Plutonium for Energy?

Explaining the Global Decline of MOX

[EXCERPT]

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NUCLEAR PROLIFERATION PREVENTION PROJECT

The University of Texas at Austin

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Recycling Plutonium: What Went Wrong?

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This introductory chapter summarizes the findings of our book, the first comprehensive global study of "plutonium for energy" – using mixed-oxide (MOX) fuel in thermal nuclear power reactors that traditionally had used uranium fuel. Plutonium, a man-made element that can be obtained by reprocessing used nuclear fuel, is controversial for three reasons: it causes cancer, may be used in nuclear weapons, and is very expensive to purify and manufacture into fuel. Our team conducted research in all seven countries that have engaged in the commercial production or use of thermal MOX: Belgium, France, Germany, Japan, the Netherlands, Switzerland, and the United Kingdom. We found an industry in rapid decline, as five of the seven countries already had decided to phase out commercial MOX activities. This retreat is not due to the fuel's early performance problems, which have been overcome, but to plutonium's inherent dangers. Because plutonium is toxic, MOX fuel manufacturers faced public opposition and took extraordinary precautions that increased costs and reduced output. Five of the world's six commercial production facilities for thermal MOX fuel have closed prematurely after underperforming. The price of thermal MOX fuel, in the six countries that have used it commercially, has been three to nine times higher than traditional uranium fuel. Due to environmental and proliferation concerns, plutonium fuel has proved politically controversial in four countries – Germany, Japan, Belgium, and Switzerland – which halted some or all MOX activities while permitting nuclear energy to continue at the time. Security is also a major concern, as each delivery of fresh MOX fuel contains enough plutonium for dozens of nuclear weapons, yet reactor operators have not significantly bolstered physical protection, and the shipments are susceptible to terrorist attack. Ironically, plutonium fuel originally was viewed as vital to the nuclear industry, but it instead has helped undermine the economics, security, and popularity of nuclear power. This chapter concludes with lessons for countries that are engaged in, or contemplating, the recycling of plutonium for nuclear energy.

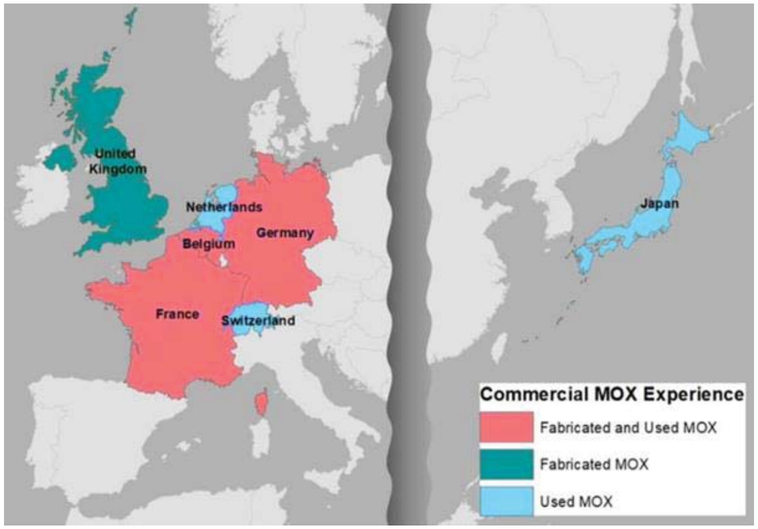
Recycling is typically considered a good thing. It turns garbage into an asset, thereby reducing the need for both raw material and waste disposal. Yet, recycling plutonium from previously used nuclear fuel to make fresh fuel for nuclear energy has proved controversial. This is mainly because plutonium has three big downsides: it can cause cancer, may be used to make nuclear weapons, and (largely due to the first two characteristics) is very expensive to purify and fabricate into fuel. Despite these challenges, seven countries – Belgium, France, Germany, Japan, the Netherlands, Switzerland, and the United Kingdom – have engaged in the commercial recycling of plutonium for energy in traditional, thermal nuclear power plants (which use "thermal" rather than "fast" neutrons to achieve fission). They have done so by fabricating and/or using mixed-oxide (MOX) fuel, which combines plutonium with uranium, to substitute for traditional low-enriched uranium (LEU) fuel. In addition, several countries – including China, India, Japan, Russia, South Korea, and the United States – are exploring new domestic facilities to recycle plutonium for energy using thermal or fast reactors. In light of the enormous potential consequences – for international security, public health, and the financial viability of nuclear energy – such decisions should be informed by a comprehensive analysis of the historical global experience of thermal MOX fuel. Regrettably, until now, no such resource had existed.[1]

This book is the first study of all seven countries that have engaged in the commercial recycling of plutonium for energy in thermal reactors (Figure 1), drawing on field research in each. Three of these countries have both produced and used such MOX fuel commercially: Belgium, France, and Germany. Three have used but not produced it commercially: Japan, the Netherlands, and Switzerland. One country has produced but not used it commercially: the United Kingdom.

