their stocks with dedicated production reactors while China and India could use nominally civilian plutonium breeder reactors.

Weapons plutonium declared excess

After the end of the Cold War, Russia, the United Kingdom and the United States all declared quantities of military plutonium excess to their weapons requirements. The United Kingdom declared excess 0.3 tons of weapon-grade plutonium. It was mixed into the United Kingdom's stock of civilian plutonium at Sellafield[49] and will not be discussed further here.

Russia. Russia has declared 40 tons of weapon-grade plutonium excess from its weapon requirements. The disposal of 34 tons of this material is covered by the Russia-United States PMDA of 2000. Of this 34 tons, 25 are actually from excess weapons. The remainder is from an additional 15 tons of plutonium Russia committed not to use for weapons because it was produced after Russia and the United States agreed in 1994 to end their production of plutonium for weapons and shut down their plutonium production reactors.[50] (All the U.S. plutonium production reactors had already been shut down by the end of 1988.[51])

In the 2010 amendments to the PMDA, Russia opted to use the 34 tons of its excess weapons plutonium covered by the agreement to fuel its BN-800 breeder reactor. In 2016, following the Obama Administration's unilateral decision to change the method of disposal of the U.S. excess 34 tons from MOX fuel to dilution and deep burial – and partially also in response to international sanctions on Russia because of its seizure of Crimea – President Putin suspended Russia's participation in the PMDA. He indicated, however, that Russia would maintain its commitment not to use the

Table 2. U.S. unirradiated plutonium declared excess for weapons use.[148] WIPP is the Department of Energy's Waste Isolation Pilot Plant, a repository in a deep bed of salt in southeast New Mexico.

Form	Quantity (tons)	Disposal plan (2019)
Pits, metal and oxide (PMDA material)	34.0	Dilution and disposal in WIPP
Pits	7.1	–
Non-pit metal and oxide	6.0	–
Plutonium-contaminated waste	3.2	Already in WIPP
Various	1.1	WIPP and in high-level waste[149]
Core fuel of the Zero-Power Plutonium Reactor	4.0	Undecided
Total	**55.4**	

plutonium covered by the agreement in weapons.[52] Reportedly, Russia is using reactor-grade instead of weapon-grade plutonium to fuel the BN-800.[53] Thus, it appears that Russia's excess weapon-grade plutonium will remain in storage for the foreseeable future.

United States. In addition to the U.S. commitment in the PMDA that it would dispose of 34 tons of its excess weapon-grade plutonium, it announced that it will dispose of more than 17 additional tons of separated plutonium of various grades (Table 2).[54]

In the 2010 amendments to the PMDA, the United States decided to dispose of all of its 34 tons of excess weapon-grade plutonium, including impure plutonium covered by the PMDA in mixed-oxide (MOX) fuel to be irradiated in U.S. power reactors. After huge cost overruns in the construction of a MOX Fuel Fabrication Plant and prolonged internal debate, however, that project was abandoned.[55] The United States is now pursuing a "dilute and dispose" strategy in which plutonium-oxide powder is to be diluted with a classified mixture of chemicals from which it would be difficult to separate. For protection and to assure against criticality, the mix is to be placed in cans stacked in tubes in the centers of large barrels.

There remain many issues that must be dealt with in the U.S. dilute-and-dispose plan, including:

- Where to site the equipment that will be used to extract plutonium from excess weapon "pits" and turn it into oxide[56]
- The regulatory analyses required to establish that placing so much plutonium in WIPP will be safe
- Whether this expansion of the mission of the WIPP repository will be accepted by New Mexico's state government[57]

The U.S. Department of Energy (DOE) has already announced, however, that it has decided to dilute and dispose of 13.1 tons of plutonium in WIPP, including 6 tons of plutonium not covered by the PMDA that is mostly already in oxide form.[58] According to DOE's budget request to Congress for Fiscal Year 2021, three gloveboxes will be installed at its

Savannah River Site that will in combination be able to blend down at least 1.5 tons of plutonium oxide per year starting in 2028.[59] Absent delays, it will take until 2049 to complete disposition of the 34 tons covered by the PMDA plus the 6 tons not covered by the agreement. According to the DOE, up to 24 tons of plutonium could be diluted by 2040.[60]

Throughout the negotiation of the original PMDA in the 1990s, Russia objected to direct disposal of plutonium. It insisted that, to forestall reextraction of the plutonium and its remanufacture into warheads, the plutonium isotopics must be changed to non-weapon-grade by irradiation in a reactor. As noted in the introduction, the furthest it would go in the original (2000) PMDA was to agree that the 8.43 tons of impure weapon-grade plutonium not from warheads included in the 34 tons of U.S. weapon-grade plutonium could be directly disposed without irradiation.[61]

In contrast, knowing that Russia still had in its weapon stocks about 90 tons of weapon-grade plutonium,[62] enough for 20,000 warheads, the United States did not consider it credible that Russia would use the weapons plutonium it had declared excess in warheads again and was more concerned about putting plutonium out of reach of sub-national groups.

The United States therefore was unenthusiastic about Russia using its excess plutonium for breeder reactor fuel. Such plutonium is supposed to be recycled indefinitely, thereby regularly reexposing it to diversion. In the 2010 amendments to the PMDA, Russia agreed only that it would neither reseparate the irradiated plutonium from the BN-800 fuel nor separate the new weapon-grade plutonium produced in the BN-800 radial blanket[63] until all 34 tons of the weapon-grade plutonium had been irradiated.[64] Now that it is not fueling the BN-800 with PMDA plutonium, Russia is free to reprocess the blanket material anytime as part of its civilian nuclear energy program.

Civilian stocks

Currently, there are seven countries with stocks of civilian plutonium: China, France, India, Japan, Russia, the United Kingdom and the United States. The United States has decided that it will dispose of all of its civilian plutonium except for 4 tons in fuel from the shutdown Zero-Power Plutonium Reactor at the U.S. DOE's Idaho National Laboratory (Table 2) whose fate is yet to be decided.

In the past, Belgium, Germany, Italy, the Netherlands, Spain, Sweden and Switzerland all had plutonium programs. Belgium and Germany also had pilot reprocessing plants. All either had MOX-fuel programs using plutonium separated and fabricated into MOX fuel by France or the United Kingdom and/or contributed plutonium for the startup cores of France's

Table 3. National stocks of unirradiated civilian plutonium as of the end of 2019 and projected to 2040.

	Stocks of civilian plutonium (tons)	
Country	End of 2019[150]	Range in 2040
China	0.04 (end of 2016)	0–40
France	67.7 (excluding foreign owned)	85
India	3–11("strategic" except for 0.4 tons)	0–14
Japan	45.5	9–45.5
Russia	61.3 (end of 2018)	60–120
South Korea	0	0–3
United Kingdom	115.8 (138.9 including foreign plutonium) (end of 2018)	140
Total	294–302	294–448

Superphénix breeder reactor.[65] Except in the Netherlands, those programs have been ended and, in the case of Belgium, Germany, Sweden, and Switzerland, the plutonium either has been irradiated in mixed-oxide (MOX) fuel or the title to the plutonium has been transferred to another country. The Netherlands has a contract with France's Orano to reprocess the spent LEU fuel from the Netherlands' single remaining operating power reactor.[66]

It is possible that Italy and/or Spain still have some separated plutonium in the United Kingdom. That could account for some of the difference between the 23.1 tons of unirradiated foreign plutonium declared by the United Kingdom as of the end of 2018 and the 21.2 tons Japan declared it had in the United Kingdom.[67] The United Kingdom has taken title to some of the foreign plutonium stranded in the United Kingdom and has indicated its willingness to do the same for the rest, "subject to … acceptable commercial arrangements", i.e., an agreed price.[68]

Since 1997, as a result of the agreed Plutonium Management Guidelines, there have been annual public reports to the IAEA of stocks of unirradiated civilian plutonium from all the countries that still reprocess except the Netherlands and India. The numbers for the end of 2019 are shown in Table 3, along with projected ranges for 2040 that are explained below.

China. After China ended separating plutonium for weapons in 1987, the China National Nuclear Corporation (CNNC) built a pilot civilian reprocessing plant next to its shutdown military reprocessing plant near Jiuquan, Gansu Province on the southern edge of the Gobi Desert. The plant reportedly has a design throughput of 50 tons of light-water reactor spent fuel per year.[69]

The site may have been selected to take advantage of the expertise and infrastructure at the adjoining military reprocessing site but it is very remote from China's nuclear power plants, which are all located on China's coast. Reportedly, it requires a 3700-km, 3-month road trip for heavy trucks to deliver spent fuel transport casks from the Daya Bay Nuclear

Power Plant, northeast of Hong Kong, the first light water reactor power plant in China to reach the limit of its spent-fuel-pool storage capacity.[70]

The pilot plant began operating in late 2010. In China's first annual declaration to the IAEA that reported a non-zero stock of civilian plutonium, it stated that, as of the end of 2010, it had separated 13.8 kg of civilian plutonium. At the pilot plant's design throughput, it would have separated annually about 500 kg of plutonium thereafter. It apparently encountered serious technical problems, however. The plant did not operate again until 2014. As of the end of that year, China reported a cumulative 25.4 kg of civilian plutonium separated. The plant operated again in 2016, at the end of which China reported a cumulative 40.9 kg separated. Had the pilot plant operated at its design capacity, the amount separated by then would have been about 3000 kg.

We have two differing unofficial reports on the plant's performance thereafter:

1. It began "normal operation since 2017" with an annual throughput of "50–60" tons of spent fuel per year[71]
2. It completed reprocessing a cumulative total of 50 tons of spent fuel during 2017–19 with plans for its subsequent use uncertain[72]

In the second scenario, China's cumulative stock of separated civilian plutonium would have increased to about 0.5 tons by the end of 2019. If China's pilot reprocessing plant operated at its design throughput from 2017, however, by 2040, it would have added about 12 tons to China's stock of separated civilian plutonium.

As of the end of October 2020, China was the only country among the nine parties to the international Guidelines for the Management of Plutonium that had not submitted a report to the IAEA on its stock of unirradiated civilian plutonium as of the end of 2017 and, since October 2019, it has been the only country that has not reported its stock as of the end of 2018.[73] The IAEA's position is that it "does not request those Member States to submit updates and has no role in connection with the implementation of these voluntary commitments."[74] The governments of other countries that have agreed to the guidelines could, however, ask China why it has not yet submitted reports on its stocks of civilian plutonium as of the end of 2017 and 2018. Arguably, France has a duty to do so because it is negotiating over construction of an Orano-designed reprocessing plant in China (discussed below).

