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The Other Fissile Material: Strengthening National and International Plutonium Management Approaches

John Carlson, Leonard S. Spector, and Miles A. Pomper

Middlebury Institute *of* International Studies at Monterey
James Martin Center for Nonproliferation Studies

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James Martin Center for Nonproliferation Studies
Middlebury Institute of International Studies
460 Pierce Street
Monterey, CA 93940, USA
Tel: +1 (831) 647-4154
Fax: +1 (831) 647-3519

Disclaimer

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Cover image: Le Hague nuclear reprocessing plant. Credit: United States Department of Energy.

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EXECUTIVE SUMMARY

This paper discusses issues relating to separated plutonium (otherwise known as unirradiated plutonium) in civilian nuclear programs, that is, plutonium that has been chemically separated from spent nuclear reactor fuel by reprocessing but has not been reintroduced into a nuclear reactor after separation and subjected to further irradiation.

Efforts to limit the spread of reprocessing in the civilian sector crystalized in the mid-1970s. The intensified attention to this issue was triggered by two developments: (1) India's 1974 test of a nuclear explosive device, which used as its core plutonium produced in an ostensibly peaceful nuclear research program, and (2) attempts on the part of several states that had not renounced nuclear weapons to obtain reprocessing plants for their civil nuclear power programs.[1]

In the intervening forty-four years, in those states that proceeded with civilian reprocessing programs, stocks of separated civilian plutonium have continued to grow in the aggregate. Taken together today, they are substantially greater than worldwide military plutonium stocks. Multiple approaches to limiting the separation of civil plutonium have been implemented, and still others have been given serious study, but stocks have increased regardless, while options for working down these stocks appear to be diminishing. Meanwhile, concern has deepened over the possible theft or diversion of this material, which could bring weapon-sufficient quantities of plutonium into the hands of violent extremists.

As noted below, placing all civil reprocessing facilities and plutonium holdings under the auditing and inspection system of the International Atomic Energy Agency (IAEA)—known as "safeguards"—is a valuable measure, but it does not fully address the risks of breakout from nonproliferation or disarmament commitments. Safeguards are intended to provide timely warning of diversion, so as to provide an opportunity for intervention. However, even if diversion of plutonium is detected immediately, the plutonium could be weaponized too quickly for effective preventive measures. Nor are safeguards designed to address nuclear material security issues. Accordingly, there is a need for institutional and technical measures to mitigate risks from separated plutonium. These measures include steps to:

Limit existing reprocessing programs and their risk

- Political measures:
    - Encourage Japan to continue its reprocessing moratorium at least until the Rokkasho mixed plutonium and uranium oxide (MOX) fuel-fabrication facility is operational and a significant number of Japanese nuclear power plants licensed to burn MOX come back online; in addition, encourage Japan to more seriously consider dry cask storage as an alternative to reprocessing.
    - Develop strategies to encourage France to shift to greater use of non-plutonium-based low-enriched uranium fuels for its domestic nuclear power plants and to refrain from exporting a reprocessing plant to China.

[1] The countries at issue were Brazil, Pakistan, and South Korea, as well as Taiwan.

- Technical measures:
  - Where possible, reactors should be operated to avoid producing plutonium at or near weapon-grade. Where such material is produced, and reprocessing cannot be avoided, such material should not be reprocessed separately but blended in-process to avoid a product at or near weapon-grade.

Limit the risk of existing civil plutonium stocks

- Political measures:
  - Acknowledge permanent disposition of separated civil plutonium as a problem common to all states possessing significant quantities of this material and establish a new multistate forum or expand the mandate of an existing forum to develop strategies for the permanent disposition of civil plutonium.
  - To further reduce horizontal and vertical proliferation risks, re-examine international plutonium storage concepts.
  - States with holdings of civil separated plutonium should work to bring all such material under active IAEA or Euratom safeguards. This step would increase transparency regarding plutonium stocks and create an additional political barrier to diversion of this material.

- Technical measures:
  - Minimize the number of sites with separated plutonium holdings and the number of transport movements of separated plutonium and conduct regular reviews of the security of such sites.
  - Accelerate and maximize mixing of separated plutonium with uranium and conversion to more-processed forms—MOX pellets and fuel assemblies—even if the product will go unused for an extended period. Consider extending this mixing to include plutonium insufficiently pure to be burned in reactor fuel and constructing a new fabrication line at La Hague, France, as well as using the existing facility at Sellafield, United Kingdom, to produce such impure MOX.
  - For countries with large stores of MOX and MOX unlikely to be burned in the near term because of impurities, consider placing these fuel rods in the same dry casks as highly radioactive spent fuel rods, providing a medium-term storage capability that will be difficult for non-state actors to exploit, pending ultimate disposal.
  - As the United States pursues its "dilute-and-dispose" option for the permanent disposal of excess military plutonium, the United States should share its dilution and packaging technologies with other states and include them in unclassified aspects of ongoing US research and development activities.

Discourage new reprocessing programs

- Sustain current technology controls
  - Continue current restraints on transfers of reprocessing equipment and technology.
  - Continue to pursue additional commitments like those in the US nuclear agreements with the United Arab Emirates and Taiwan, where the US partners have agreed to renounce reprocessing (and enrichment) into the indefinite future.

- Block clandestine activities and illicit procurement
  - Technology holders and others should declare that clandestine reprocessing-related (and enrichment-related) activities, including procurement activities, will expose the perpetrator government to sanctions.
  - Uranium enrichers (all government controlled) should be directed to include a provision in commercial enrichment contracts that shipments will be withheld if the government of the other party to the contract is found to have engaged in clandestine reprocessing (or enrichment) activities, including procurement activities.
- Actively promote dry cask storage technology as an alternative to reprocessing.
- Proliferation resistance and safeguards-by-design should be built into any new technologies and facilities that are deployed for plutonium processing and use.

PROLIFERATION RISK OF REPROCESSING

"Separated plutonium," that is, plutonium separated from irradiated fuel through reprocessing (including plutonium mixed with uranium before the combined product is further irradiated in a reactor), presents both proliferation and nuclear security risks. Such plutonium, including that from civilian reactors, can be used by a state to produce nuclear weapons for military deployment or by terrorist groups to produce less sophisticated improvised nuclear-explosive devices. Each tonne of plutonium has the potential to provide the cores for about 120 nuclear weapons (using the IAEA's "significant quantity" standard of 8 kilograms as a baseline).[2] Accordingly, plutonium programs—reprocessing, storage, transport, and use of plutonium—cannot be considered the exclusive prerogative of the states engaged in these activities. There is a compelling international interest in minimizing risks from these programs.

Reprocessing has been a proliferation concern since the early years of the nuclear age. In the subsequent half century, all of the nuclear-weapon-possessor states—China, France, India, Israel, North Korea, Pakistan, Russia, the United Kingdom, and the United States—have engaged in this activity to produce plutonium for nuclear weapons, building reprocessing facilities specifically dedicated to this purpose. Several other countries have also sought to obtain reprocessing capabilities apparently with a view toward producing plutonium for nuclear arms, although these efforts were ultimately abandoned.

Reprocessing has also played a role in a number of nuclear power programs. Currently, such programs are being pursued in France, Japan, India, Russia, and until recently the United Kingdom, generally in order to produce plutonium-based reactor fuels. In this setting, reprocessing separates plutonium from nuclear power reactor fuel typically made of low-enriched uranium (LEU).[3] After separation, the plutonium, in the form of plutonium oxide, can be combined with natural or depleted uranium oxide[4] to produce "mixed oxide" (MOX) fuel. This material can be used in lieu of LEU fuel in nuclear power reactors. By reusing the plutonium in this manner, this component of a nuclear power program is said to extract additional "energy value" from nuclear fuels. However, this path is fraught with significant economic and technical challenges.

Because of plutonium's nuclear weapon potential, its extraction and accumulation within peaceful nuclear programs poses inevitable risks. Most notably, the accumulation of separated plutonium provides the possessor state with a nuclear weapon "break-out" option, i.e., the ability to contravene any nonproliferation or disarmament commitments by seizing the plutonium to manufacture nuclear weapons in a matter of months, or by some estimates a matter of weeks, if the necessary preparations have been made.

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[2] The "significant quantity" is a metric applied by the IAEA for the quantity of nuclear material for which the manufacture of a nuclear weapon cannot be excluded. US Nuclear Regulatory Commission, "Glossary: Mixed Oxide (MOX) Fuel," https://www.nrc.gov/reading-rm/basic-ref/glossary/mixed-oxide-mox-fuel.html.

[3] With some incidental exceptions, civil plutonium is initially produced in enriched uranium fuel, the fuel used in most modern nuclear power reactors. (India and the United Kingdom have reprocessed natural uranium fuel used in a number of their older nuclear power plants.) As the reactors operate and the fuel is irradiated, about 1 percent of the fuel is transmuted into plutonium. The irradiated fuel, after removal from the reactor and cooled for period of years, is then taken to a reprocessing plant, where plutonium is extracted through a series of chemical processes.

[4] Depleted uranium is a byproduct of uranium enrichment, as the desired, readily split uranium atoms—the isotope U-235—are separated from the predominant isotope in natural uranium, U-238, and concentrated in an "enriched" product. The uranium from which the U-235 has been separated is thus depleted in that isotope, creating "depleted uranium."

During the 1970s, Pakistan, South Korea, Taiwan, and probably Brazil, sought to acquire reprocessing capabilities for their civil nuclear programs from advanced supplier states with this objective apparently in mind. More recently, concerns regarding this scenario can be seen in the 2015 Joint Comprehensive Plan of Action (JCPOA) restricting Iran's nuclear program.[5] The JCPOA rules out plutonium separation in Iran for fifteen years and contains a declaration by Iran that it has no intention of engaging in reprocessing after that date. Similarly, in recent US nuclear-cooperation agreements, the United States has pressed partner countries to renounce reprocessing for the thirty-year duration of the agreements; it achieved this result in agreements with the United Arab Emirates and Taiwan, but settled for a declaration in its agreement with Vietnam that the latter had no intention of engaging in this activity and would rely on the international market—i.e., existing reprocessing states—for any reprocessing services.

Still, minimizing risks from production and use of plutonium has not been given the same level of attention as given the other material used as the core of a nuclear weapon—highly enriched uranium (HEU). There has been concerted international action to cease production of HEU, reduce stocks of the material, and as far as possible to eliminate it from civilian use. Similar efforts have yet to be made for plutonium, with only limited guidelines for managing stocks (discussed further below) approved by some plutonium-holding states.