In the meantime, 90 km to the east of the Jiuquan pilot reprocessing plant, CNNC is building a "demonstration" reprocessing plant with a design throughput of 200 tons of spent fuel per year. The plant is to be commissioned in 2025.[75] If, after a linear ramp-up over the first five years, it were to operate at an average of 50 to 100% of its design throughput, by 2040, it could have separated 12.5 to 25 tons of reactor-grade plutonium.

Since 2007, CNNC has been negotiating with France over the construction of an Orano-designed 800 ton/yr reprocessing plant with an associated MOX fuel fabrication facility to be sited on China's coast.[76] Originally, Orano's price was reported to be €20–25 billion.[77] By 2019, it was reported as €10 billion.[78] For that price, Orano would provide only the design and pieces of equipment that China is unable to produce.[79]

A coastal location would make it possible to transport spent fuel by ship to the reprocessing plant from China's nuclear powerplants, all of which are located on the coast. The plant has been rejected by one coastal city, however,[80] and consummation of Orano's contract with CNNC reportedly has been strongly opposed by the U.S. government.[81]

In April 2018, Orano projected that, if the deal with China were finalized in 2018/19, the reprocessing plant could be in operation "in the early 2030s."[82] Given the continuing delay, it is assumed here that the earliest date for operation has slipped to the mid-2030s. Assuming a linear ramp up to full capacity over 5 years, if operation began in 2035, the plant could separate up to 20 tons of reactor-grade plutonium by 2040.

At least some of the plutonium China plans to separate would be used to fuel the two 600-MWe breeder reactors China is building. Having no information about the design of CFR-600, we scale by power from calculations done by Glaser and Ramana for India's 500-MWe Prototype Fast Reactor: 2 tons of plutonium for the initial core and an annual reload of 1 ton for a capacity factor of 75%.[83] Assuming five annual reloads before the plutonium in the spent fuel could be recycled, the core and fuel-cycle inventory requirement for each CFR-600 would be 8.4 tons. For two CFR-600s, therefore, China's stock of unirradiated plutonium would be reduced by 17 tons.

In total, therefore, China's stock of civilian plutonium in 2040, could range from about 0 to 45 tons.[84]

France. As already noted, France's Orano today has only one remaining foreign power reactor as a customer for its reprocessing services in the Netherlands. Orano's costly reprocessing operation therefore is now essentially entirely supported by Électricité de France's (EDF's) fifty-six nuclear power reactors in France.

Orano's current contract to reprocess EDF's spent fuel lasts until 2040, with the amount of low-enriched uranium spent fuel to be reprocessed set at 1100 tons annually until 2022.[85] Orano fabricates most of the recovered plutonium into mixed-oxide (MOX) fuel. The operation also packages defective MOX pellets into rods that we describe as "scrap MOX." This scrap MOX is stored in the spent-fuel pools at France's reprocessing plant

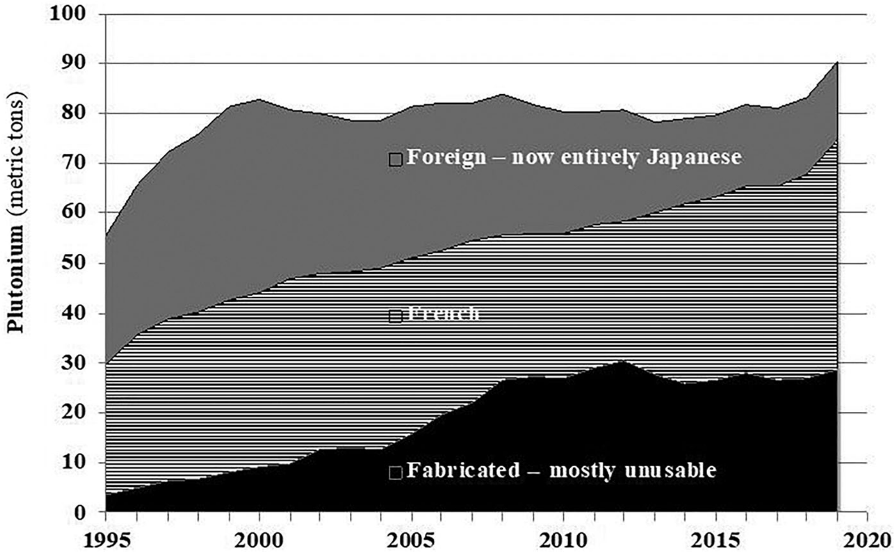

Figure 2. France's national stock of unirradiated plutonium (black and horizontal lines) has increased at an average rate of 1.9 tons/yr from 1995 to 2019, offsetting the reductions of its stock of foreign plutonium as foreign reprocessing contracts were not renewed.[144] As of the end of 2019, all of the foreign unirradiated plutonium in France belonged to Japan. It is being slowly fabricated into MOX fuel and shipped back to Japan to be used in the few Japanese reactors licensed to use MOX fuel.[145].

at La Hague. Also stored in those pools is scrap MOX from decommissioned MOX fuel-fabrication facilities in Belgium, Germany and France plus an unused core of MOX containing 1.6 tons of plutonium from Germany's SNR-300 breeder reactor, which was never operated because of safety concerns. France also has the unused second core of France's permanently shut-down *Superphénix* breeder reactor, containing about 6 tons of plutonium, in that reactor's pool. [86]

As of the end of 2018, France had a total of 282 tons of scrap MOX and unusable breeder fuel containing more than 20 tons of plutonium for which France has no firm disposal plans.[87] This is part of the 26.9 tons of "plutonium contained in unirradiated MOX fuel or other fabricated products at reactor sites or elsewhere," that France reported to the IAEA for that year, with the remainder being fresh MOX fuel either still at Orano's Melox fuel fabrication plant or at France's reactor sites not yet loaded into cores or in reactor cores but not yet irradiated. France's national stock of unirradiated plutonium in this category (shown in black in Figure 2) increased at an average rate of about 1 ton per year between the end of 1995 and the end of 2019. A continuing accumulation at this rate would increase France's stock of unirradiated civilian plutonium by roughly another 20 tons by 2040.

In an alternative scenario, France could follow the examples of its foreign customers and the preference of its national nuclear utility, Électricité de France (EDF) (see United Kingdom section below) and end reprocessing. France could then work down its own stock of about 40 tons of already separated plutonium at La Hague. This would leave for disposal France's approximately 20 tons of unirradiated plutonium in breeder and scrap MOX fuel. France could try to dissolve this unirradiated MOX fuel and fabricate it into usable MOX fuel or simply dispose of it directly in a deep repository with irradiated MOX and unreprocessed low-enriched uranium fuel.

Given that Orano's current reprocessing contract with EDF does not expire until 2040, however, this alternative scenario does not appear plausible before then and we assume that, with the accumulation of more scrap MOX, France's stock of unirradiated uranium will increase to 85 tons by 2040.

India. The only separated plutonium in India that is clearly civilian is 0.4 tons derived from the reprocessing during 1982–86 of spent fuel from India's first two heavy-water power reactors, Rajasthan 1 and 2 (RAPS-1 & 2). The two reactors were built with Canadian assistance prior to India's nuclear test in 1974. Canada's agreement with India requires that this plutonium be kept under IAEA safeguards.

All the plutonium India has separated since 1986 is from unsafeguarded heavy-water reactors and India has refused to place this plutonium under safeguards. Although India reportedly tested a nuclear explosive using reactor-grade plutonium in 1998, the most likely reason it refuses to put the bulk of its separated plutonium under safeguards is to keep its breeder program from falling under safeguards.[88]

India has declared its breeder program to be "strategic," i.e., that it may be used for nuclear-weapon-related purposes.[89] If India put any safeguarded plutonium into breeder reactor cores, the IAEA would demand that the reactors and any plutonium they produced be placed under safeguards as well.

For the purposes of this discussion, it will be assumed that India's unsafeguarded reactor-grade plutonium will be used to provide startup fuel for its breeder reactors. As has been discussed in the projection of India's stock of weapons plutonium, it is also assumed that the weapon-grade plutonium produced in the uranium "blanket" around the cores of India's unsafeguarded breeder reactor will be available for making nuclear weapons.

India currently has three plants that reprocess heavy-water-reactor fuel: two at Tarapur north of Mumbai and one at Kalpakkam in southern India, each with a design capacity to reprocess annually spent fuel originally containing 100 tons of natural uranium. The oldest of these, the PREFRE I

(Power Reactor Fuel Reprocessing I) plant at Tarapur, began operations in 1982 and PREFRE II in 2010. The Kalpakkam reprocessing plant, located at the Madras Atomic Power plant, near the headquarters of India's breeder program, began operations in 1998. A Fast Reactor Fuel Cycle Facility to reprocess the spent fuel from the Prototype Fast Breeder Reactor is under construction at Kalpakkam.[90]

India's reprocessing plants have had prolonged shutdowns for repairs and upgrades. Public information about their operation is scarce. The uncertainty of the estimate of the amount of plutonium they have separated is therefore quite large: between 3 and 11 tons as of the end of 2019.[91] This range translates into an average capacity factor for the reprocessing plants of between 12 and 44%.[92]

Even at the high end of the range, quite a bit of unsafeguarded plutonium would remain in unreprocessed spent fuel. As of the end of 2019, India's eight unsafeguarded heavy-water reactors (Madras 1&2; Kaiga 1,2,3&4; and Tarapur 3&4) had produced 41 thermal TWt-days (1 TWt-day = 1000 GWt-days).[93] Assuming 3.75 kg of plutonium per ton for a burnup of 7000 MWt-days/ton, the associated spent fuel would contain about 22 tons of plutonium. Assuming at least three years of cooling before reprocessing, operating with their historical weighted average capacity factor of 71%, the same unsafeguarded heavy-water reactors could discharge spent fuel containing another 21 tons of plutonium by the end of 2037. All the reactors India has under construction have been committed to be under IAEA safeguards.[94]

In the past, India's Department of Atomic Energy floated plans for building additional reprocessing capacity.[95] There are no reports of these plans being implemented. If India did build sufficient reprocessing capacity and that capacity operated well, however, it could separate cumulatively up to 43 tons of plutonium by 2040. If India stays with its current reprocessing capacity and that capacity continues to operate within the historical range, as of the end of 2040, India would have cumulatively separated 6 to 21 tons of power-reactor plutonium.

Ramana and Suchitra estimated that 5 tons plutonium will be required to fuel the Prototype Fast Breeder Reactor, including its first three annual reloads – about 2 tons for the initial core and 1 ton annually thereafter.[96] If India builds its two planned commercial breeder reactors with basically the same design, the startup requirement of plutonium for all three reactors would be about 15 tons. If, more realistically, five annual reloads would be required before India could reprocess the fuel and fabricate the recovered plutonium into fresh MOX fuel, the startup plutonium requirement for the three breeder reactors would increase to about 21 tons. Thus, if India actually built three breeder reactors by 2040, depending upon the operation of its reprocessing plants, it would have between a shortage of 15 tons and zero tons of plutonium relative to its expected requirements. In the most extreme case of shortage, it would use its total inventory of reactor grade plutonium to fuel one breeder reactor and it would have an inventory of zero reactor-grade plutonium.[97] On the other hand, if India's government decided not to authorize the construction of the two proposed commercial breeder reactors, it could have up to 14 tons of unirradiated separated plutonium as of 2040.[98]

Japan. Japan has been slowly drawing down its plutonium stock in France as capacity becomes available to use it in the few operating reactors Japan has licensed to use MOX fuel. The average rate of reduction of Japan's stock of plutonium in France through MOX use in Japan's power reactors between the end of 1998 and the end of 2019 was about 0.21 tons per year. Japan's stock of plutonium in France at the end of 2019 was 15.4 tons.[99]

Except for about 0.8 tons shipped to Japan between 1970 and 1981, Japan's plutonium stock in the United Kingdom remains entirely unused due to the failure of the United Kingdom's MOX-fuel-production plant, which was abandoned in 2011, after the Fukushima accident.[100] Since then, Japan's plutonium in the United Kingdom (21.8 tons as of the end of 2018[101]) has been trapped there by an apparently de facto policy that plutonium can be shipped from Europe to Japan only in the form of MOX fuel.[102]

As already noted, the United Kingdom has offered to take title to the foreign plutonium that it holds and dispose of it with the United Kingdom's own, much larger stock. Japan and the United Kingdom have opened discussions on the management of Japan's plutonium in the United Kingdom.[103] The discussions are proceeding slowly, however – perhaps in part because of the poor optics of Japan's utilities paying to get rid of their separated plutonium in the United Kingdom at the same time Japan's government is pushing them to start separating more in Japan at a projected cost of about ¥10 trillion yen ($96 billion) over 40 years.[104]

Table 4 shows the makeup of Japan's stock of unirradiated plutonium in Japan as of the end of 2019. Japan will be unable to convert any of this

Table 4. Forms and locations of the approximately 9 tons of unirradiated plutonium in Japan as of the end of 2019 (metric tons) and total quantities in France and the United Kingdom.[105]

	Plutonium oxide and nitrate	In partially fabricated MOX fuel	In fabricated fuel
In R&D facilities	2.77	0.90	0.97
At Rokkasho Reprocessing Plant	3.60	–	
At power reactors	–	–	0.62
Subtotal: In Japan	6.37	0.90	1.59
In France	15.4		
In the United Kingdom	21.2		
Total	42.97	0.90	1.59

plutonium into MOX fuel until the MOX plant under construction next to the Rokkasho Reprocessing Plant has been completed.

Although Japan's official position is that its fast reactor development program continues, its plutonium research and development (R&D) complex has been shrinking. Its prototype breeder reactor, *Monju*, and the pilot reprocessing plant at Tokai are being decommissioned. The experimental (140 MWt) fast-neutron reactor, *Joyo*, has been shut down since 2007 by damage due to a refueling accident.[106] The Japan Atomic Energy Agency (JAEA) plans to apply for a license to restart its pilot MOX fuel fabrication facility at Tokai after satisfying the more stringent post-Fukushima-accident safety rules. The facility's remaining missions are to support *Joyo* and the MOX fuel fabrication facility being built next to the Rokkasho Reprocessing Plant. Restart is projected to be after 2027.[107]

At the end of 2019, 72% of Japan's in-country plutonium was in either oxide or nitrate form, mixed with an equal amount of reprocessed (recovered) uranium as a token response to the U.S. concerns about the proliferation and terrorism dangers associated with Japan's separated plutonium.

Reactor-grade plutonium contains 14 to 15% plutonium-241 when it is discharged from a reactor core.[108] Plutonium-241 decays with a 14-year half-life into americium-241, which has a half-life of 432 years and emits gamma rays when it decays, creating a radiation hazard for workers in MOX fuel fabrication plants.

Because of that radiation hazard, France's MELOX plant, the model for Japan's under-construction MOX plant, does not process plutonium in which americium-241 has been allowed to build up for more than six years.[109] Processing Japan's older plutonium into MOX fuel therefore would require either removing the americium-241 first or diluting the plutonium with freshly separated plutonium.

Several processes for removing ingrown americium from plutonium have been developed in the United States for weapons plutonium.[110] Japan Nuclear Fuel Limited (JNFL), which owns the Rokkasho reprocessing and MOX plants, reportedly plans, however, to deal with the problem of americium-241 buildup in stored plutonium by diluting its old plutonium with freshly separated plutonium.

Regular operations at the Rokkasho Reprocessing Plant were originally scheduled to begin in 1997. Currently, the plan is to start them in Fiscal Year 2023, which begins 1 April 2023.[111] Separations are to ramp up over a period of four years during which about 1500 tons of spent fuel are to be reprocessed.[112] Thereafter, the plant is to reprocess 800 tons of spent fuel annually from which about 7 tons of plutonium are to be recovered.[113] If reprocessing began in 2023 and were carried out according to this plan, about 111 tons of plutonium would have been separated by 2040.

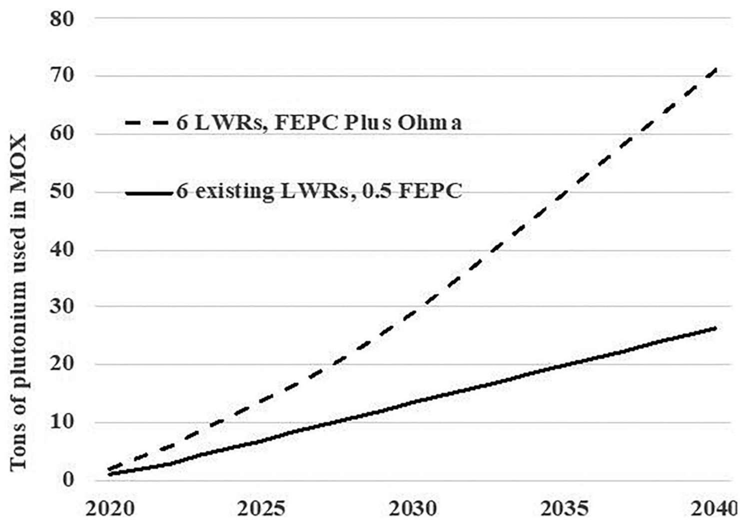

Figure 3. Two scenarios for Japan's irradiation of plutonium in MOX fuel. For the upper curve, the six existing LWRs licensed for MOX fuel and operating or likely to operate soon, irradiate plutonium in MOX fuel at the rate assumed by Japan's Federation of Electric Power Companies (FEPC) and the Ohma reactor begins to operate in 2028 and ramps up to a full core of MOX fuel in 2033. In the second, the Ohma reactor is not completed and the six existing LWRs irradiate MOX at half of the rate assumed by FEPC.

Japan has six reactors that were licensed to use MOX fuel before the March 2011 Fukushima accident that either have been allowed to resume operating or are being reviewed for restart after post-Fukushima safety upgrades.[114] There appears to be no interest on the part of the Japan's nuclear utilities in applying for licenses to use MOX fuel in reactors not previously licensed to use it. According to the projections by Japan's Federation of Electric Power Companies (FEPC), the six reactors should use on average MOX fuel containing 2.6 tons of plutonium per year.[115] During 2018–2020, however, the rate of consumption (loading into the core and irradiation) by Japan's four operating MOX fueled reactors was less than one third the rate projected by FEPC. In projecting future MOX use, therefore, we have included a scenario in which the six reactors use plutonium at half the rate projected by FEPC. At that rate, the six reactors would irradiate 26 tons of plutonium in MOX by the end of 2040.[116] In an optimistic scenario, the six reactors would irradiate plutonium at the rate projected by FEPC and, in addition, the under-construction Ohma reactor is completed and comes into operation in 2028 as currently planned.[117] The control system of the Ohma reactor is designed to enable it to be fueled entirely with MOX. If it were operated in that way with the other six reactors using fuel at the rate projected by FEPC, Japan could irradiate 71 tons of plutonium by the end of 2040 (Figure 3).

In 2018, under pressure from the United States, Japan's Cabinet approved a declaration in Japan's Strategic Energy Plan that "The Japanese government remains committed to the policy of not possessing [unirradiated] plutonium without specific purposes on the premise of peaceful use of plutonium and work to reduce … the size of [its] plutonium stockpile."[118] Even with the optimistic scenario for Japan's plutonium use in MOX shown in Figure 3, however, that goal could not be achieved consistent with JNFL's operating plan for the Rokkasho Reprocessing Plant. The 40 to 85-ton increase from the excess plutonium separated at the Rokkaho Reprocessing Plant by 2040 could be partially offset if Japan agreed to accept the United Kingdom's offer to take title to the 22 tons of Japanese separated plutonium in the United Kingdom. Even so, however, to live up to the Government's commitment, JNFL would have to keep its rate of plutonium separation 16 to 57% below the design capacity of the Rokkasho Reprocessing Plant, leading to a still higher cost per ton reprocessed, which might turn out to be the final death knell for the project.[119] Assuming that Japan lives up to its commitment, the net result will be to reduce the amount of unirradiated plutonium Japan owns in Europe in exchange for an increase of the amount of separated plutonium in Japan.

In fact, JNFL is not planning a "just-in-time" minimal inventory policy such as that for which Japan's Toyota automobile company is justly famous. It has built into the Rokkasho Reprocessing Plant a storage capacity for up to 30 tons of plutonium.[120] This is in line with France's practice at La Hague. As of the end of 2019, Orano was storing there 52 tons of separated plutonium– about five years of output – in the form of plutonium oxide.[121]

Based on France's practice, JNFL's MOX fuel fabrication plant, which is under construction, will have on the order of an additional six tons working stock of plutonium in process at its MOX Fuel Fabrication Plant plus perhaps two tons of plutonium in scrap MOX by 2040.[122]

If JNFL's MOX plant failed to operate – as occurred with the United Kingdom's separated at Rokkasho would have no path for disposition, as is the case today for approximately 140 tons of unirradiated plutonium at the Sellafield reprocessing site in the United Kingdom.[123]

To avoid such an outcome, Japan could refrain from operating the Rokkasho Reprocessing Plant until JNFL's MOX fuel fabrication plant is complete and has demonstrated that it is fully operable. If JNFL continues in refusing to clean the americium-241 out of its existing stock of separated plutonium (Table 4) to make it useable as feed for the MOX plant, the plant could be tested making low-enriched uranium fuel.