There are several factors contributing to this low traction in addressing plutonium minimization and management. To begin with, HEU has been considered at far greater risk of theft and use by non-state groups because, once obtained, HEU might be readily fabricated into a nuclear device using a "gun-type" design. Building a plutonium-based device, on the other hand, would require the use of the far more complex "implosion" design, considered to be substantially more challenging for non-state groups to master unless they had help from a nuclear weapons expert.[6] After successful efforts in recent years to reduce global civilian HEU stocks, however, today the hundreds of tonnes of separated civil plutonium represent by far the greatest stock of civilian nuclear weapon-usable material remaining at risk.

With respect to state-level proliferation, one explanation for the apparently lower level of progress regarding plutonium minimization compared to HEU may be that few states currently have civilian reprocessing programs, and most of these states already have nuclear weapons. The states currently with civilian reprocessing programs are, in order of capacity, France, the United Kingdom (recently closed), Russia, India, and China; Japan is completing a civil reprocessing plant that will give it a capacity roughly equal to that of France. Japan is the only one of these states that does not have nuclear weapons, but its strong commitment to remaining without such arms has reduced concerns that it might misuse its civil plutonium stocks. Thus reprocessing is not seen as a pressing issue of *horizontal* proliferation (the risk of spread of nuclear weapons to additional states). This, however, overlooks several important issues:

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[5] The United States withdrew from the JCPOA on May 8, 2018. As of this writing, Iran and the other parties to the JCPOA—China, France, Germany, Russia, and the United Kingdom—continue to adhere to it.

[6] Matthew Bunn has raised this concern repeatedly. See for example, Matthew Bunn and Anthony Wier, "Terrorist Nuclear Weapon Construction: How Difficult?" *Annals of the American Academy of Political and Social Science,* Vol. 607 (September 2006), pp. 133–49. Also US Congress, Office of Technology Assessment, *Nuclear Proliferation and Safeguards* (Washington, DC: OTA, 1977), http://www.princeton.edu/~ota/disk3/1977/7705/7705.PDF p. 140. US Department of Energy, Office of Arms Control and Nonproliferation, *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives*, DOE/NN-0007 (Washington, DC: DOE, 1997), http://www.osti.gov/bridge/servlets/purl/425259-CXr7Qn/webviewable/425259.pdf, pp. 37–39.

- Reprocessing states' transfers of separated plutonium to several other states pursuant to reprocessing contracts, usually in the form of MOX, widens the risks from civil plutonium holdings beyond the reprocessing states themselves. Therefore, efforts to reduce stocks of separated plutonium should look beyond the reprocessing states to include all states that handle separated unirradiated plutonium in any quantity and any form.
- The existence of civil separated plutonium stocks poses an ongoing risk of theft or diversion by non-state actors that can never be fully eliminated.
- Additional states may be interested in reprocessing and plutonium use in the future. Reprocessing states set an example that the technology is a desirable component of a civil nuclear power program. Such an example enables other states, including those with a heightened risk of sudden seizure of plutonium, to justify their own pursuit of this technology. Saudi Arabia, for example, has used this justification to refuse to renounce reprocessing in its current negotiations with the United States on a nuclear-cooperation agreement.
- More broadly, extant reprocessing programs make it difficult to build support for international restraints on reprocessing, since opponents can claim that it is a legitimate component of the use of nuclear energy for peaceful purposes, which all parties to the Treaty on the Non-proliferation of Nuclear Weapons (NPT) have the "inalienable right" to pursue;
- The risk of misusing civilian reprocessing facilities for *vertical* proliferation (the increase in nuclear weapon numbers) is a concern in the case of India and, in the view of some, China. In the future, if major nuclear-arms reductions agreements or a Fissile Material Cutoff Treaty were to proceed, a civil reprocessing program would provide the ability to sidestep the restrictions and launch a nuclear weapon breakout strategy.[7]

Adding complexity to the consideration of civil reprocessing is that, in some settings, reprocessing can actually *support* nonproliferation objectives. This is the case when a non-nuclear-weapon state in a region of tension agrees to send its spent fuel to a nuclear-weapon-possessing state for reprocessing and does not receive back the resulting plutonium. Instead, the plutonium is usually made into MOX fuel that is burned in nuclear power plants in more stable regions or in the reprocessing state. This is the arrangement Russia has negotiated with Iran, for example, with respect to spent fuel produced in Iran's Bushehr nuclear power plant.[8] Similarly, the United Arab Emirates is authorized to use this approach under its 2009 nuclear-cooperation agreement with the United States, in that case, by sending its spent fuel for reprocessing to France or the United Kingdom.[9] It would also be possible for a supplier state to take back spent fuel for direct disposal without reprocessing. Although the option has not been used with respect to spent fuel from power reactors, the United States and Russia have repatriated limited quantities of research reactor fuel containing HEU or plutonium in a number of cases without the expectation of reprocessing.

[7] A Fissile Material Cutoff Treaty, as previously debated, would only ban the production of fissile materials "for weapons purposes." See the FMCT draft, as submitted by Canada, the Netherlands, and Japan, to the Conference on Disarmament, CD/1878, September 2, 2009, https://www.unog.ch/80256EDD006B8954/(httpAssets)/224DE1746ADA4B55C12579C8005472FF/$file/1878.pdf.
[8] "Bushehr Nuclear Power Plant," Nuclear Threat Initiative website, last updated July 10, 2017, http://www.nti.org/learn/facilities/184/; "Nuclear Power in Iran, World Nuclear Association website, last updated in April 2018, http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/iran.aspx.
[9] Agreement Between the United States and the United Arab Emirates for Cooperation in the Peaceful Uses of Nuclear Energy, December 17, 2009, https://www.gpo.gov/fdsys/pkg/CDOC-111hdoc43/pdf/CDOC-111hdoc43.pdf.

To be sure, the scale of any stockpile matters, but so does how the material is handled. UK stocks, though they do not at the moment have an associated disposition path, are consolidated in a single site with high security. In contrast, French plutonium is rather mobile. Plutonium oxide is shipped across France from the reprocessing facility on France's west coast to the French MOX fuel-fabrication facility on the opposite side of the country.[10] Thereafter, the unirradiated MOX fuel is shipped to more than thirty French and Western European nuclear power reactors, and additional shipments are made for use in Japanese nuclear plants.[11] Because, as noted below, it is not particularly difficult to separate plutonium oxide from uranium oxide, the IAEA classifies MOX fuel as a Category I nuclear material, requiring the same level of security as pure plutonium.[12] Questions may also be raised regarding the quality of the security measures in individual plutonium-using states.

Indeed, virtually any utilization or disposition scheme discussed above carries added risks beyond those associated with the maintenance of the stockpile itself. All may call for additional locations where plutonium would be processed and associated, potentially vulnerable, transportation links. Thus, while plutonium use and disposition programs play a positive role in reducing the size of plutonium stockpiles, they also introduce new dangers.

Initially, states established civilian reprocessing programs either for spent-fuel management reasons—because early fuel types (such as Magnox[13] used in UK power plants) had limited safe storage life—or for energy-security concerns, i.e. ensuring continuing domestic supply of fuel given limited domestic uranium resources (as was the case in France). Reprocessing was also considered necessary for the sustainability of nuclear power programs, generally; uranium was considered scarce and was predicted to become increasingly expensive. Hence, it was believed the future of nuclear power would lie with the use of next-generation fast neutron reactors fueled with recycled plutonium: the *closed fuel cycle*. Subsequently, however, two major developments undercut the rationale both for reprocessing and for fast reactors: the rate of growth of nuclear power has been much lower than expected, and substantial new uranium resources have been discovered. In addition, there were safety problems with some fast reactors, and the technology has not been shown to be commercially viable. Economically recoverable uranium is not scarce, and today it appears use of even very high-cost uranium would be less expensive than reprocessing and recycling plutonium.[14]

In the technical, economic, and political circumstances that have developed over the past few decades, most states with nuclear power programs have either decided to proceed with the once-through or *open fuel cycle*, where spent fuel will be disposed of as a waste material, or have adopted a wait-and-see attitude. From a technical perspective, most spent fuel can be stored for many decades, so there is no pressing reason to commit in the near term to final disposal or to recycle. A number of states are

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[10] David Albright, Serena Kelleher-Vergantini, and Daniel Schnur, "Civil Plutonium Stocks Worldwide: End of 2014," Institute for Science and International Security," November 16, 2015, https://isis-online.org/uploads/isis-reports/documents/Civil_Plutonium_Stocks_Worldwide_November_16_2015_FINAL.pdf.

[11] World Nuclear Association, "Mixed Oxide Fuel," (updated September 2017), http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/mixed-oxide-fuel-mox.aspx.

[12] See, e.g., *The Security of Nuclear Material in Transport,* International Atomic Energy Agency Nuclear Security Series 26-G, (2015), https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1686_web.pdf.

[13] Fuel with magnesium alloy cladding used in early gas-cooled graphite-moderated reactors.

[14] Recovery of uranium from seawater is estimated at around $660/kg, which would result in a cost for LEU of around $7,000/kg (almost four times current costs). By comparison, MOX fuel currently costs around $22,500/kg. A 2015 Korea Atomic Energy Research Institute study suggests a fuel cost for using fast reactors and pyroprocessing—a variant of reprocessing—of $3,000–9,000/kg, but these figures must be treated with caution as there is no experience with use of pyroprocessing on an industrial scale. See J. Carlson, *The Case for a Pause in Reprocessing in East Asia: Economic Aspects*, NTI 2016, http://www.nti.org/analysis/reports/case-pause-reprocessing-east-asiaeconomic-aspects/.

waiting to see what developments ensue in recycling technology, in particular whether fast neutron reactors become commercially viable.

Civil Plutonium-Possessing Countries: Current Status

Civil separated plutonium stocks and reprocessing capabilities

Stockpiles of separated plutonium from civil nuclear programs can be found in only a handful of countries. These civil-origin material holdings are shown in Table 1.

Table 1: Civilian stocks of separated plutonium (tonnes), end 2016.