A truly responsible policy would be to decommission the Rokkasho Reprocessing Plant and place Japan's spent fuel in dry-cask storage until a deep underground repository becomes available. That would remove large unnecessary burdens from both Japan's electricity rate payers and the global nonproliferation regime. If Japan used up in MOX the plutonium it has stored in France and transfer the title of the plutonium it has stored at Sellafield to the United Kingdom, it would then have only the 9 tons of unirradiated plutonium it currently has in Japan left to deal with.

The above two scenarios: 1) Japan not starting the Rokkasho Reprocessing Plant, transferring its separated plutonium in the United Kingdom to British ownership and irradiating its plutonium stock in France in MOX fuel in Japan's power reactors, and 2) Barely living up to its commitment not to increase its stock of separated plutonium, would result in Japan having 9 or about 45 tons of unirradiated plutonium in 2040. An intermediate scenario could result if the Rokkasho Reprocessing Plant operated poorly due to technical malfunctions such as the failure of its vitrification process (in which the liquid high-level radioactive waste is immobilized in glass) during active testing in 2006–8.

Russia. Russia is currently shifting its new BN-800 breeder reactor from mostly enriched uranium to MOX fuel.[124] Operating at 75% capacity, the BN-800 could irradiate about 1.8 tons of weapon-grade plutonium annually, which, based on Russia's annual declarations to the IAEA on the growth of its stock of civilian plutonium, is about as much plutonium as the Mayak reprocessing plant has been separating annually.[125]

Rosatom plans, however, to expand the rate of plutonium separation at Mayak to its nominal design capacity of 4 tons per year, and to build a 1500-ton/year spent fuel reprocessing plant in Zheleznogorsk.[126] If realized, these plans would increase plutonium separation in Russia to 17 tons per year by 2028.

These are decades-old plans that have been delayed year after year, however, and there in no reason to believe that Russia's nuclear conglomerate, Rosatom, focused as it is on profits, will commit the necessary funds to build a huge reprocessing plant at Zheleznogorsk at a time when Russia already has more separated plutonium than it knows what to do with.

For the purposes of projecting, we assume a range of plutonium separation rates in Russia from zero increase to an increase of two tons per year in the 2020s and four tons per year in the 2030s for a resulting increase in Russia's stock of reactor-grade plutonium by 0 to 60 tons in 2040.

United Kingdom. With the projected completion of its reprocessing of legacy Magnox spent fuel in 2021, the United Kingdom's days of plutonium separation will be over.[127] The question becomes: how can the United Kingdom dispose of its stock of about 140 tons of separated plutonium, including the approximately 23 tons of Japanese and other foreign plutonium stranded in the United Kingdom?

The U.K. Nuclear Decommissioning Authority's (NDA) preferred option has been to contract with France's Orano to build a new MOX fuel fabrication plant at Sellafield. NDA's rationale is that MOX fuel fabrication, as implemented in France, is a "mature" technology.[128] With this approach, the spent MOX fuel could be stored with other spent power reactor fuel until a radioactive waste repository can be built and there would be no need to devise secure storage arrangements for a new waste form.

Even though the U.K. government has provided Électricité de France (EDF) a huge subsidy to build two 1630-MWe reactors on the Bristol Channel in southwest England that could be adapted to use full cores of MOX fuel and irradiate two tons of plutonium each per year, and EDF's sister company, Orano, could make many additional billions of dollars constructing a MOX fuel fabrication plant for the United Kingdom, EDF has refused to use MOX fuel in those reactors.[129]

The U.S. DOE had the same problem finding a utility willing to use the MOX fuel that was to be produced from excess U.S. weapons plutonium – even when it offered to supply the MOX at a significantly lower cost than the equivalent amount of low-enriched uranium fuel. The utilities lacked confidence that DOE's planned MOX fuel fabrication plant would produce MOX fuel on schedule or that the fuel would have the same durability as modern LEU fuel. They also would have had to obtain licenses to use MOX fuel, which would involve a potentially costly and contentious process.

The safety issues associated with MOX fuel include both the technical issue of the reduced effectiveness of control rods with MOX fuel and the political issue of possible public opposition.[130] Given that fuel costs account for less than ten percent of the cost of generating electricity from a new nuclear power plant, it is understandable that a utility would be hesitant about using untried MOX fuel that might reduce the operational availability of the plant.[131]

Two other reactor vendors: Atomic Energy of Canada Limited (AECL) and GE-Hitachi have offered to build dedicated nuclear reactors to irradiate the United Kingdom's plutonium.[132] Their proposals would, however, require the government to finance the reactors as well as the associated fuel fabrication plants.

In the case of the GE-Hitachi proposal, an additional complication is that the sodium-cooled reactors it proposes to build would require fabricating the plutonium into fuel containing sodium to conduct heat from the metal fuel "meat" to the cladding. This is necessary because the metal fuel meat swells as it is irradiated. Therefore there must be an initial gap between the meat and the cladding. The purpose of the liquid sodium is to conduct the fission heat across that gap.

This fuel design was used in U.S. Experimental Breeder Reactor II (EBR II, 1965–94). The EBR II spent fuel is considered unsafe for disposal in an underground repository because the sodium in the fuel could react with water to generate explosive hydrogen. As a result, the Idaho National Laboratory persuaded the U.S. DOE to fund it to use its experimental reprocessing (pyroprocessing) technology to convert the EBR II spent fuel into more stable waste forms. Unfortunately, the process has not worked well and there have been prolonged delays and huge cost increases and the products produced are still not suitable for disposal in a spent fuel repository.[133] The U.K. Nuclear Decommissioning Authority has understood that the GE-Hitachi proposal therefore would not necessarily put the United Kingdom's plutonium into a stable form for disposal.[134] The spent fuel also would not be sufficiently irradiated to meet the requirement of a self-protecting radiation barrier around the spent fuel of at least one Sievert/hour at 1 meter's distance, 30 years after discharge.[135]

Meanwhile, the United Kingdom is developing a capability to immobilize plutonium in an insoluble waste form. This approach is focused on plutonium that would be difficult to clean up for use in MOX fuel but could become an option for the disposal of the United Kingdom's entire plutonium stock.[136] Given that it is very uncertain how soon a deep underground national radioactive repository can be sited in the United Kingdom, however, the current de facto U.K. policy for its separated plutonium is secure interim storage.[137]

It is possible that a strategy for how to move U.K. plutonium disposal forward could be decided by 2040 but it seems unlikely that a significant amount of plutonium could be disposed by then. This is assumed in Table 3. It is also assumed that, by 2040, the United Kingdom will have taken ownership of the Japanese plutonium that is marooned in the United Kingdom.

United States. The DOE under the Trump Administration backed the Idaho National Laboratory in its push to build a larger version of the Experimental Breeder Reactor II that the Clinton Administration shut down in 1994 for lack of a mission. The proposed new \$2.6–5.8 billion reactor is called a "Versatile Test Reactor" (VTR) and the need for it is posited on the expectation that fast-neutron reactors will emerge as economically competitive sources of electrical power and that a fast-neutron test reactor is therefore required to test the durability of reactor and fuel materials. The VTR would require 0.4 tons of plutonium in its fuel annually.[138] This plutonium could come from the material that the United States has declared excess for weapons purposes. Given the cost of the

VTR, the continuing lack of evidence for the economic viability of fast-neutron power reactors, and the history of the DOE's inability to complete large projects, there is a good chance that the project will not be completed.

Other countries. The only country not currently reprocessing that is seriously interested in doing so is South Korea (the Republic of Korea or ROK). For decades, the Korea Atomic Energy Research Institute (KAERI) has been arguing that the ROK should have the same right to reprocess as Japan.[139] In the absence of U.S. agreement, however, the ROK government has refused to give KAERI the go ahead.

The issue did result, however, in protracted and difficult negotiations on the renewal of two countries' Agreement on Cooperation on the Peaceful Use of Atomic Energy. As part of that agreement, in 2015, the two countries agreed to complete a ten-year joint study on the "feasibility" of pyroprocessing, a type of reprocessing developed by Argonne National Laboratory and transferred to KAERI during the G.W. Bush Administration. The feasibility study will conclude at the end of 2020.

If the United States agreed, KAERI's proposal would be to build a "demonstration" pyroprocessing facility with a capacity to reprocess annually 30 tons of light water reactor (LWR) spent fuel at an estimated cost of 1.1 trillion won ($1 billion).[140] This capacity is small relative to the approximately 500 tons of spent fuel that South Korea's LWRs discharge annually.[141] The quantity of separated plutonium would not be insignificant from a nonproliferation perspective, however. Thirty tons of spent LWR fuel contains about 300 kilograms of plutonium – enough by the IAEA's metric to make about 40 nuclear warheads. If KAERI were given permission in 2021 to proceed with the demonstration reprocessing plant, and the plant began to operate at design capacity in 2030, then, by 2040, South Korea could have separated up to 3 tons of plutonium.

Conclusions

The end of the Cold War brought the production of plutonium for weapons to an end in Europe, Russia and the United States but such production continues in regions of international tension: the Middle East (in Israel), South Asia (in India and Pakistan), and East Asia (in North Korea). It is also possible that China might resume the production of plutonium for weapons.

In 2000, in their PMDA, Russia and the United States agreed, to each dispose of 34 tons of excess weapons plutonium – enough for on the order of 10,000 warheads each. In the context of deteriorating U.S.-Russian relations, Russia suspended the agreement. The United States plans to continue with the disposal of its excess plutonium but slowly and with a different process than agreed to in the PMDA. Russia's planned disposition method, although accepted by the United States, was problematic because it would involve the indefinite recycle in breeder reactors of the excess plutonium and plutonium made with it, thereby continuing indefinitely the exposure of plutonium to diversion.

Three decades after the end of the Cold War, therefore, although the global number of operational nuclear warheads has dropped to about one sixth of its Cold War peak, very little of the plutonium from the excess warheads has been disposed.[142] This contrasts with the situation with HEU where the U.S. weapons stock has been reduced by 70% and Russia's by about 40%.[143]

Incompleteness in these tasks is dangerous. Plutonium-239 has a half-life of 24,000 years – much longer than the halflife of human governments. (Uranium-235 has a half-life of 0.7 billion years.)

With regard to separated civilian plutonium, the worldwide failure of the effort to commercialize sodium-cooled breeder reactors brought to an end the justification for the reprocessing of spent power reactor fuel to recover plutonium. Shutting down existing reprocessing complexes in France, Japan and Russia appears to be considered unthinkable, however, due to their rigid governing systems, while China, with its economy continuing to strengthen, has decided to add two prototype breeder reactors, a demonstration reprocessing plant, and perhaps a large commercial reprocessing plant to its portfolio of technologies.

France and Japan have implemented an alternative – although grossly uneconomic – use for the plutonium they continue to separate: fabrication into mixed-oxide fuel for their fleets of LWRs. Russia has finally begun to use plutonium to fuel its BN-800 prototype breeder reactor at a rate comparable to the rate of plutonium separation in Russia but that equilibrium will be only temporary if Russia carries through on its plan to greatly expand the scale of civilian reprocessing activities in the three closed cities originally established to produce plutonium for Soviet Cold War nuclear weapons.

Reprocessing in the United Kingdom is finally coming to an end because of the refusal by the U.K.'s domestic nuclear utility – ironically, a subsidiary of France's EDF – to renew its reprocessing contract. EDF also refuses to use MOX fuel in its U.K. reactors. This leaves the United Kingdom, the owner of the world's largest stock of separated civilian plutonium, with no strategy for its disposal.

Our projections for global civilian plutonium stocks in 2040 range from relatively little change to a 50% increase. If Japan were to join the United Kingdom in ending reprocessing, the reduction in its stock might be partially offset by an increase in the United Kingdom's as a result of a transfer of title to Japan's stock in the United Kingdom. If Japan continues with its plutonium separation program while China, France, India and Russia all expand their plutonium stocks, the result could be somewhere around the higher end of the projections.

Given the lack of an economic rationale for using plutonium as a fuel, plutonium is not a plausible nuclear fuel of the future. Instead, as a nuclear-weapon material, it poses an existential risk to the future of humanity. The global effort to end all production and to reduce plutonium stocks and the number of locations where they can be found must be reenergized.

Notes and References

Notes

1. Gordon, M.R., "It's Official: U.S. Stops Making Material for Nuclear Warheads," *New York Times,* 14 July 1992, https://www.nytimes.com/1992/07/14/us/it-s-official-us-stops-making-material-for-nuclear-warheads.html; France announced that it had ended the production of plutonium for weapons in November 1992, "French Action on Nuclear Disarmament: Key Figures," https://www.francetnp.gouv.fr/presentation-77; "Agreement Between the Government of the United States of America and the Government of the Russian Federation Concerning the Shutdown of Plutonium Production Reactors and the Cessation of Use of Newly Produced Plutonium for Nuclear Weapons," https://media.nti.org/pdfs/StateandRussiaReactorShutdown1994.pdf. The agreement came into force in September 1994, Perry, T. "Stemming Russia's Plutonium Tide: Cooperative Efforts to Convert Military Reactors," *Nonproliferation Review,* Winter 1997, 39, https://www.nonproliferation.org/wp-content/uploads/npr/perry43.pdf; U.K. Secretary of State for Foreign and Commonwealth Affairs, statement at the 1995 Nonproliferation Treaty Review Conference, 18 April 1995, cited by Mr. David Davis in answer to a parliamentary question from Mr. Paul Flynn, https://publications.parliament.uk/pa/cm199495/cmhansrd/1995-05-01/Writtens-5.html.
2. Zhang, H., *China's Fissile Material Production and Stockpile* (International Panel on Fissile Materials [IPFM], 2017), http://fissilematerials.org/library/rr17.pdf; See for example, the transcript of an exchange between Chinese and U.S. delegates to the U.N. Conference on Disarmament in Geneva on 8 August 2019, https://undocs.org/cd/PV.1515. At p. 23, a member of China's delegation stated, "In our view, a moratorium on production is not the fundamental path to completely and effectively resolving the FMCT [Fissile Material Cutoff Treaty] issue." At p. 27: a member of the U.S. delegation stated, "A moratorium … is a fundamental demonstrative trust-building measure that any State serious about negotiating an FMCT should, at a minimum, be able to support. China is the only nuclear-weapon State [party to the Nonproliferation Treaty] without such a moratorium."
3. "U.S.-Russian Plutonium Management and Disposition Agreement," 2000, http://fissilematerials.org/library/PMDA2000.pdf.

4. "U.S.-Russian Plutonium Management and Disposition Agreement," as amended in 2010, 11 May 2010, http://fissilematerials.org/library/PMDA2010.pdf; IPFM, "United States to discontinue construction of MOX Fuel Fabrication Facility," 10 February 2016, http://fissilematerials.org/blog/2016/02/united_states_to_disconti.html.
5. IPFM, "Russia suspends implementation of plutonium disposition agreement," 3 October 2016, http://fissilematerials.org/blog/2016/10/russia_suspends_implement.html.
6. Carson, M.J., "Explosive Properties of Reactor-Grade Plutonium," *Science & Global Security* (1993): 111–128, http://scienceandglobalsecurity.org/archive/sgs17mark.pdf; U.S. Department of Energy, "Reactor-Grade and Weapons-Grade Plutonium in Nuclear Explosives" in Nonproliferation and Arms Control Assessment of Weapon-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives, DOE/NN-0007, 1997, 37–39, http://fissilematerials.org/library/doe97.pdf.
7. Albright, D. Frans Berkhout and William Walker, *Plutonium and Highly Enriched Uranium 1996, World Inventories, Capabilities and Policies* (Stockholm International Peace Research Institute, 1997), https://www.sipri.org/sites/default/files/files/books/SIPRI97AlBeWa/SIPRI97AlBeWa.pdf.
8. von Hippel, F.N., Masafumi Takubo and Jungmin Kang, *Plutonium: How Nuclear Power's Dream Fuel Became a Nightmare* (Singapore: Springer, 2019).
9. International Atomic Energy Commission (IAEA), "Communication Received from Certain Member States Concerning their Policies Regarding the Management Of Plutonium," 1998, https://www.iaea.org/sites/default/files/infcirc549.pdf.
10. Stocks of plutonium from *Global Fissile Material Report 2010* (IPFM, 2010), http://fissilematerials.org/library/gfmr10.pdf and Kütt, Moritz, Zia Mian and Pavel Podvig, "Global stocks and production of fissile materials, 2019," *SIPRI Yearbook 2020* (Stockholm International Peace Research Institute, 2020), Table 10.12, https://www.sipri.org/sites/default/files/YB20%2010%20WNF.pdf. Stocks of nuclear weapons from Kristensen, H., Robert Norris, "Global nuclear weapons inventories, 1945–2013," *Bulletin of the Atomic Scientists* 69 (2013): 75–81, https://doi.org/10.1177/0096340213501363 and "Nuclear Notebook," *Bulletin of the Atomic Scientists*, https://thebulletin.org/nuclear-notebook/.
11. International Atomic Energy Commission (IAEA), "Communication[s] Received from Certain Member States Concerning Their Policies Regarding the Management of Plutonium," https://www.iaea.org/publications/documents/infcircs/communication-received-certain-member-states-concerning-their-policies-regarding-management-plutonium.
12. As of the end of 2013, there were approximately 240,000 tons of spent fuel in storage (International Atomic Energy Commission (IAEA), *Status and Trends in Spent Fuel and Radioactive Waste Management*, 2018, https://www-pub.iaea.org/MTCD/Publications/PDF/P1799_web.pdf), Table 5. This spent fuel was mostly produced by a mixture of reactor types: light water reactors (LWRs), gas and water-cooled graphite moderated reactors, and heavy-water reactors (HWRs) with plutonium weight percentages measured relative to original uranium content ranging from about 1 percent for LWR to about 0.4 percent for HWR spent fuel.
13. "Weapon-grade plutonium' means plutonium with an isotopic ratio of plutonium 240 to plutonium 239 of no more than 0.10." U.S.-Russian Plutonium Management and Disposition Agreement, 2000, Article 1.1.
14. Zhang, H. *China's Fissile Material Production and Stockpile.*

15. The Nagasaki bomb contained about 6 kilograms but there were great advances in implosion systems thereafter. As discussed in the caption of Figure 1, a comparison of declassified historical numbers for U.S. separated plutonium and nuclear warheads prior to the mid-1960s finds an average of 3 kg of plutonium per U.S. warhead; Kristensen, H., "DIA Estimates For Chinese Nuclear Warheads," 31 May 2019, https://fas.org/blogs/security/2019/05/chinese-nuclear-stockpile/; Xijin, H., "China needs to increase its nuclear warheads to 1,000," editorial, *Global Times*, 8 May 2020, https://www.globaltimes.cn/content/1187766.shtml.
16. IPFM, *Global Fissile Material Report 2010,* 155–160.
17. Wu, J., "The regulation and technology of Chinese nuclear material accounting," Center for International & Security Studies, University of Maryland, 2014, 2, https://www.jstor.org/stable/pdf/resrep05024.pdf?refreqid=excelsior%3Add42c5d274f471641f82675c2f4f3773; Personal communication from a Canadian safeguards expert.
18. May, M., Chaim Braun, George Bunn et al., *Verifying the Agreed Framework* (Stanford University and Livermore National Laboratory, 2001), Figure 4.8, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/VAF-June.pdf.
19. Bunn, M., Hui Zhang and Li Kang, *The Cost of Reprocessing in China*, Belfer Center for Science and International Affairs, Harvard Kennedy School, 2016, 27, https://dash.harvard.edu/bitstream/handle/1/27029093/Bunn_The_Cost_of_Reprocessing_in_China.pdf?sequence=1&isAllowed=y.
20. Glaser, A. and M.V. Ramana, "Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor," *Science & Global Security* 15 (2007): 85–105, https://www.princeton.edu/~aglaser/2007aglaser_sgsvol15.pdf.
21. Zhang, H., "China is Speeding Up its Plutonium Recycling Programs," *Bulletin of the Atomic Scientists* 76, 210–216, https://doi.org/10.1080/00963402.2020.1778372.
22. Lewis, G. and Frank von Hippel, "Improving U.S. Ballistic Missile Defense Policy," *Arms Control Today,* May 2018, https://www.armscontrol.org/act/2018-05/features/improving-us-ballistic-missile-defense-policy.
23. Kütt et al., "Global stocks and production of fissile materials, 2019."
24. IPFM, *Global Fissile Material Report 2010,* 119. When a heavy-water reactor is started up, some of the first fuel discharged has a low burnup and therefore contains weapon-grade plutonium. An upper bound of about 95 kilograms from this source is included in the IPFM range estimate.
25. IPFM, *Global Fissile Material Report 2010*, 119.
26. IPFM, "India's prototype breeder reactor is delayed again," 12 March 2020, http://fissilematerials.org/blog/2020/03/indias_prototype_breeder.html.
27. Financial Express, "Prototype Fast Breeder Reactor likely to be commissioned by Oct 2022: Govt," https://www.financialexpress.com/defence/prototype-fast-breeder-reactor-likely-to-be-commissioned-by-oct-2022-govt/2089342/.
28. Jha, S., "Waiting for the Fast Breeder Reactor," *Deccan Herald,* 25 March 2019, https://www.deccanherald.com/opinion/in-perspective/waiting-for-the-fast-breeder-reactor-725104.html.
29. Indian Ministry of External Affairs, "Implementation of the India-United States Joint Statement of July 18, 2005: India's Separation Plan," http://mea.gov.in/Uploads/PublicationDocs/6145_bilateral-documents-May-11-2006.pdf.