	A. Holdings in-country	B. Holdings in other states (included in C for the relevant holding state)	C. Holdings for other states (included in A)
France	81.7		16.3
Germany	0.5	1.5 (est)	
India	0.4 (a)		
Japan	9.9	37.1	
Russia	57.2 (b)		
UK	133.5		23.2
USA	49.4 (c)		
Others		1.2 (est)	
Totals (rounded)	**332.6**	39.8 (d)	39.5 (d)

(a) International Panel on Fissile Materials (IPFM) 2016 estimate. India also has, in addition to weapon-grade plutonium in the military program, a strategic reserve of around 6 tonnes of unsafeguarded reactor-grade plutonium from power reactors which it could use for civilian or military purposes. (b) In addition, Russia announced that it will release 40–50 tonnes of plutonium from its military program. Since this as not yet happened, this quantity is not included here. (c) Plutonium declared excess to national security needs. (d) The slight difference between totals for B and C is due mainly to plutonium held in states other than those included in the table, and also to rounding. Sources: National INFCIRC/549 reports (except for India which does not participate), supplemented by information from the IPFM website, http://www.fissilematerials.org. At the time of writing, INFCIRC/549 reports for 2017 were available for some but not all of these states, so this table is limited to information for 2016.

In addition to civil material, Russia and the United States each have at least 50 tonnes of plutonium originally produced for nuclear weapons that has been declared excess and will be disposed of. Although this material was not created for peaceful nuclear purposes, its removal from military stocks means that its status is now roughly comparable to plutonium that has been in non-military nuclear programs from the time of its creation. Accordingly, the previously military material is included in the subsequent discussion in the category of civil separated plutonium.

Of the countries with significant stockpiles of civil separated plutonium, only four are currently operating civil reprocessing plants: China, France, India and Russia. [15] The United Kingdom has recently ceased reprocessing. The United States rejected civil reprocessing in the 1970s, but, as indicated above, is now attempting to dispose of 34 tonnes of military-origin plutonium.[16]

Japan halted operations at its reprocessing plant at Tokai-Mura in 2006, and announced in 2014 that it would shut the plant down permanently.[17] Japan's commercial-scale reprocessing plant at Rokkasho-Mura is undergoing further commissioning and is scheduled to come online in mid-2021.[18] However, given the Japanese public's deep concern about nuclear safety issues in the wake of the 2011 Fukushima Daiichi accident and the need for the Rokkasho facility to meet costly post-Fukushima Japanese nuclear safety standards, it is uncertain whether it will ever open.

The United Kingdom ceased reprocessing at Sellafield in November 2018 and is not planning a replacement facility.[19] If Rokkasho remains in suspension, and the United States holds to its long-time ban on domestic civil reprocessing, the United Kingdom is the third out of the six states possessing civil separated plutonium to halt the further separation of the material. It appears, however, that France, Russia, and India are currently committed to continue or initiate (in the case of China) significant reprocessing. [20]

Utilization Strategies of the Major Plutonium-Possessing Countries

Mechanisms for utilizing or disposing of existing plutonium stocks, and future plutonium accumulations by the reprocessing states, vary widely.

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15 China has built a small demonstration plant only; according to one respected source, it has reprocessed only limited amounts of spent fuel and is thought to have ceased operations in 2014. See text at note 32, below.

16 China, France, Russia, the United Kingdom, and the United States are no longer producing plutonium for military purposes. The US has already sent 5 US tons of excess plutonium from the former Rocky Flats Department of Energy site for disposal in the Waste Isolation Pilot Plant (WIPP) in New Mexico. Government Accountability Office, *Plutonium Disposition: Proposed Dilute and Dispose Approach Highlights Need for More Work at the Waste Isolation Pilot Plant*, GAO-17-390, September 2017, p. 8, https://www.gao.gov/assets/690/686928.pdf.

17 Kyodo News Agency, "Closure of Tokai Reprocessing Plant to cost an estimated ¥800 billion: JAEA source," *Japan Times*, April 23, 2017, https://www.japantimes.co.jp/news/2017/04/23/national/closure-tokai-reprocessing-plant-cost-estimated-%C2%A5800-billion-jaea-source/#.XAArc5NKhTZ.

18 Ibid. The Rokkasho reprocessing plant will not produce pure separated plutonium, but a product that combines uranium and plutonium and is not directly usable for nuclear weapons. However, separation of plutonium from that product would be a relatively simple process. See discussion below.

19 "Reprocessing ceases at UK's Thorp plant," *World Nuclear News*, November 14, 2018, http://world-nuclear-news.org/Articles/Reprocessing-ceases-at-UKs-Thorp-plant.

20 Despite the 2017 de facto bankruptcy of Areva—the French government-owned corporation that had operated France's reprocessing facilities at La Hague (known as UP3 and UP4) and that was also responsible for constructing French-designed nuclear power plants at home and abroad—it appears that Areva's reprocessing activities will continue. Areva was reorganized in January 2018. Its fuel-cycle activities—including reprocessing—were spun off into a new company called Orano, while Areva's reactor-construction activities—the substantial losses of which were the key trigger for its de facto bankruptcy—were partly taken over by the French government-owned Electricité de France and organized as a unit now known as Framatome. "New AREVA Changes Its Name to Orano," *World Nuclear News*, January 23, 2013, www.world-nuclear-news.org/C-New-Areva-changes-name-to-Orano-2301185.html; Frederic Gatte, "Where Did It All Go Wrong for AREVA?" Energy and Carbon.com blog, February 15, 2016, http://energyandcarbon.com/where-did-it-all-go-wrong-for-french-nuclear-giant-areva/. Reports of Areva's intensifying financial troubles indicated that its fuel-cycle services, in contrast to its reactor-construction activities, were a major profit center for the company, "with €1.3 billion coming from its uranium mining, €2.2 billion coming from enrichment and fuel, and €1.5 billion coming from spent fuel reprocessing" in 2014, according to one article. According to that same article, Areva—now Orano—had sales of approximately €5 billion and "a huge order book." "UPDATE 2 –Rescued Areva Faces Uncertain Future as Nuclear Fuel Group," Reuters, June 4, 2015, https://www.reuters.com/article/areva-edf/update-2-rescued-areva-faces-uncertain-future-as-nuclear-fuel-group-idUSL5N0YQ13720150604.

France

Of all the separated-plutonium-possessing states, only France has a facility able to produce traditional MOX fuel for use in existing nuclear power reactors. Nonetheless, France's holdings of domestic unirradiated plutonium have continued to grow by more than a tonne a year for the past two decades, in part because an estimated 10 to 20 percent of the MOX fuel it produces does not meet commercial specifications (so-called "Kentucky Fried MOX.")[21] Moreover, at any given time, several dozen tonnes of unirradiated plutonium exist in France awaiting MOX fuel fabrication, and this problem (as noted below) may worsen in coming years.

Japan

Japan's program to use MOX fuel in its fleet of power reactors would eventually reduce its stocks of separated plutonium, but execution of this plan is many years behind schedule, a delay greatly exacerbated by the fact that only a handful of Japan's MOX-burning reactors have come back online after being shut down in the wake of the Fukushima accident and the inauguration of the Rokkasho MOX plant has been repeatedly delayed.[22] Only four Japanese reactors currently use MOX fuel, all of which was fabricated in France.

In July 2018, Japan's Atomic Energy Commission adopted "Basic Principles on the Utilization of Plutonium," detailing significant changes aimed at minimizing its stockpile of separated plutonium and unirradiated MOX fuel ("the feedstock between reprocessing and irradiation," essentially the definition used in this paper). The commission also called for the country's reactor operators to coordinate so as to maximize the use of MOX produced overseas (i.e. in France) from Japanese spent fuel.[23] Two leading Japanese experts, Tatsujiro Suzuki and Masa Takubo, characterized the new policy as a step forward but pointed to the difficulty of realizing the goal of freezing the plutonium stockpile at current levels:

> The new policy is based on the assumption that the Rokkasho reprocessing plant will be operated. Unless the government changes this policy, it will be difficult to reduce Japan's plutonium stockpile substantially... . Certainly, the stock of unirradiated plutonium in Japan is likely to increase greatly as long as the necessary minimum MOX feed stock and use plans remain undefined... . Minimizing the "feedstock" is the right policy but will have no significant impact on the utilities' reprocessing plans in the absence of a clear specification of what is expected to be the acceptable "minimum" stock of unirradiated plutonium.[24]

A major factor in Japan's commitment to reprocessing has been local residents' opposition to long-term storage of spent fuel at reactor sites. Residents have been concerned that nearby spent fuel ponds

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21 Kingsley Burns, "MOX in France: Reassessment as Foreign Customers Fade," in *Plutonium For Energy Explaining the Global Decline of MOX*, 2018, p. 74, http://sites.utexas.edu/prp-mox-2018/files/2018/10/3-France-Plutonium-for-Energy.pdf.
22 "Japan's Nuclear Fuel Cycle," World Nuclear Association, (updated November 2018), www.world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-fuel-cycle.aspx>.
23 Japan Atomic Energy Commission, "The Basic Principles on Japan's Utilization of Plutonium," July 31, 2018 http://www.aec.go.jp/jicst/NC/iinkai/teirei/3-3set.pdf.
24 Tatsujiro Suzuki and Masa Takubo, "Japan's new policy on its plutonium stockpile," *IPFM Blog*, International Panel on Fissile Materials, August 20, 2018, http://fissilematerials.org/blog/2018/08/japans_new_policy_on_its_.html.

have become overcrowded and unsafe.[25] These vocal concerns could prompt Japanese authorities to reconsider the need for reprocessing.

Russia

Russia is accumulating plutonium for its breeder reactor program, which will use specialized MOX fuel with a higher proportion of plutonium (approximately 20 percent) than that used in traditional nuclear power reactor fuel (typically 8 to 9 percent), as well as plutonium-uranium nitride fuel. While it is difficult to make the calculation with any precision, it would appear that Russia will see growth in its already substantial stock of separated plutonium that will outpace its use of MOX in its breeder reactor program. Russia operates the MOX-fueled 800-megawatt BN-800 breeder reactor, but has decided not to build additional reactors of this design, favoring the larger, 1200 megawatt BN-1200. Construction of the first such facility is on hold, however, even as Russia continues reprocessing at its RT-1 reprocessing plant at Mayak.[26] Separately, although Russia has declared that its 34 tonnes of excess military plutonium will be consumed in its breeder reactor program, as of this writing, it is operating the BN-800 reactor on fuel containing non-military-origin plutonium.[27]

India

India's situation is complicated by its decision to separate, for safeguards reasons, its military and civilian nuclear activities. Facilities that are unambiguously peaceful are subject to IAEA safeguards to ensure they are not being used for nuclear-weapon purposes. Certain other facilities are explicitly included on India's military facilities list and excluded from IAEA safeguards. A third category of facilities are those seen as serving civilian purposes, such as electricity generation or research and development of advanced reactors, India has also excluded facilities from IAEA safeguards and has reserved the right to use such facilities in its nuclear weapons program.