30. Mian, Z., A.H. Nayyar, R. Rajaraman, and M.V. Ramana, *Fissile Materials in South Asia: The Implications of the U.S.-India Nuclear Deal* (IPFM, 2006), http://fissilematerials.org/publications/2006/09/fissile_materials_in_south_asi.html.
31. Glaser, A. and M.V. Ramana, "Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor."
32. Dhruva, 0.4 tons, plus 5 tons from the breeders.
33. Robert, J., J. Hainzelin and V. Raievski, "The EL.3 Reactor," Second International Conference on the Peaceful Uses of Atomic Energy, 1958, https://www.osti.gov/servlets/purl/4263421; International Atomic Energy Commission (IAEA), Research Reactor Database, https://nucleus.iaea.org/RRDB/RR/HeaderInfo.aspx?RId=203.
34. IPFM, *Global Fissile Material Report 2010* (IPFM, 2010), 109–112.
35. Kütt et al., "Global stocks and production of fissile materials, 2019."
36. Bob, Y.J., "Experts agree Dimona nuke reactor can exceed original life expectancy," *Jerusalem Post*, 12 July 2019, https://www.jpost.com/israel-news/experts-agree-dimona-nuke-reactor-can-exceed-original-life-expectancy-595404.
37. IPFM, *Global Fissile Material Report 2010,* Figure B.5. The reactor core contains about 50 tons of natural uranium fuel, Kang, J., "Using the Graphite Isotope Ratio Method to Verify the DPRK's Plutonium-Production Declaration," *Science & Global Security* 19 (2011): 121–129, Table 1, http://scienceandglobalsecurity.org/archive/sgs19kang.pdf. At full power, the average incremental burnup of this fuel would only be about 150 MWt-days/tonU per year. An average discharge burnup of 300 MWt-days/tonU has been assumed.
38. Albright, D., "North Korea's Nuclear Capabilities: A Fresh Look," ISIS, April 22, 2017, https://isis-online.org/uploads/isis-reports/documents/North_Korea_Talk_April_28_2017_Final.pdf.
39. International Atomic Energy Commission (IAEA), Report by the Director General, "Application of Safeguards in the Democratic People's Republic of Korea," 3 September 2020, https://www.iaea.org/sites/default/files/gc/gc64-18.pdf, and previous annual reports in this series at the website, https://www.iaea.org/gc-archives/gc.
40. Hecker, S., "A Return Trip to North Korea's Yongbyon Nuclear Complex," November 20, 2010, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/HeckerYongbyon.pdf.
41. May et al., *Verifying the Agreed Framework,* Figure 4.8.
42. Albright, D., Sarah Burkhard, Claire Chopin, and Frank Pabian**, "**New Thermal Power Estimates of the Khushab Nuclear Reactors," 23 May 2018, https://isis-online.org/isis-reports/detail/new-thermal-power-estimates-of-the-khushab-nuclear-reactors/12.
43. IPFM, *Global Fissile Material Report 2010,* Figure B.5.
44. Kütt, et al., "Global stocks and production of fissile materials, 2019."
45. Mian, Z., A. H. Nayyar, R. Rajaraman, "Exploring Uranium Resource Constraints on Fissile Material Production in Pakistan," *Science & Global Security* 17 (2009): 77–108, http://scienceandglobalsecurity.org/archive/sgs17mian.pdf.
46. For a fuel burnup of about 1000 MWt-days/tonU, a heavy-water reactor would require about 7 tons of natural uranium to produce 6 kg of weapon-grade plutonium, the amount in the Nagasaki bomb, IPFM, *Global Fissile Material Report 2010,* 159. At today's market cost of about \$100/kgU, that amount of natural uranium would cost \$0.7 million. Re-enriching the uranium recovered from the spent fuel could significantly reduce the uranium requirements.

47. Ahmad, A., Frank N. von Hippel, Alexander Glaser and Zia Mian, “A Win-Win Solution for Iran’s Arak Reactor,” *Arms Control Today,* April 2014, https://www.armscontrol.org/act/2014-04/win-win-solution-iran’s-arak-reactor.
48. Joint Comprehensive Plan of Action, 2015, Nuclear section, paras. 8 and 12, https://2009-2017.state.gov/documents/organization/245317.pdf.
49. U.K. Ministry of Defense, *Strategic Defense Review*, 1998, para. 72, http://fissilematerials.org/library/mod98.pdf.
50. IPFM, *Global Fissile Material Report 2010*, 54. Russia continued to operate two of its production reactors at Seversk until 2008 and one at Zheleznogorsk until 2010 because the reactors provided heat and electricity to those cities.
51. U.S. Department of Energy, “*Plutonium: The First 50 Years* (Washington, DC: U.S. Dept. of Energy,1996), 25, 30, http://fissilematerials.org/library/1996/02/plutonium_the_first_50_years.html.
52. IPFM, “Russia suspends implementation of plutonium disposition agreement,” 3 October 2016, http://fissilematerials.org/blog/2016/10/russia_suspends_implement.html.
53. IPFM, “Russia uses civilian reactor-grade plutonium to produce MOX fuel for BN-800,” 29 August 2019, http://fissilematerials.org/blog/2019/08/russia_uses_civilian_reac.html.
54. International Atomic Energy Commission (IAEA), “Communication Received from the United States of America Concerning its Policies Regarding the Management of Plutonium,” INFCIRC/549/Add.6/22, 11 October 2019, https://www.iaea.org/publications/documents/infcircs/communication-received-certain-member-states-concerning-their-policies-regarding-management-plutonium.
55. Judy, S., “DOE Terminates MOX Contract, Likely Killing Controversial Project,” *Engineering Record,* 15 October 2018, https://www.enr.com/articles/45529-doe-terminates-mox-contract-likely-killing-controversial-project.
56. U. S. Government Accountability Office, “Surplus plutonium disposition: NNSA’s long-term plutonium oxide production plans are uncertain,” United States Government Accountability Office (U.S. GAO), 2019, https://www.gao.gov/assets/710/702239.pdf.
57. U. S. Government Accountability Office, “Proposed Dilute and Dispose Approach Highlights Need for More Work at the Waste Isolation Pilot Plant,**”** United States Government Accountability Office, (U.S. GAO), 2017, https://www.gao.gov/assets/690/686928.pdf
58. U.S. Department of Energy, “Surplus Plutonium Disposition,” *Federal Register,* Vol. 81, 65, 5 April 2016, 19588, https://www.govinfo.gov/app/details/FR-2016-04-05/2016-07738; and Vol. 85, 165, 26 August 2020, 53350, https://www.federalregister.gov/documents/2020/08/28/2020-19023/surplus-plutonium-disposition.
59. U.S. Department of Energy, *FY 2021 Congressional Budget Request* 1 (2020): 661, 664, https://www.energy.gov/sites/prod/files/2020/03/f72/doe-fy2021-budget-volume-1_2.pdf.
60. U.S. National Academy of Sciences, *Review of the Department of Energy’s Plans for Disposal of Surplus Plutonium in the Waste Isolation Pilot Plant*, (National Acamies Press, 2020), Figure 3.7, https://www.nap.edu/catalog/25593/review-of-the-department-of-energys-plans-for-disposal-of-surplus-plutonium-in-the-waste-isolation-pilot-plant.
61. Plutonium Management and Disposition Agreement, 2000, “Annex on Quantities, Forms, Locations, and Methods of Disposition.”

62. IPFM, *Global Fissile Material Report 2010*, 54.
63. Operated to achieve the minimum change in the isotopic mix of Russia's weapon-grade plutonium, the BN-800 would produce about 9% as much weapon-grade plutonium in its blankets as it irradiated in its core, Kütt, Moritz, Friederike Frieß and Matthias Englert, "Plutonium Disposition in the BN-800 Fast Reactor: An Assessment of Plutonium Isotopics and Breeding," *Science & Global Security* 22 (2014): 188–208, Table 8, http://scienceandglobalsecurity.org/archive/sgs22kutt.pdf.
64. Plutonium Management and Disposition Agreement, as amended in 2010, Protocol, Article VI.
65. Albright, D., Frans Berkhout and William Walker, *Plutonium and Highly Enriched Uranium 1996*.
66. The Netherlands also sends its spent MOX fuel to France for storage. However, it receives extra MOX fuel so that there is no net transfer of plutonium to France, Kuperman, A., *Plutonium for Energy? Explaining the Global Decline of MOX* (Austin,Texas: University of Texas, 2018), http://sites.utexas.edu/prp-mox-2018/downloads/.
67. The U.K. reprocessing contracts with Italy were for 143 tons of spent fuel and with Spain for 145 tons, Forwood, M., Gordon MacKerron and William Walker, *Endless Trouble: Britain's Thermal Oxide Reprocessing Plant (THORP)*, (IPFM, 2019), Table 1, http://fissilematerials.org/library/rr19.pdf. See also the discussions of Italy and Spain in Albright, D., Serena Kelleher-Vergantini, and Daniel Schnur, *Civil Plutonium Stocks Worldwide: End of 2014* (Washington, DC: Institute for Science and International Security, 2015), https://isis-online.org/uploads/isis-reports/documents/Civil_Plutonium_Stocks_Worldwide_November_16_2015_FINAL.pdf. A complication with regard to the quantity of foreign plutonium that might be attributed to Italy and/or Spain is that Japan's Atomic Energy Commission (JAEC) has been declaring in its recent annual statements that it expects the U.K. to attribute to its reprocessing of Japan's spent fuel an additional 0.6 tons of separated plutonium, Japan Atomic Energy Commission (JAEC), "The Status Report of Plutonium Management in Japan – 2019," (provisional translation), 2020, http://www.aec.go.jp/jicst/NC/iinkai/teirei/siryo2020/siryo24/200825e.pdf. It is not clear whether the U.K. included that 0.6 tons in the unirradiated plutonium in the U.K. that it declared as foreign owned in 2018.
68. "Statement by Michael Fallon [U.K. Minister of State for Energy]: Management of overseas owned plutonium in the U.K.," 23 April 2013, https://www.gov.uk/government/speeches/written-ministerial-statement-by-michael-fallon-management-of-overseas-owned-plutonium-in-the-uk.
69. Zhang, H., *China's Fissile Material Production and Stockpile*.
70. Forrest, R. and Chaim Braun, "Managing China's spent nuclear fuel: a model framework for interim storage," *Nonproliferation Review* 24 (2017): 31–45, https://doi.org/10.1080/10736700.2017.1385732.
71. Gu, Z., China Institute of Atomic Energy, Graduate School of Nuclear Industry, "Safe and Secured Management of Spent Fuel in China (Mainland)," 16th PIIC Beijing Seminar on International Security, Shenzhen, China, 17 October 2019.
72. Zhang, H., "China is speeding up its plutonium recycling programs."
73. International Atomic Energy Commission (IAEA), "Communication Received from Certain Member States Concerning Their Policies Regarding the Management of Plutonium," last checked on 21 November 2020.
74. IAEA Press and Public Information e-mail to Frank von Hippel, 15 March 2019.

75. Zhang, H., "Pinpointing China's new plutonium reprocessing plant."
76. Orano, "Orano in China: A major reprocessing-recycling project," undated, https://www.orano.group/en/orano-across-the-world/china#OranoactivityinChina.
77. Bunn, M, et al., *The Cost of Reprocessing in China*, 26.
78. Reuters, "China still pursuing nuclear fuel reprocessing plant with France," 3 September 2019, https://uk.reuters.com/article/uk-china-nuclear-idUKKCN1VO1IG.
79. Chaffee, P., "Orano Launched Into Uncertain Future," *Nuclear Intelligence Weekly*, 26 January 2018.
80. Buckley, C., "Thousands in Eastern Chinese City Protest Nuclear Waste Project," *New York Times,* 8 August 2016, https://www.nytimes.com/2016/08/09/world/asia/china-nuclear-waste-protest-lianyungang.html.
81. Chaffee, P., "Can Beijing-Paris Nuclear Relations Withstand Washington?," *Nuclear Information Weekly,* 14 August 2020.
82. Orano, *Orano in China*, Press Kit, April 2018, 10, https://www.orano.group/docs/default-source/orano-doc/orano-monde/china/press-kit_orano-in-china_04-2018-en.pdf?sfvrsn=eb685cb1_4.
83. Glaser, A. and M.V. Ramana, "Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor."
84. 0.5 to 12 tons from the pilot-reprocessing plant, 12.5 to 25 tons from the demonstration reprocessing plant, 0 to 20 tons from the plant supplied by Orano, depending upon whether or not it is built, less 17 tons in the fuel cycle of the two CFR-600s results in a range of -1.5 (rounded up to zero) to 40 tons.
85. Orano, "An industrial cooperation agreement," undated, https://www.orano.group/en/nuclear-expertise/from-exploration-to-recycling/world-leader-in-recycling-used-nuclear-fuels.
86. IPFM, *Plutonium Separation in Nuclear Power Programs – Status, Problems, and Prospects of Civilian Reprocessing Around the World* (International Panel on Fissile Materials, 2015), 37–38, http://fissilematerials.org/library/rr14.pdf.
87. ANDRA, *Inventaire national des matières et déchets radioactifs* (2020): 13, https://inventaire.andra.fr/sites/default/files/documents/pdf/fr/andra-maj_essentiels_2020-web.pdf.
88. Perkovich, G., *India's Nuclear Bomb* (University of California Press, 1999), 428.
89. Indian Ministry of External Affairs, "Implementation of the India-United States Joint Statement of July 18, 2005: India's Separation Plan."
90. IPFM, *Plutonium Separation in Nuclear Power Programs, 52.*
91. Including the 0.4 tons of IAEA-safeguarded plutonium from the Rajasthan 1 and 2 reactors which the DAE keeps in separate storage and does not intend to use in its breeder program, Kütt et al., "Global stocks and production of fissile materials, 2019."
92. Operating at full capacity starting the year after they began operating, the three reprocessing plants would have reprocessed 6700 tons of spent fuel by the end of 2019. Assuming, 3.75 kilograms of plutonium per ton of spent fuel, that spent fuel would have contained about 25 tons of plutonium.
93. Operating data from the IAEA's Power Reactor Information System, https://pris.iaea.org/pris/.
94. As of mid-2020, India had six reactors under construction: two pressurized water reactors being built by Russia's Rosatom, which will be under safeguards, and four indigenous pressurized heavy water reactors (PWHR). The government of India has informed the IAEA that the four PHWRs will be added to the safeguards list,

International Atomic Energy Commission (IAEA), "Agreement between the Government of India and the International Atomic Energy Agency for the Application of Safeguards to Civlian Nuclear Facilities," INFCIRC/754/Add.10, 10 January 2020, https://www.iaea.org/publications/documents/infcircs/agreement-between-government-india-and-international-atomic-energy-agency-application-safeguards-civilian-nuclear-facilities.

95. IPFM, *Plutonium Separation in Nuclear Power Programs*, 56.
96. Ramana, M.V. and J.Y. Suchitra, "Slow and stunted: Plutonium accounting and the growth of fast breeder reactors in India," *Energy Policy* 37 (2009): 5028–36, https://doi.org/10.1016/j.enpol.2009.06.063.
97. Six tons of heavy-water reactor plutonium separated minus 7 tons required for the initial core of the PFBR and five annual reloads.
98. Twenty two tons of heavy-water-reactor plutonium separated minus 7 tons required for the initial core of the PFMR and five annual reloads.
99. Japan Atomic Energy Commission (JAEC), *Status Report[s] of Plutonium Management in Japan*, 2019, Tables on pages 4 and 6. The first shipment of MOX fuel from France to Japan was in 1999, for Fukushima-Daiichi Unit 3.
100. Harvey, F., "Sellafield Mox nuclear fuel plant to close," *The Guardian,* 3 August 2011, https://www.theguardian.com/environment/2011/aug/03/sellafield-mox-plant-close.
101. Including "approximately 0.6 ton of plutonium … expected to be added to the stockpile in the future," JAEC, *Status Report of Plutonium Management in Japan -2019*, 2.
102. This policy appears to have been adopted after an international uproar over a shipment of separated plutonium oxide from France to Japan in 1992. David Sanger, "Plutonium Cargo Arrives in Japan," *New York Times,* 5 January 1993, https://www.nytimes.com/1993/01/05/world/plutonium-cargo-arrives-in-japan.html; World Nuclear Association, "Japanese Waste and MOX Shipments from Europe," March 2017, https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/transport-of-nuclear-materials/japanese-waste-and-mox-shipments-from-europe.aspx.
103. Ministry of Foreign Affairs of Japan, "Seventh Annual Japan-U.K. Nuclear Dialogue," 25–26 October 2018, https://www.mofa.go.jp/files/000432421.pdf.
104. Takubo, M. and Frank N. von Hippel, "An Alternative to the Continued Accumulation of Separated Plutonium in Japan: Dry Cask Storage of Spent Fuel," *Journal for Peace and Nuclear Disarmament* 1 (2018): 281–304, https://www.tandfonline.com/doi/full/10.1080/25751654.2018.1527886.
105. JAEC, *Status Report of Plutonium Management in Japan – 2019*, 21.
106. Japan Atomic Energy Agency, *Current status of experimental fast reactor "Joyo,"* undated, https://www.jaea.go.jp/04/o-arai/joyo/english/Restoration/1.Current%20Status.pdf; Japan's Atomic Energy Agency (JAEA), which manages Japan's nuclear-energy R&D, was reported in September 2020 to have postponed its goal of restarting Joyo from fiscal year 2022 to 2024, World Nuclear Association, "Japan's Nuclear Fuel Cycle," April 2020, https://world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-fuel-cycle.aspx.
107. https://www.jaea.go.jp/about_JAEA/facilities_plan/keikaku.pdf (in Japanese).
108. *Plutonium Fuel: An Assessment* (OECD Nuclear Energy Agency, 1989), Table 9, https://www.oecd-nea.org/jcms/pl_14464.
109. Lee, Y.K., J. C. Nimal, J. P. Degrange, and M. Chiron, "Radiation Shielding Calculation for the MOX Fuel Fabrication Plant MELOX," Proceedings of the 8th

International Conference on Radiation Shielding, Arlington, Texas, USA, 24–28 April 1994, Vol. 1, 336–343, https://inis.iaea.org/collection/NCLCollectionStore/_Public/25/073/25073910.pdf.

110. Navratil, J.D. and Wallace W. Schulz eds., *Transplutonium Elements—Production and Recovery* (American Chemical Society Symposium Series, 1981), https://pubs.acs.org/isbn/9780841206380.
111. Tō-Ō Nippō Press, Aomori, 2 Sept. 2020, https://www.toonippo.co.jp/articles/-/403363 (in Japanese).
112. 80 tons in the first year, 320 tons in the second, 480 tons in the third, 640 tons in the fourth and 800 tons per year thereafter, https://www.jnfl.co.jp/ja/release/press/2017/detail/file/20171222-1-1.pdf (in Japanese).
113. JNFL recovered 3,604 kg of plutonium from the reprocessing of 425 tons of spent fuel at Rokkasho during 2006–2008, i.e. 8.5 kg/ton. (For plutonium recovered: JAEC, "Status Report of Plutonium Management in Japan – 2019." For spent fuel reprocessed, see JAEC, Technical Subcommittee on Nuclear Power, Nuclear Fuel Cycle, etc., Data Sheet 1, "Estimation of Nuclear Fuel Cycle Cost," 10 November 2011, slide 30, http://www.aec.go.jp/jicst/NC/about/kettei/seimei/111110_1_e.pdf). For higher burnups and more recently discharged spent fuel, the amount of plutonium recovered would be somewhat larger. For spent fuel with a burnup of 43 MWt-days/kgU reprocessed 10 years after reactor discharge, for example, the amount recovered would be about 10 kg/ton if there were no process losses. For a burnup of 53 MWt-days/kgU the amount recovered would be about 11 kg/ton, OECD Nuclear Energy Agency, *Plutonium fuel: An assessment* (Paris: N.E.A., 1989), Table 9.
114. As of November 2020, Genkai-3, Ikata-3 and Takahama 3 and 4 were operating, and Shimane-2 and Tomari-3 had been in relicensing review since 2013. World Nuclear Association, "Nuclear Power in Japan,", https://www.world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-power.aspx.
115. Takubo, M. and Frank von Hippel, "An Alternative to the Continued Accumulation of Separated Plutonium in Japan: Dry Cask Storage of Spent Fuel."
116. One uncertainty stems from the fact that the reactors are currently only licensed to operate for 40 years, although a 20-year extension is possible. The 40-year licenses expire as follows: Takahama-3 & 4, 2025; Shimane-2, 2029; Genkai-3 and Ikata-3, 2034; and Tomari-3, 2049. With regard to using Japan's separated plutonium in France, there is also the problem that the utilities that own Genkai-3, Ikata-3, Shimane-2 and Tomari-3 collectively own only 1 ton, while the utility that owns Takahama-3 & 4 owns 7.7 tons and TEPCO, which owns no reactors licensed to use MOX fuel, owns 3.2 tons (The prior consent by the local authorities for TEPCO's Kashiwazaki-Kariwa-3 was withdrawn in 2002). In principle, the utilities are supposed to cooperate in irradiating the plutonium but, in practice, that has not happened and may not happen in the future.
117. The projected operational date of the Ohma reactor has been delayed till fiscal year 2028, https://www.fukuishimbun.co.jp/articles/-/1161958, 10 September 2020, in Japanese.
118. Japan Ministry of Economy, Trade and Industry, *Strategic Energy Plan*, July, 2018, 65, https://www.meti.go.jp/english/press/2018/pdf/0703_002c.pdf.
119. Operated as planned, Rokkasho would separate 111 tons of plutonium. That would be offset by transferring 22 tons in the United Kingdom to U.K. ownership and by the use of 26 to 71 tons in MOX fuel resulting in an 18–63 ton increase that would

have to be offset by reduced reprocessing. While this article was already in proof, the Federation of Electrical Power Companies of Japan announced its intention to help close the gap by increasing the number of power reactors using MOX fuel to 12 by fiscal year 2030. No specifics were provided about which additional reactors would be licensed to use MOX, NHK World Japan, "Utilities aim to use MOX fuel in 12 reactors," 17 December 2020, https://www3.nhk.or.jp/nhkworld/en/news/20201217_32/. This was an update of the 2009 plan, which was to have 16-18 reactors using MOX fuel by 2015.