India's breeder reactor program and planned related reprocessing activities fall into this third category and currently are not included on its roster of IAEA-safeguarded, unambiguously peaceful facilities because India wishes to keep open the option of using plutonium produced in the breeder program for military purposes. However, India has also indicated that it might be prepared at a later time to move this and/or other unsafeguarded, civil-style facilities to its list of safeguarded facilities.[28]

The great proportion of India's separated plutonium is dedicated to its unsafeguarded breeder reactor program. Thus, for the moment, this material would not be considered "civil" plutonium as the term is being used here. However, in years past, some reprocessing was undertaken under IAEA safeguards and that material, roughly 0.4 tonnes, cannot be transferred to military use and therefore meets the

[25] Masa Takubo and Frank 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*, October 16, 2018, https://www.tandfonline.com/doi/full/10.1080/25751654.2018.1527886.
[26] "Russia's Nuclear Fuel Cycle," World Nuclear Association, (updated April 2018), http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-fuel-cycle.aspx.
[27] Charles Diggs, "Russian Fast Reactor Program Stalls, While Economy Plummets," Bellona.org, January 19, 2017, http://bellona.org/news/nuclear-issues/2017-01-russian-fast-reactor-program-stalls-while-economy-plummets; email exchange with former senior US official. Latest results, however, show reduced income from reprocessing/MOX activities because of "production difficulties in the recycle business." Orano Press Release, "Annual Results for 2017," http://www.orano.group/home/liblocal/docs/PR_Orano_Annual_results_for_2017.pdf.
[28] Kalman Robertson and John Carlson, "The Three Overlapping Streams of India's Nuclear Program," Belfer Center for Science and International Affairs, April 2016, https://www.belfercenter.org/sites/default/files/files/publication/thethreesoverlappingtreamsofindiasnuclearpowerprograms.pdf.

definition of civil plutonium.[29] In addition, India is planning to construct a reprocessing facility to handle foreign-supplied IAEA-inspected spent fuel; this facility would be subject to safeguards. Importantly, in its 2008 agreement with India on the peaceful uses of nuclear energy, the United States gave India advance approval ("prior consent") to reprocess US-origin spent fuel in such a facility. India has produced a modest amount of MOX fuel for recycling in its nuclear power reactors and may be planning a more extensive program to utilize the planned safeguarded reprocessing plant.[30] Thus, at the moment, India's stocks of civil plutonium are modest. However, if the just noted plans are realized, these stocks could become more substantial, possibly to be accompanied by a MOX-focused utilization plan.

United Kingdom

The United Kingdom has the world's largest stocks of civil plutonium, amounting to 133.5 tonnes as of the end of 2016. This includes 4.4 tonnes of military-origin plutonium declared excess and moved to the civilian stockpile and 23.2 tonnes of foreign-owned material.[31] The UK government has not been able to decide on an approach for reducing this accumulation, given the lack of a MOX fuel-fabrication plant, the dearth of domestic reactors able to use such fuel, and its lack of a permanent repository for direct disposal of the plutonium. For the time being, indefinite storage at the Sellafield reprocessing site continues as the default option.

China

China does not yet have a commercial reprocessing program but is well on its way to launching one. It launched an estimated 50 tonnes (annual throughput) pilot civil reprocessing plant in 2010 but has had difficulty operating it even close to full capacity. Mark Hibbs observed that "The pilot plant has operated infrequently, that very little spent fuel has been reprocessed, and that operation may have been indefinitely halted in 2014." Nonetheless, China has broken ground on a larger, 200-megaton facility intended to be finished by 2025. And it has been negotiating for years with the French company Orano (formerly Areva, see footnote 22) over the purchase of a Rokkasho-sized facility. According to Hibbs, China's nuclear complex seems determined to move forward with the project before commercial constraints intrude. In addition, Hibbs notes that "Chinese decisionmakers will therefore observe carefully how France and Russia, which presently lead in advanced fuel cycle industrial development, proceed in coming years."[32]

United States

Finally, the United States must dispose of its nearly 50 tonnes of former military plutonium that it has declared as excess. The longstanding plan, under a 2000 bilateral agreement (amended in 2010), was to dispose 34 US tons of this material in concert with Russia's disposition of a similar amount of military-origin plutonium.[33] While the Department of Energy's proposed disposition strategies and

29 Ibid.
30 "Nuclear Power in India," World Nuclear Association, (updated March 2018), www.world-nuclear.org/information-library/country-profiles/countries-g-n/india.aspx.
31 "Countries: United Kingdom," International Panel of Fissile Materials, updated February 12, 2018, http://fissilematerials.org/countries/united_kingdom.html; "Managing the UK Plutonium Stockpile," UK Parliamentary Office Postnote, September 2016, http://researchbriefings.files.parliament.uk/documents/POST-PN-0531/POST-PN-0531.pdf.
32 Mark Hibbs, *The Future of Nuclear Power in China*, Carnegie Endowment for International Peace, May 2018, https://carnegieendowment.org/2018/05/14/future-of-nuclear-power-in-china-pub-76311.
33 Agreement Between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes and

material mixes have shifted again and again during the two decades since the agreement was approved, the lion's share of the US plutonium was to be made into MOX fuel for use in power reactors, while Russia opted more recently to burn MOX in fast reactors.[34] The costs associated with this option for the United States greatly increased, however, as construction of the US MOX plant proceeded, and the Donald J. Trump administration has formally notified contractors that it is terminating its support for further construction in favor of diluting these 34 US tons and disposing of some or all of it in an existing nuclear-waste repository in New Mexico.[35] The United States is already in the process of diluting and disposing in this manner 6 tonnes of separated plutonium previously determined to be insufficiently pure to be made into MOX.[36] Russia rejected the shift in US strategy, arguing that the "dilute and dispose" option would permit future recovery of the material, and withdrew in October 2016 from its agreement with the United States on plutonium disposition.[37]

Related Cooperation, 2000; 2000 Plutonium Management and Disposition Agreement as amended by the 2010 Protocol, 2010 http://fissilematerials.org/library/PMDA2010.pdf; Department of State, "Fact Sheet: Plutonium Management and Disposition Agreement: April 13, 2010," https://www.nti.org/media/pdfs/Dept_of_State_2000_Plutonium_Management_and_Disposition_Agreement_Fact_Sheet.pdf?_=1440607117; Government Accountability Office, *Plutonium Disposition*.

34 The National Nuclear Security Administration (NNSA) has wrestled since the inception of the program with the question of to what degree less pure (i.e. plutonium not suitable for the use in a US nuclear-weapon "pit") could be made into MOX and has also struggled with identifying the processes for disposing of this material. This became a key cost-driver of the program. Nearly a decade ago, it declared excess an additional 8 tons (in US measurements) of pit plutonium and sought another disposition pathway for 13 tons of less-pure plutonium. Under the Barack Obama administration, the National Nuclear Security Administration designated 6 of those tons for disposal in WIPP. No disposal pathway was determined at that time for the other 7 tons. The many twists in turns in the US–Russia agreement and US MOX policy are detailed in Edwin Lyman, "Excess Plutonium Disposition: The Failure of MOX and the Promise of Its Alternatives," Union of Concerned Scientists, 2014, pp. 10–25; www.ucsusa.org/sites/default/files/attach/2015/01/Excess%20Plutonium%20Disposition.pdf.

35 Text of the NNSA letter is available at: http://www.srswatch.org/uploads/2/7/5/8/27584045/nnsa_letter_on_mox_contract_termination_october_10_2018.pdf. Paul Sonne, Steven Mufson, "Billions of Dollars Later, Energy Department Pulls Plug on Partly Built Nuclear Fuel Plant," *Washington Post,* May 12, 2018, https://www.washingtonpost.com/world/national-security/billions-of-dollars-later-energy-department-pulls-plug-on-partly-built-nuclear-fuel-plant/2018/05/11/aad411da-5532-11e8-b00a-17f9fda3859b_story.html?noredirect=on&utm_term=.2f93607d1464. South Carolina is also making a last-ditch effort to halt the shutdown through litigation. Union of Concerned Scientists, "U.S. Appeals Court Rules Energy Department Can Stop Building MOX Plant," Octover 9, 2018. https://www.ucsusa.org/press/2018/us-appeals-court-rules-energy-department-can-stop-building-mox-plant#.W750Mc5KiM8.

36 International Panel on Fissile Materials, "United States asks IAEA to monitor dilute and dispose steps for 6 tons of plutonium," IPFM blog, December 5, 2016. http://fissilematerials.org/blog/2016/12/united_states_commits_to_.html.

37 Andrew Kramer, "Vladimir Putin Exits Nuclear Security Pact, Citing 'Hostile Actions' by U.S.," *New York Times,* October 3, 2016, https://www.nytimes.com/2016/10/04/world/europe/russia-plutonium-nuclear-treaty.html. For additional details on the dilute and dispose option see, Edwin Lyman and Frank von Hippel, "Alternatives to MOX," presentation to Savannah River Site Citizens Advisory Board, Aiken South Carolina, March 26, 2016, http://www.lasg.org/Disposition/Documents/PuDispositionAlternativestoMOX_FvH-EL_29Mar2016.pdf; Rick Lee, "Outline of Discussion of Dilute and Dispose," prepared for South Carolina Governor's Nuclear Advisory Council, (n.d.), http://dels.nas.edu/resources/static-assets/nrsb/miscellaneous/WIPP3/wipp3-lee.pdf.

HISTORICAL AND POLITICAL BACKGROUND: PAST AND ONGOING EFFORTS TO LIMIT NATIONAL REPROCESSING PROGRAMS AND MANAGE PLUTONIUM STOCKS

As noted above, international efforts to control civilian use of separated plutonium have been far more limited than those for highly enriched uranium. Those related to separated civil plutonium include broad formal arrangements pursued though multilateral organizations, as well as measures pursued on a more limited or national basis.