120. From JNFL's application document to Nuclear Regulation Authority dated March 8, 2018 https://www.nsr.go.jp/data/000264096.pdf, 208–209 (in Japanese). Japan's separated plutonium is stored mixed with an equal amount of reprocessed uranium.
121. International Atomic Energy Commission (IAEA), "Communication Received from France Concerning Its Policies Regarding the Management of Plutonium," INFCIRC/549/Add. 5/23, 2020.
122. As of the end of 2019, France had 8.9 tons of plutonium in process at its Melox MOX fuel fabrication plant from spent fuel being processed at a rate of 1100 tons/yr, International Atomic Energy Commission (IAEA), "Communication Received from France Concerning Its Policies Regarding the Management of Plutonium," INFCIRC/549/Add. 5/23, 2020. Scaling down to 800 tons/yr gives 6.5 tons of plutonium per year. It is assumed that approximately 5% of the plutonium ends up in unusable MOX as in France, *Plutonium Separation in Nuclear Power Programs,* 38.
123. Brady, B., "Revealed: £2bn cost of failed Sellafield [MOX] plant," *The Independent*, 6 January 2015, https://www.independent.co.uk/news/uk/politics/revealed-ps2bn-cost-failed-sellafield-plant-8650779.html; International Atomic Energy Commission (IAEA), "Communication Received from the United Kingdom… Concerning Its Policies Regarding the Management of Plutonium," INFCIRC/549/Add. 8/22, 2020.
124. IPFM, "BN-800 reactor to fully transition to MOX fuel in 2022," 9 June 2020, http://fissilematerials.org/blog/2020/06/bn-800_reactor_to_fully_t.html.
125. International Atomic Energy Commission (IAEA), *Fast Reactor Database, 2006 Update,* 33 (core inventory), 37 (full power days between refuelings), 45 (fraction of core replaced), https://www.iaea.org/publications/7581/fast-reactor-database-2006-update.
126. IPFM, "Russia is expanding its reprocessing program at Mayak," 9 June 2016, http://fissilematerials.org/blog/2016/06/russia_is_expanding_its_r.html. For reprocessing plans at Zheleznogorsk, see World Nuclear Association, "Russia's Nuclear Fuel Cycle," 2020, https://www.world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-fuel-cycle.aspx.
127. Sellafield Ltd. "Greenlight to restart Magnox reprocessing," 3 August 2020, https://www.gov.uk/government/news/green-light-to-restart-magnox-reprocessing.
128. U.K. Nuclear Decommissioning Authority, *Progress on approaches to the management of separated plutonium*, 2014, 7, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/457874/Progress_on_approaches_to_the_management_of_separated_plutonium_position_paper_January_2014.pdf.
129. Watt, H., "Hinkley Point: the 'dreadful deal' behind the world's most expensive power plant," *The Guardian*, 21 December 2017, https://www.theguardian.com/environment/2016/nov/29/french-nuclear-power-worst-situation-ever-former-edf-director; Arslan, M., I., Leboucher, E. Bouvier (AREVA), "Fuel cycle strategies to

optimize the MOX in reactors," *Energy Procedia* 39 (2013): 59–68, https://doi.org/10.1016/j.egypro.2013.07.192.

130. *Status and Advances in MOX Fuel Technology* (IAEA, 2003), chapter 4, https://www-pub.iaea.org/MTCD/Publications/PDF/TRS415_web.pdf; United States Government Accountability Office, *DOE Needs to Address Uncertainties with and Strengthen Independent Safety Oversight of Its Plutonium Disposition Program*, 2010, , 22–28, https://www.gao.gov/new.items/d10378.pdf; Maria Blake, "The Trouble with MOX," *The New Republic*, 7 April 2011, https://newrepublic.com/article/86335/fukushima-nuclear-mox-flaws.
131. The cost of fuel for U.S. nuclear power plants in 2019 was about 0.7 cents/kWh, U.S. Energy Information Administration (U.S. EIA), "Average Power Plant Operating Expenses for Major U.S. Investor-Owned Electric Utilities, 2009 through 2019," https://www.eia.gov/electricity/annual/html/epa_08_04.html, while the cost of electricity from a hypothetical new nuclear plant was estimated at 8 cents/kWh, U.S. EIA, "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the *Annual Energy Outlook 2020*," https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.
132. U.K. Nuclear Decommissioning Authority, *Progress on Plutonium Consolidation, Storage and Disposition*, 2019, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/791046/Progress_on_Plutonium.pdf.
133. Lyman, E., "External Assessment of the U.S. Sodium-Bonded Spent Fuel Treatment Program," International Conference on Fast Reactors and Related Fuel Cycles: Next Generation Nuclear Systems for Sustainable Development, 26–29 June 2017, Yekaterinburg, Russian Federation, https://s3.amazonaws.com/ucs-documents/nuclear-power/Pyroprocessing/IAEA-CN-245-492%2Blyman%2Bfinal.pdf.
134. U.K. Nuclear Decommissioning Authority, *Progress on approaches to the management of separated plutonium*, 2014, 16–17, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/457874/Progress_on_approaches_to_the_management_of_separated_plutonium_position_paper_January_2014.pdf.
135. Fichtlscherer, C., Friederike Frieß & Moritz Kütt, "Assessing the PRISM reactor as a disposition option for the British plutonium stockpile," *Science & Global Security* 27 (2019): 124–149, https://www.tandfonline.com/doi/full/10.1080/08929882.2019.1681736.
136. Hyatt, N. C., "Safe management of the U.K. separated plutonium inventory: a challenge of materials degradation," *NPJ Materials Degradation* 4, Article number 28 (2020), https://doi.org/10.1038/s41529-020-00132-7.
137. Vaughan, A., "Search restarts for area willing to host highly radioactive U.K. waste," *The Guardian*, 21 January 2018, https://www.theguardian.com/environment/2018/jan/21/search-area-willing-host-highly-radioactive-waste-uk-geology.
138. Pasamehmetoglu, K., Idaho National Laboratory, "Versatile Test Reactor: Solving global energy challenges through science," https://line.idaho.gov/wp-content/uploads/sites/84/2020/10/2020-1014-vtr.pdf.
139. Kang, J. and H.A. Feiveson, "South Korea's Shifting and Controversial Interest in Spent Fuel Reprocessing," *Nonproliferation Review*, Spring 2001, 70, https://www.nonproliferation.org/wp-content/uploads/npr/81kang.pdf; Lim, E., "South Korea's Nuclear Dilemmas," *Journal for Peace and Nuclear Disarmament* 2 (2019): 297–318, https://www.tandfonline.com/doi/full/10.1080/25751654.2019.1585585.

140. Kang, J., Frank von Hippel, "Reprocessing policy and South Korea's new government," *Bulletin of the Atomic Scientists,* 15 May 2017, https://thebulletin.org/2017/05/reprocessing-policy-and-south-koreas-new-government/.
141. Estimated assuming 20 tons of spent fuel discharged annually per GWe of LWR generating capacity and 26 GWe of LWR capacity in operation and under construction in 2020, International Atomic Energy Commission (IAEA), Power Reactor Information System.
142. Kristensen H.M. and Robert S. Norris, "Global nuclear weapons inventories, 1945–2013," *Bulletin of the Atomic Scientists* 69 (2013): 75–81, https://doi.org/10.1177/0096340213501363.
143. *Global Fissile Material Report 2010*, Tables 2.2 and 4.3.
144. International Atomic Energy Commission (IAEA), "Communication Received from France Concerning Its Policies Regarding the Management of Plutonium," 2019, https://www.iaea.org/publications/documents/infcircs/communication-received-certain-member-states-concerning-their-policies-regarding-management-plutonium.
145. In its annual declaration to the IAEA under the Plutonium Management Guidelines, France declared 15.5 tons of foreign plutonium as of the end of 2019, about same as the 15.435 tons of unirradiated Japanese plutonium that Japan's Atomic Energy Commission declared was in France, JAEC, *Status Report of Plutonium Management in Japan* – 2019.
146. IPFM, *Global Fissile Material Report 2010*, as updated in Kütt, M. et al., "Global stocks and production of fissile materials, 2019."
147. Kütt, M., Zia Mian and Pavel Podvig, "Global stocks and production of fissile materials, 2019," *SIPRI Yearbook 2020* (Stockholm International Peace Research Institute, 2020), Table 10.12, https://www.sipri.org/sites/default/files/YB20%2010%20WNF.pdf.
148. In addition, 7 tons of plutonium in government-owned spent fuel have been declared excess for weapons use, U.S. National Academy of Sciences, *Review of the Department of Energy's Plans for Disposal of Surplus Plutonium in the Waste Isolation Pilot Plant* (National Academy Press, 2020), Figures 2–1 and 3–7, https://www.nap.edu/catalog/25593/review-of-the-department-of-energys-plans-for-disposal-of-surplus-plutonium-in-the-waste-isolation-pilot-plant.
149. Some of the plutonium has been dissolved in the "H-canyon," a former military reprocessing plant at the U.S. Department of Energy's Savannah River Site, and piped to high-level waste tanks on that site. The material in those tanks is being vitrified (glassified) for disposal in a future deep geological repository.
150. Kütt, M., et al., "Global stocks and production of fissile materials," 2019.

Funding

This work was funded by the MacArthur Foundation, the Carnegie Corporation and the Nonproliferation Education Policy Center.