Early proposals for international control of fissile materials

Immediately after World War II, the United States and Soviet Union supported the concept of nuclear energy being controlled by a UN Atomic Energy Commission. This concept was developed in the Acheson-Lilienthal Report, which proposed that all fissile material would be owned by an international agency, the Atomic Development Authority, and released to states in small quantities as required for the development of nuclear energy.[38] However, the level of mistrust between the Cold War rivals prevented such an agreement.

The concept re-emerged in 1953 in the US Atoms for Peace initiative, which included a proposal to establish an international organization under the United Nations to operate a bank of nuclear material that would be allocated to states for peaceful uses.[39]

IAEA Statute: Authority to acquire, store, and supply nuclear material

When the IAEA was established in 1957, its Statute reflected elements of the nuclear-material bank concept. However, it was left to member states to determine if they would set up an actual bank: at their discretion, member states could make nuclear materials available to the IAEA, which would store them and supply them to other member states on request.[40] Nonetheless, the IAEA was given specific authority to prevent the stockpiling of special fissionable materials, including plutonium. Specifically, the Agency is authorized to require states to deposit excess materials with it. These materials, including plutonium, would be returned to the state concerned when it was needed.[41]

No member state has sought to activate these provisions.[42] In 1975–77, the IAEA Secretariat undertook internal studies on the possibility of regional fuel-cycle centers, which could include reprocessing and storage, and an international storage scheme for excess plutonium. These studies were considered by the International Nuclear Fuel Cycle Evaluation (INFCE).

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[38] David E. Lilienthal et al, *A Report on the International Control of Atomic Energy*, The Secretary of State's Committee on Atomic Energy, March 16, 1946, http://fissilematerials.org/library/ach46.pdf
[39] Address by Mr. Dwight D. Eisenhower, President of the United States of America, to the 470th Plenary Meeting of the United Nations General Assembly, December 8, 1953, https://www.iaea.org/about/history/atoms-for-peace-speech
[40] IAEA Statute Articles IX and XI.C.
[41] IAEA Statute Article XII.A.5.
[42] It may be noted, however, that civil separated plutonium in Japan is subject to IAEA safeguards, to verify that this material is being used for exclusively peaceful purposes. Although this does not involve managing Japanese plutonium stocks, it does provide transparency as to the nature, quantities, and location of such stocks.

International Nuclear Fuel Cycle Evaluation

INFCE was an international study examining the potential proliferation risks of a wide range of nuclear fuel cycles. The initiative launched in 1977 and issued its final report in 1980. INFCE concluded that institutional barriers to proliferation would be more effective than technical measures and reported favorably on concepts such as multinational/regional fuel-cycle centers, an International Nuclear Fuel Authority, and International Plutonium Storage, though noting there were many issues to be resolved before such schemes were likely to be accepted.[43]

IAEA International Plutonium Storage

The IAEA convened an international expert group on International Plutonium Storage, which met from 1978 until 1982. This study examined approaches for implementing the IAEA Statute provisions on preventing the stockpiling of plutonium.[44] The IAEA director general requested Board of Governors approval to continue the study, but approval was not forthcoming. At that time, the states with civil plutonium programs did not see a need for multilateral involvement.

Guidelines for the Management of Plutonium (INFCIRC/549)

By the later 1990s, there was increasing public and political interest in plutonium issues, and a number of the governments involved realized the value of transparency measures. A group of nine states[45] developed the Guidelines for the Management of Plutonium, published by the IAEA in 1998 as document INFCIRC/549.[46] This document set out what is currently the only internationally agreed statement of principles for managing plutonium in peaceful nuclear activities. The guidelines are intended to increase transparency of the management of civilian plutonium, through each participating state:

(a) declaring that its policies for the management of plutonium are based on these guidelines; and
(b) publishing annual statements of its holdings of separated plutonium.[47]

Currently the nine states that formulated the guidelines continue to subscribe to them. Other states are invited to join.

The guidelines refer to:

> … the need to avoid contributing to the risks of nuclear proliferation, especially during any period of storage before the plutonium is either irradiated as fuel in a reactor or permanently disposed of; … (and) … the importance of balancing supply and demand, including demand for reasonable working stocks for nuclear operations, as soon as practical.[48]

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43 The International Fuel Cycle Evaluation, an international review in 1977–78 of reprocessing and other nuclear fuel-cycle options seeking to find consensus on approaches that minimized proliferation risks. R. Skjoldebrand, "The International Nuclear Fuel Cycle Evaluation INFCE," *IAEA Bulletin*, Vol. 22, No. 2, p. 30 ff., https://www.iaea.org/sites/default/files/22204883033.pdf; 1980 INFCE Report of WG 4, pages 177–85.
44 IAEA Statute Article XII.A.5.
45 The five NPT nuclear-weapon states plus Belgium, Germany, Japan, and Switzerland.
46 "Plutonium Management Guidelines," International Atomic Energy Agency document INFCIRC/549, March 16, 1998.
47 The INFCIRC/549 reporting *pro forma* does not indicate the isotopic composition of plutonium holdings.
48 INFCIRC/549, paragraph 13.

Balancing supply and demand: the issue of "working stocks"

As indicated in INFCIRC/549, plutonium should not be separated if it is intended for long-term stockpiling, specifically, beyond the requirements for "reasonable working stocks" for near-term use, as this would be inconsistent with the principle of minimizing stocks.

The guidelines do not define *reasonable* working stocks. This would have to take into account overall fuel requirements in the state concerned, fabrication flow rates, schedule of reactor loading, facility-specific considerations, etc. There also may be a case for having spare fuel assemblies on hand in case of a need to replace defective assemblies. In general terms, a working stock is equivalent to one to three years of throughput, depending on circumstances. One consideration would be the form of the plutonium, especially how quickly it is converted from bulk material to a less accessible form, such as MOX fuel pellets.

Other factors complicating plutonium supply and demand include:

- The United Kingdom and France store plutonium on behalf of customer states as well as themselves, and inevitably have some surplus. One approach could be to turn these substantial holdings over to an international plutonium storage scheme;
- In the United States and Russia, transfers of excess military plutonium could also contribute to stock growth;
- Postponements or cancellations in plutonium-fuel programs (such as in Japan) result in unintended delays in consumption.

In current circumstances, with limited use of plutonium fuel, actions to maintain a supply/demand balance could include closing reprocessing plants (as the UK has done), postponing the start-up of reprocessing plants, deferring new plants, and operating large plants on reduced throughput or on a campaign basis.

INFCIRC/549 also contains important guidelines on international transfers (including consideration of the recipient's plutonium management strategy and timetable for utilization) and levels of security.

These guidelines are voluntary, and there are no arrangements for accountability; that is, there is no mechanism for checking whether the states subscribing to the guidelines are in fact acting in accordance with them. As the previous descriptions of national civil reprocessing and MOX programs make clear, a number of subscribing states are experiencing difficulty in achieving a balance between separated plutonium supply and demand.

Multinational nuclear approaches (MNA)

In 2004, the IAEA initiated a study on Multilateral Approaches to the Nuclear Fuel Cycle, usually referred to as MNA.[49] This study reported in 2005 that previous MNA proposals had failed partly because the waning interest in nuclear energy eroded the perceived need for additional fuel cycle facilities, whether national or multinational. However, the study noted the likely increase in the number of states acquiring latent nuclear weapon capabilities by accumulating stocks of separated civil plutonium over coming decades and considered that proliferation concerns arising from this development could create a more conducive political environment for MNAs in the future.

The study concluded multilateral facilities for reprocessing were favorable to national facilities, subject to the following conditions:[50]

(a) Only MOX fuel, and not separated plutonium, should be returned to customer states;
(b) A reprocessing plant should have a co-located MOX fuel-fabrication facility, to reduce the risks associated with transporting separated plutonium;

[49] *Multinational Approaches to the Nuclear Fuel Cycle,* Expert Group Report to the Director General, International Atomic Energy Agency (Vienna, 2005), https://www-pub.iaea.org/books/iaeabooks/7281/Multilateral-Approaches-to-the-Nuclear-Fuel-Cycle.
[50] MNA study paragraph 179.

(c) Any multilateral arrangement should adopt "just in time" reprocessing—synchronizing reprocessing and MOX fuel fabrication in order to prevent excessive storage of separated plutonium;
(d) Any multilateral arrangement should also adopt "just in time" MOX delivery—synchronizing the delivery of fresh MOX fuel with reactor refueling cycles in order to prevent the customer state from storing this fuel for extended periods.

Euratom Treaty

The 1957 Euratom Treaty establishing the European Atomic Energy Community sets out the principle of multinational ownership and control of nuclear materials. Special fissile materials (which include plutonium-239 and any substance containing plutonium-239) are to be the property of Euratom, and the Euratom Supply Agency (ESA) has the right to acquire nuclear materials.[51] However, where ESA does not do so, the possessor (member state, person, or entity) has unlimited right of use and consumption, subject to treaty provisions. These provisions have never been exercised, however. Thus, in practice, it appears that the regime for reprocessing plutonium in the European Union is no different from that of non-EU states, though there is potential for the EU to take full control.

It may be noted, however, that civil separated plutonium in France and the United Kingdom is subject to Euratom safeguards, to verify that this material is being used for exclusively peaceful purposes. Although this does not involve management of French and UK stocks of this material, it does provide transparency as to the nature, quantities, and location of such stocks.

Supplier-state restrictions

Supplier-state restrictions on transfers of reprocessing equipment and technology have had a direct impact on slowing the spread of national reprocessing programs and are another component of the international nuclear landscape.

France's 1978 decision to terminate proposed reprocessing plant sales to Pakistan, South Korea, and Taiwan, for example, slowed the advent of reprocessing in the first of these states and helped preclude subsequent reprocessing activities in the other two. Similarly, Germany's retreat from its 1975 agreement to supply Brazil with a commercial-scale reprocessing plant largely ended Brazil's pursuit of the technology. Agreement by the Nuclear Suppliers Group (NSG) to exercise restraint in transferring such sensitive technology has further helped limit the spread of national reprocessing facilities and forced states pursuing such capabilities to obtain the necessary hardware through clandestine channels, increasing costs and delays.[52] These NSG Guidelines require strong restraints on transfers of reprocessing technology.

As also mentioned, in their bilateral civil nuclear-cooperation agreements, a number of supplier states, most notably the United States and Russia, have imposed restrictions on partner-state reprocessing.[53]

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[51] Treaty Establishing the European Atomic Energy Community, March 25, 1957, Articles 86 and 57.
[52] Nuclear Suppliers Group Guidelines, http://www.nuclearsuppliersgroup.org/en/guidelines.
[53] Examples include US agreements for cooperation in the peaceful uses of nuclear energy pursuant to Section 123 of the US Atomic Energy Act and Russia's nuclear-cooperation agreement with Iran covering the Bushehr Nuclear Power Plant.

Ad hoc diplomacy, incentives, and sanctions

Finally, the increasing international attention to the potential risks associated with reprocessing and plutonium accumulations has created a backdrop for numerous targeted initiatives. These include the unsuccessful US effort in the 1980s to use sanctions to dissuade Pakistan from pursuing enrichment and reprocessing;[54] the intensive US diplomatic engagement with North Korea in 1993 and 1994 that led to the suspension of North Korean reprocessing activities in return for certain economic and energy incentives under the Agreed Framework; and the negotiation of the JCPOA after the imposition of sanctions by the UN Security Council and numerous individual states.

[54] See the "Glenn Amendment," Section 102(b), US Arms Export Control Act, Title II of Pub. L. 94–329, 90 Stat. 729, enacted June 30, 1976, codified at 22 U.S.C. Ch. 39.

RECOMMENDATIONS AND POLICY OPTIONS

The dangers described above fall into two categories: immediate concerns—namely, continued reprocessing and the management of existing plutonium stocks—and potential future concerns—namely, the emergence of new reprocessing states. In effect, it is necessary to mitigate the existing risks and prevent the future ones.

Limiting existing reprocessing programs

There are great differences in the activities and plans of the individual civil reprocessing states. Efforts to terminate or limit these programs must be examined case by case.

The United Kingdom has just ended civil reprocessing, and Japan, as noted, is not currently engaged in reprocessing, but hopes to bring its commercial-scale Rokkasho plant online within the next several years. This would be a significant setback for efforts to limit the further accumulation of separated plutonium, since it appears that the MOX plant at the site will open only after the reprocessing plant has been operating. It is not clear how long this situation will last, but during this period, the Rokkasho reprocessing plant could separate up to 8 tonnes of plutonium annually, further adding to Japan's domestic stocks.

The French case is more complex. Until recently, French MOX fuel fabrication and MOX utilization in domestic nuclear power plants appeared to be approaching relative balance with the plutonium output from the reprocessing of domestic spent fuel, although the production of MOX not suitable for commercial use, and possibly other factors, meant that stocks of separated plutonium from domestic spent fuel were slowly growing. At the same time, France has completed its existing contracts for the reprocessing of foreign spent fuel, so that accumulations of separated plutonium from foreign-origin spent fuel have plateaued. Thus, overall, the rate of growth of separated plutonium stocks in France is slowing, although growth in absolute terms continues.

Nonetheless, France's closed fuel cycle system is threatened by both political commitments and the aging of the French reactor fleet and the La Hague facility. The French government has promised to lower nuclear power's share of electricity generation by one-third by 2025 (from three-quarters to one-half of all electricity generation). While total fulfillment of this promise is viewed with skepticism, the permanent closure of a half-dozen or more reactors is widely anticipated. Given that the nearly two dozen reactors licensed to burn MOX in France are among the country's oldest, this likely entails a lower demand for MOX in the country. At the same time, the La Hague facility is in the process of a costly overhaul, amounting to at least €700 million and will take the facility offline for a considerable period. The result could be a buildup of spent fuel at La Hague that further strains the facility's already limited spent-fuel storage capacity, requiring France to devote substantial additional financial resources to an effort that would further exacerbate security risks. These costs have contributed to ongoing concerns about the financial burden reprocessing imposes on the financially challenged French electricity utility, Electricité de France.[55]

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[55] See, for example, an op-ed by Christian Stoffaes, a former EDF Planning Director, "Plutonium: le débat manqué de la transition énergétique" [Plutonium: A debate missed by the energy transition], *La Tribune*, October 2016, https://www.latribune.fr/opinions/blogs/cercle-des-ingenieurs-economistes/plutonium-le-debat-manque-de-la-transition-energetique-575405.html; International Panel on Fissile Materials, "France," in *Plutonium Separation in Nuclear Power*

The likely reduced demand for MOX because of nuclear power plant shutdowns, the high costs of refurbishing La Hague, and the possibility that financial challenges at Electricité de France could create pressure to switch to far less expensive LEU fuel in lieu of MOX, casting a deepening shadow over the French reprocessing program and creating some doubt as to its future.

Reprocessing in Russia and India appears to be greatly in excess of current utilization needs and, as noted, is justified by these states on the grounds that increased plutonium stocks are required for the future fueling of breeder reactors. It is hard to judge from available information whether these stocks are currently in balance with projected needs or when these stocks might meet this objective. Given chronic delays that have typically plagued breeder reactor development and construction programs, however, it is possible that a reprocessing pause or slow-down might be feasible without impacting future breeder plans. Such actions might prove unacceptable on other grounds, however, such as the potential impact on local economies from ending or scaling back work at an important nuclear facility, and, for the moment, the two states appear to have little incentive to constrain their reprocessing programs.[56]

Thus, while current reprocessing activities appear to be declining, at this juncture it is not clear if it would be possible to accelerate this trend appreciably and, if Japan continues its current plans to operate the Rokkasho reprocessing plant, the trend would be partially reversed. Nonetheless, it is important to encourage Japan to continue its reprocessing moratorium, at the very least until the Rokkasho MOX facility is operational and until a significant number of Japanese nuclear power plants licensed to burn MOX come back online. Changing attitudes toward dry storage of spent fuel should enable Japan to more seriously consider dry cask storage as an alternative to reprocessing. In the case of France, it is important to develop strategies to encourage France to phase out MOX-burning plants and shift to LEU fuels for its domestic nuclear power plants. Meanwhile, as a means of reining in the spending enthusiasms of China's civil nuclear complex, Chinese economic officials should be reminded that reprocessing is not currently an economically viable technology.

Technical measures to increase proliferation resistance of reprocessing

Where possible, reactors should be operated to avoid producing plutonium at or near weapon-grade. Where there is plutonium in irradiated material at or near weapon-grade—for example, fast-breeder blanket assemblies or light-water reactor fuel discharged with very low burn-up—this material should not be reprocessed separately. If reprocessing cannot be avoided, such material should be blended in-process with higher burn-up material to avoid a weapon-grade product.[57]

Developing plutonium-recycle technologies should be deferred until it can be demonstrated that they are actually needed. Where such technologies are developed, proliferation resistance and safeguards-by-design should be built in. This principle has been adopted by the Generation IV International

Programs: Status, Problems, and Prospects of Civilian Reprocessing Around the World, 2015, p. 32, http://fissilematerials.org/library/rr14.pdf.

[56] It is also not clear what party might successfully raise the matter with Moscow and New Delhi. The United States seems an unlikely candidate, given its fraught relations with Russia over the two states' plutonium disposition agreement, among other matters, and given it has granted India advance approval to reprocess spent fuel from any US-supplied nuclear power plant. At best, it would seem the matter might be broached by another adherent to the Plutonium Management Guidelines.

[57] Japan undertook to do this with fast-breeder blanket assemblies if the Recycle Equipment Test Facility at Tokai had proceeded.

Forum.[58] Consistent with this approach, recycle technologies that do not produce plutonium in readily accessible form are preferred, to reduce the risk of proliferation and sub-national theft.

Limiting the risk of existing civil plutonium stocks

Because most reprocessing states have no obvious path toward fully utilizing or disposing of existing plutonium stockpiles in the near term, both political and technical measures should be taken to reduce the risk of these stocks.

Political measures

Establishing a multistate forum for discussing intermediate- and long-term civil plutonium management and disposition issues

A collaborative dialogue among states with inventories of civil plutonium to examine options for long-term management and disposal of this material is urgently needed. This could begin with establishing a platform where these issues could be regularly discussed and future policies and recommendations developed. One starting point for such a platform could be the INFCIRC/549 plutonium management group, with India invited to participate, which could function as a regular forum for cooperation or policy coordination. (Currently the group meets for less than one hour per year.) A working group under the IAEA, or some other ad hoc formation, are other options. The group, however situated, could also look back to the International Nuclear Fuel Cycle Evaluation of the late 1970s as a model for a technical study on these issues. A key point is to recognize that difficulties in establishing permanent disposition and medium- and long-term management are common to all states with civil plutonium stocks and to establish a forum to develop solutions. Such a forum could consider some or all of the following institutional measures, while national governments might consider several technical options described further below for short-, medium-, and long-term management and disposal.

Revisiting the international plutonium storage concept

The IAEA Statute has a number of provisions giving the Agency authority to operate a storage scheme for separated plutonium. Particularly relevant here is Article XII.A.5. This applies where the IAEA is applying safeguards, and gives the Agency certain rights and responsibilities "to the extent relevant to the (safeguards) arrangement" (on "extent relevant" see discussion below). Specifically, the IAEA has the right

> to require deposit with the Agency of any excess of any special fissionable materials recovered or produced as a by-product over what is needed for [peaceful purposes under continuing Agency safeguards for research or in reactors, existing or under construction] *in order to prevent stock-piling of these materials*, provided that thereafter at the request of the Member or Members concerned special fissionable materials so deposited with the Agency shall be returned promptly to the Member or Members concerned for use under the same provisions as stated above. (emphasis added)

[58] See the Generation IV International Forum Charter, https://www.gen-4.org/gif/upload/docs/application/pdf/2016-07/charter_nov2006.pdf.

It is noteworthy that this text is expressed, not as a *discretion* of the Agency, but as a *right and responsibility*. This suggests that when the IAEA was established, the member states intended the Agency to exercise control over plutonium in order to prevent stockpiling.

The text is unclear whether the IAEA can do so only if there is an express agreement to this effect with the state concerned; "to the extent relevant to the … arrangement" is prone to different interpretations, but traditionally, Article XII of the Statute is considered *non-self-executing*, that is, it has effect only if reflected in an agreement with the particular state. To date, no agreement has given this authority to the Agency, and the Agency has never taken action pursuant to Article XII.A.5.

An international plutonium bank?

Recently, the IAEA has become involved with international fuel-bank arrangements for LEU. Although not dealing with *excess* materials, these arrangements might provide precedent for a plutonium storage scheme. However, a bank for plutonium, which is a weapon-usable material, would raise many important issues not present with LEU, which cannot be used in weapons. In the case of plutonium, holdings and movements should be minimized.

The LEU fuel bank arrangements are based on two different approaches: a bank owned and controlled by the IAEA itself, as in Kazakhstan,[59] and a bank owned by the host state, with guaranteed transfer of LEU to the IAEA, as in Russia. To the extent that the LEU banks are a precedent, the Russian bank at Angarsk—taking advantage of an existing facility—is a better model than the Kazakh bank, although with respect to the IAEA's possible future control over plutonium, the Kazakh bank may be the preferred institutional arrangement.

While some of the specific mechanisms envisioned in the Statute do not appear appropriate in today's circumstances (with most materials stored reasonably securely in nuclear-weapon states), the need to prevent plutonium stockpiling and ensure transparency and accountability to the international community remains relevant. In this light, it might be useful to leverage this longstanding authority to enact clearer guidelines to reduce stockpiles of separated plutonium and establish an effective accountability mechanism to ensure plutonium only would be supplied where there are strong assurances of immediate use.

In taking decisions on the transfer of plutonium (in the form of MOX) to reprocessing customers, the United Kingdom and France have accepted the principles in INFCIRC/549 of requiring a utilization timetable and seeking to balance supply and demand "as soon as practicable."[60] This is broadly consistent with what an international plutonium storage scheme would do. However, greater consistency and transparency, and quite possibly greater rigor, would apply if the plutonium held for other states in the United Kingdom and France were under IAEA control. The IAEA could prohibit any withdrawals without its approval and based on a demonstrated need, and confirm that the declared utilization timetable is met.

For similar reasons, it would be preferable to have excess plutonium in Japan under the control of the IAEA rather than national authorities alone.

[59] https://www.iaea.org/topics/iaea-low-enriched-uranium-bank
[60] INFCIRC/549, paragraphs 10–13.

In the future, it would be desirable to have excess plutonium in all the civil reprocessing states—United Kingdom, France, Russia, India, and China, if its reprocessing plans proceed—under close monitoring or control by the IAEA. At present, nonproliferation is nearly always considered as preventing horizontal proliferation, but if major nuclear-arms reductions proceed, vertical proliferation (in this case, the reconstitution of military programs) will become an issue. If a Fissile Material Cutoff Treaty is negotiated and enters into force, existing civil plutonium stocks could become more attractive for breakout to weapons. The IAEA could have a major confidence-building role in monitoring plutonium stocks.

Placing all civil separated plutonium under IAEA or Euratom safeguards

Placing civil separated plutonium under IAEA or Euratom safeguards is a less comprehensive approach than international management of the material, but such safeguards would almost certainly be an essential element of any substantial internationalization arrangement. Moreover, as mentioned earlier, this measure has already been implemented in Japan, France, and the United Kingdom, with the IAEA doing the monitoring in the first of these states, and Euratom doing so in the other two. Russia and the United States have permitted only very limited IAEA monitoring of their civilian nuclear activities. Both states, however, pledged in their now-suspended agreement on the management and disposition of excess military-origin plutonium that the IAEA would monitor the disposition process in each country. India, as noted, has not permitted its breeder reactor program, where most plutonium use for energy production is currently focused, to be placed under IAEA safeguards at this time, but it has declared that it might take this step in the future. Moreover, a portion of its civilian reprocessing and MOX activities involving foreign-origin reactors and/or fuel is currently under IAEA safeguards.

In effect, it would require only a limited new initiative to bring virtually all separated plutonium currently designated as civil under IAEA or Euratom safeguards, namely gaining Russian acceptance of IAEA monitoring of its non-military plutonium-related activities, and China's acceptance with respect to its currently modest demonstration reprocessing program. India's reclassifying its breeder program as civil and subject to IAEA safeguards would be a next step, along with continued Chinese acceptance of the practice in the event that its civil plutonium program advances. Should the United Kingdom leave Euratom as part of its withdrawal from the European Union ("Brexit"), it would be important for the IAEA to take over safeguarding plutonium in that country. It should be added that, in the case of Russia, the United States, and post-Brexit United Kingdom, IAEA safeguards over plutonium should be directly applied; it is not sufficient that these states merely make the material eligible for safeguarding.

For now, the civil plutonium-possessor states, with the support of outside parties, should work to bring all such material under international safeguards.

Technical measures

Long-term: Elimination and permanent disposal

All reprocessing and civil plutonium-possessor states will confront the common challenge of disposing of certain quantities of separated plutonium.[61] This includes:

- US excess military material;
- The United Kingdom's post-civil-reprocessing stocks separated from domestic and foreign spent fuel;
- Possibly the Japanese stocks of plutonium held domestically, if Japan's MOX plant is not completed;
- French holdings of foreign-origin plutonium;
- Certain French, Indian, and Russian stocks not pure enough for use in various existing or planned MOX programs.

A number of approaches to eliminating or permanently disposing separated plutonium have been discussed over the years. Two approaches are currently receiving the most active attention.

Russia is planning to use its breeder reactors to "burn" plutonium, that is, to consume more plutonium in the reactors' MOX than is produced during the reactors' operation.

The United States, as noted earlier, is proposing a new approach to dispose of some 34 tonnes of pure plutonium declared excess to military needs, namely diluting the material with inert substances and placing at least a portion of the resulting product in an existing underground nuclear-waste facility in Carlsbad, New Mexico, known as the Waste Isolation Pilot Project, or WIPP. The United States has been using this technology since 1999, although certain modifications may be made as the current project moves forward, and decisions will be needed on how WIPP might be enlarged to accommodate the substantial quantity of diluted material anticipated. A degree of risk reduction could be achieved, however, by diluting the plutonium, even if final disposition were delayed. However, it appears that, for the current project, the rate of dilution may be merely 175 kilograms of plutonium per year, thus requiring more than five years to process a single tonne.[62]

It is not clear if either of these approaches might have wider application. Only Russia and India are actively pursuing development and deployment of breeder reactors, and the US dilute-and-dispose option may be too drawn out and complex to attract duplication, although it is a proven technology with a track record of nearly two decades of use. However, certain elements that add to the complexity and lengthy timeline of the US approach—in particular the need to disassemble nuclear-weapon pits and to convert the resulting plutonium metal into another chemical form—would not be needed to dilute and dispose civil plutonium in other countries. Thus it is possible that the US approach to dilution might have utility elsewhere. The United States should share its dilution and packaging

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[61] And not just separated plutonium: countries that have their spent fuel reprocessed (and thus have high-level waste), like all other states with spent fuel, will need to find a geological repository for this material in any case.
[62] See references in note 37.

technologies with other states and include them in unclassified aspects of ongoing US research and development activities.

The short- and medium-term: Regulatory measures

As part of risk minimization, states with plutonium stocks should commit to minimizing their holdings both in total quantity and in the number of sites and transport movements involved. It is important to regularly review the security measures for separated plutonium and to develop appropriate mechanisms as needed. These issues could be addressed by the multistate forum suggested above.

Short-term technical adjustment: Accelerated mixing with uranium and conversion to more-processed forms

One physical step that would make pure plutonium nitrate or plutonium oxide extracted through reprocessing less readily usable in a nuclear-explosive device (but without precluding its possible future use in most MOX fuel configurations), would be to mix the plutonium with natural or depleted uranium as early as possible, and to convert this material into MOX pellets and MOX fuel assemblies. Although subsequent re-separation of the plutonium is not technically difficult—a fact, as noted earlier, that has led the IAEA to treat MOX fuel as posing the same proliferation risk as pure plutonium[63]—practically speaking, amalgamating the two elements does create at least a temporary barrier to rapid use of the plutonium in a nuclear-explosive device.[64]

Currently, nearly all of the plutonium produced in Japan (at the now-closed Tokai-Mura facility and during trial runs at the Rokkasho reprocessing plant) was recombined with uranium after initial separation, and nearly all plutonium held at these facilities and others in Japan is in the form of various plutonium-uranium mixes.[65] In France, plutonium and depleted uranium are combined at the MELOX MOX fuel-fabrication plant.

In Russia, a portion of the country's separated civil plutonium is mixed with uranium at several facilities to produce MOX fuel for current and future breeder reactors. With construction of BN-1200 reactors now delayed, it appears that activities at the fuel facilities may be producing MOX—and thus drawing down stocks of pure plutonium nitrate and oxide—at a pace that exceeds near-term needs.

The Russian case, however, offers a strategy for reducing the risks from pure plutonium that might be pursued more extensively, namely, maximizing the mixing of plutonium and uranium at existing or specially constructed facilities, even if the product will go unused for an extended period or if the product would not be suitable as power-reactor fuel. The form can be bulk MOX powder, sintered MOX pellets, or fabricated MOX fuel assemblies; the greater the degree of processing, the greater the effective delay in separating pure plutonium (for example, MOX fuel assemblies are better than MOX powder). If there is excess capacity at France's MELOX MOX fuel-fabrication plant beyond that needed to meet domestic MOX fuel needs, this excess capacity could be used to mix additional separated plutonium with depleted uranium, reducing France's overall inventory of pure plutonium nitrate and oxide.

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[63] See INFCIRC/225.
[64] J. Kang, F. N. von Hippel, A. Macfarlane, R. Nelson, "Storage MOX: A Third Way for Plutonium Disposal?," *Science & Global Security*, 10, no. 2, (2002), pp. 85–101, http://scienceandglobalsecurity.org/archive/2002/06/storage_mox_a_third_way_for_pl.html.
[65] "The Status Report of Plutonium Management in Japan – 2017," July, 31, 2018, Office of Atomic Energy Policy Cabinet Office, provisional translation (copy available from authors), "Reprocessing," Japan Nuclear Fuel Limited, undated (c. 2017), https://www.jnfl.co.jp/en/business/reprocessing/.

Use of this strategy in Russia could, at the least, slow the possible growth of stocks of pure plutonium nitrate and oxide in that setting. This approach might also be useful for India, where its small MOX production capacity could reduce somewhat the risks posed by the country's stock of civil plutonium nitrate and oxide.

In the United Kingdom, where it appears that virtually none of its separated plutonium has been mixed with uranium, developing a strategy for taking this step or otherwise diluting the plutonium is needed.

Medium-term risk reduction

As noted above, long-term disposal will be needed for some separated plutonium in nearly all countries possessing these materials under almost all circumstances. And should countries like France and Japan reduce or opt out of producing MOX, these challenges are likely to grow. However, the politics of licensing and operating long-term nuclear disposal facilities have been extraordinarily challenging; only Finland and Sweden appear within sight of this final goal.

Officials in the French MOX program have discussed the possibility of more intentionally creating "Kentucky Fried MOX" (KFM), the MOX product deemed too impure for commercial use, as a means of improving the security of other plutonium that cannot be used in commercial fuel. Rather than sending this material to the MELOX facility, it might make sense to create a small dedicated line at La Hague to produce this "KFM." Similarly, the United Kingdom's shuttered Sellafield MOX plant, which was deemed unsuitable for commercial production, could be used to create "KFM" with the many tonnes of plutonium there, pending ultimate disposal.[66]

This material might then be stored in the dry casks along with spent fuel rods, providing a medium-term storage capability, pending ultimate disposal, with a radiation barrier equivalent to that of spent fuel before reprocessing—thus meeting the so-called "spent fuel standard," at least as regards security against non-state actors. This option, which relies on two proven technologies—MOX-style plutonium-uranium mixing and dry cask spent fuel storage—merits active, near-term consideration.

Discouraging new reprocessing programs

Sustaining current technology controls

All reprocessing and civil separated plutonium-possessor states are members of the NSG, except for India, which nevertheless implements the NSG Guidelines. At present, it appears a new reprocessing transfer is under consideration, specifically, the sale of a commercial-scale reprocessing plant by France to China.[67] China had put that transfer on hold, first because of local opposition to the proposed site for the facility, but now because of haggling over commercial terms. The two sides

[66] For a history of the Sellafield MOX plant and the UK's MOX program, as well as a comprehensive review of past, ongoing, and planned programs for the utilization of MOX in conventional nuclear power plants, see Alan J. Kuperman, ed., *Plutonium for Energy? Explaining the Global Decline of MOX*, University of Texas at Austin, 2018, http://sites.utexas.edu/prp-mox-2018/files/2018/10/4-UK-Plutonium-for-Energy.pdf.
[67] "France and China to Enhance Nuclear Energy Cooperation," World Nuclear News, January 10, 2018, http://www.world-nuclear-news.org/NP-France-and-China-to-enhance-nuclear-energy-cooperation-1001185.html.

claim, however, that they will reach a deal by the end of this year and that the facility will be completed by 2030. Site preparation work has already begun.[68]

Given the long-standing cohesiveness of the current technology holders against sharing this technology, it is not likely to be offered for the foreseeable future to any other would-be civil reprocessing state, and it is important that current restraints on transfers of reprocessing equipment and technology continue. States such as Vietnam and Saudi Arabia, as they negotiate nuclear-cooperation agreements with the United States, may refuse to formally renounce reprocessing, but the point is at least somewhat moot, given that no commercial supplier would likely be prepared to share reprocessing technology with either of them. Nonetheless, it is desirable to continue to build on the examples set in the US–UAE and US–Taiwan nuclear agreements, where the US partners have agreed to renounce reprocessing (and enrichment) into the indefinite future.

Blocking illicit procurement

Pakistan and North Korea have, of course, turned to clandestine procurement efforts to acquire reprocessing capabilities to support their nuclear-weapon programs. This would not meet the definition used here of civil reprocessing, but one could imagine a country in the future following the model Iran used with respect to its enrichment program: illegal acquisition of key commodities, then declaring facilities where they are used to be peaceful in nature and placing them under IAEA safeguards once they are discovered, thus retaining a break-out option.

One approach to discouraging such a strategy—and clandestine procurement activities more generally—would be for the current technology holders to declare that clandestine reprocessing (or enrichment) activities, including illicit procurement activities, would expose the perpetrator government to sanctions. To date, illegal procurement activities have not triggered UN Security Council or unilateral sanctions against governments. However, before the next case of nationally sponsored illegal nuclear-procurement activities involving reprocessing (or enrichment) arises, key supplier countries should announce that such behavior will expose any offending government to sanctions. This could provide a valuable deterrent to the pursuit of the clandestine route to plutonium separation.[69]

One variant of this sanctions-focused option would involve the governments of the key commercial suppliers of enriched uranium—France, Russia, and, through the Urenco consortium, Germany, the Netherlands, and the United Kingdom—all of which are also connected to the plutonium issue.[70] These states could direct their enrichment companies to include in their commercial enrichment contracts a clause reserving the right to withhold shipments of enriched uranium if the host

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68 "City Suspends Project after Thousands Protest," China Digital Times, August 10, 2016, "Areva and CNNC to Start Work on China Reprocessing Plant This Year," *Nuclear Engineering International,* January 10, 2018, http://www.neimagazine.com/news/newsareva-and-cnnc-to-start-work-on-china-reprocessing-plant-this-year-6024797https://chinadigitaltimes.net/2016/08/city-suspends-nuclear-project-thousands-protest/. The article indicates that negotiations are continuing. See also International Panel on Fissile Materials, "France believes reprocessing plant in China will begin operations in 2030," IPFM Blog, September 18, 2018, http://fissilematerials.org/blog/2018/09/france_believes_reprocess.html.

69 For a detailed discussion of this approach, see Leonard S. Spector, "Outlawing State-Sponsored Nuclear-Procurement Programs and Pursuing Recovery of Misappropriated Nuclear Goods," CNS Occasional Paper 25, December 2016, https://www.nonproliferation.org/25-outlawing-state-sponsored-nuclear-procurement-programs-recovery-of-misappopriated-nuclear-goods/.

70 The Netherlands and Germany have sent spent fuel to France and the United Kingdom for reprocessing and the return of MOX fuel, but their contracts have been completed. All four of these countries are also adherents to the Plutonium Management Guidelines.

government of the other party is found to have engaged in clandestine reprocessing (or enrichment) activities, including illicit procurement activities.

Reducing incentives to reprocess

Retaining plutonium in spent nuclear power plant fuel is the most efficient means for avoiding the stockpiling of separated civil plutonium. Historically, however, a number of states, including Japan, have pursued domestic reprocessing and/or reprocessing of domestic spent fuel abroad because of local opposition to retaining spent fuel in the storage ponds of the nuclear reactors where it was produced. In recent years, however, the use of dry spent fuel storage casks has become increasingly accepted as a proven, robust storage technology that can keep spent fuel safe and secure for a century or more, either at reactor sites or at centralized storage facilities. Among other strengths, the casks do not require mechanical means to cool stored spent fuel, unlike storage ponds, and thus are not vulnerable to power outages of the type that threatened fuel meltdowns in the spent fuel pools of Japan's Fukushima Daiichi reactor complex.

Although market forces and the inherent efficiency of dry cask storage are bringing the technology into wider use, a program to actively promote dry cask storage technology would help dampen pressure for governments to turn to reprocessing as the preferred solution to spent fuel management, as well as help build public acceptance of the safety and security dry cask storage provides. Nuclear supplier countries, at least those not engaged in the reprocessing of foreign spent fuel, might, for example, encourage the use of dry cask storage in their bilateral nuclear-trade agreements, and reactor vendors might include dry cask storage arrangements as an attractive component of their bids for new reactor sales.

Conclusion

Current civil reprocessing and plutonium use pose numerous challenges to international nonproliferation objectives. However, because a number of key programs are deeply entrenched in national nuclear policies, wholesale changes that might terminate all of these programs do not appear achievable at this time. On the other hand, the six countries with civil separated plutonium stocks face common issues in the management of this material, making certain modifications of these programs, in line with past international initiatives, a potentially workable goal. A reprocessing pause or slowdown, joint efforts to develop plutonium disposition strategies, and reinforced mechanisms to deter the spread of these capabilities would all serve to mitigate the potential dangers associated with current reprocessing and plutonium use policies.

ABOUT THE AUTHORS

John Carlson is a member of the Asia Pacific Leadership Network for Nuclear Non-Proliferation and Disarmament, a counselor to the Nuclear Threat Initiative, and an associate of the Project on Managing the Atom at the Belfer Center for Science and International Affairs at the Harvard Kennedy School of Government. Other current appointments include the Advisory Council of the International Luxembourg Forum and VERTIC's International Verification Consultants Network. Mr. Carlson was previously director general of the Australian Safeguards and Non-Proliferation Office, a statutory position which he held from 1989–2010. He retired from Australian government service in October 2010, after forty-six years, including thirty-four years in the Senior Executive Service. Other appointments included chairman of the International Atomic Energy Agency's Standing Advisory Group on Safeguards Implementation 2001–06; member of the Advisory Board of the International Commission on Nuclear Non-Proliferation and Disarmament (which reported in 2009); and founding chair of the Asia-Pacific Safeguards Network, 2009–12.

Leonard S. Spector is deputy director of the Washington, DC, office of the James Martin Center for Nonproliferation Studies (CNS). Prior to joining CNS, Mr. Spector served as assistant deputy administrator for arms control and nonproliferation at the US National Nuclear Security Administration, and as director of the Nuclear Nonproliferation Project at the Carnegie Endowment for International Peace. Earlier in his career, Mr. Spector served as chief counsel to the Senate Energy and Nonproliferation Subcommittee and as a Special Counsel at the US Nuclear Regulatory Commission. Mr. Spector is the author or coauthor of six books (his latest book is *Preventing Black-Market Trade in Nuclear Technology* [Cambridge University Press, 2018], coedited by Matthew Bunn, William C. Potter, and Martin B. Malin) and numerous articles on nonproliferation. His current research focuses on the elimination of chemical weapons in Syria, mechanisms for restraining Iran's nuclear program, and tools to prevent nuclear commodity smuggling.

Miles A. Pomper is a senior fellow in the Washington, DC, office of CNS. His work focuses on nuclear energy, nuclear nonproliferation, nuclear security, and nuclear arms control. Before joining CNS, he served as editor-in-chief of *Arms Control Today* from 2003–09. Previously, he was the lead foreign policy reporter for *CQ Weekly* and *Legi-Slate News Service*, where he covered the full range of national security issues before Congress, and a foreign service officer with the US Information Agency. Pomper chairs the Fissile Material Working Group, a coalition of eighty civil society organizations from around the world working to provide actionable policy solutions to keep the world safe from nuclear terrorism. He holds a BA in history and an MA in international affairs from Columbia University, and an MA in journalism from Northwestern University.

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