A major finding of our research is that the thermal MOX industry is in rapid decline. As of 2018, five of the seven countries had already ended, or decided to phase out, their commercial MOX activities (Table 1). Belgium halted both MOX production and use in 2006. Switzerland ended its MOX use in 2007. The UK terminated commercial MOX production in 2011. Germany halted MOX production in 1991, and inserted its final MOX fuel assembly in

2017, so irradiation should end in 2020. The Netherlands plans to load its last MOX fuel assembly in 2026 and remove it four years later. Except in the last case, commercial MOX activities were reduced prior to any decision to phase out nuclear power. This track-record leaves only two countries that still plan to continue commercial MOX for thermal reactors – France and Japan – and their programs too face financial and political challenges.

Figure 1
Seven Countries Involved in Commercial MOX for Thermal Reactors



Source: Yeo-Ri Kim.

To assess the causes of the overall decline, and the variation in national outcomes, this book examines five aspects of the thermal MOX experience in each country: economics, security, safety/environment, performance, and public acceptance. Some information on these questions had previously been available in public literature but typically was dated and incomplete. In many cases, our researchers obtained key data only by conducting interviews with current and retired officials from government, utilities, industry, and non-governmental organizations (NGOs) – who provided oral and documentary evidence. After drafting our chapters, we solicited additional expert feedback prior to revising them for publication.

Table 1
Decline of Commercial MOX for Thermal Reactors

Country	Produce MOX?	Use MOX?
Belgium	✗	✗
France	✓	✓
Germany	✗	↘
Japan		✓
Netherlands		↘
Switzerland		✗
UK	✗	

Key:
✗ = Ended
↘ = Phasing out
✓ = Ongoing

Misperceived Necessity

The idea of recycling plutonium for energy took hold in the 1960s based on two misconceptions: global reserves of uranium for fuel were scarce, and the demand for nuclear energy would grow exponentially. The perceived solution was to increase the energy that uranium could produce by transforming its main isotope (U-238) – which cannot produce power in thermal reactors because it is not "fissile" – into an energy-producing isotope of plutonium (Pu-239). Since over 99 percent of uranium is the non-fissile isotope, such transformation could greatly increase the energy available from global uranium supplies. When traditional LEU fuel is irradiated in a nuclear power reactor, a small amount of U-238 is transformed into plutonium, which later can be separated out by a reprocessing plant and used to make fresh fuel.

To transform a sufficient amount of U-238 into plutonium would require development of fast breeder reactors (FBRs), which have more fast (high-energy) neutrons than traditional light-water reactors (LWRs) that rely on thermal (low-energy) neutrons. In the 1970s, nuclear utilities started commercially reprocessing their used ("spent") uranium fuel to separate out plutonium to make fuel for FBRs. However, the commercialization of FBRs was delayed, so the utilities instead started recycling a fraction of their plutonium in

MOX fuel for LWRs, while accumulating the rest in large stockpiles.[2]

By this century, most of the world's FBR development programs had failed. Nuclear utilities realized that if they reprocessed their spent fuel, the only way to recycle plutonium commercially would be in MOX fuel for LWRs. In most countries with nuclear power, utilities chose not to pursue such recycling. Instead, they opted to dispose of their spent fuel as waste, especially as it became clear by the 1970s that global uranium resources were much larger, and the demand for nuclear energy much smaller, than previously anticipated. Starting in 1976, the United States also discouraged worldwide reprocessing of spent fuel, due to concerns that the separation of plutonium would increase risks of nuclear proliferation and nuclear terrorism.[3] Nevertheless, the seven countries examined in this book initiated commercialization of thermal MOX fuel.

The subsequent decline of MOX for thermal reactors has not been due mainly to problems with fuel performance. Initially, MOX did face several technical challenges in thermal reactors. Fabricators had trouble uniformly mixing the oxides, resulting in clumps of plutonium in fuel pellets, which during irradiation led to hot spots, higher fission gas release, cladding failures, and radioactive contamination of the reactor's water that serves as both coolant and moderator. In addition, plutonium has greater tendency both to absorb thermal neutrons and to be fissioned by them. This resulted in a harder neutron spectrum that reduced the effectiveness of "poisons" – used to control excess fission – and subjected reactor equipment to higher amounts of destructive fast neutrons. A related problem was the emergence of neutron flux gradients between adjacent MOX and LEU assemblies, which complicated core management and necessitated using several different percentages of plutonium in the MOX fuel of a single core. MOX fuel also had lower burnup than traditional low-enriched uranium (LEU) fuel, which necessitated two different refueling cycles in the same reactor core. Another problem was that fission of plutonium, compared to uranium, produces fewer delayed neutrons, thereby requiring modification of reactor-control mechanisms. Eventually, however, these underlying technical problems were overcome to the extent that MOX today performs fairly similarly to LEU. Despite such technical success, the thermal MOX industry has declined rapidly due to plutonium's three risks – cancer, weapons, and cost – which have inhibited both the manufacture and use of such fuel.

Manufacturing Thermal MOX Fuel

Five of the six commercial fabrication facilities for thermal MOX fuel that ever operated have closed prematurely, and most of them underperformed while they were open. A seventh facility was canceled after construction. The main underlying cause of this poor track-record was that plutonium is far more hazardous than uranium, leading to high costs and public opposition. Most plutonium is composed of isotopes that are fairly long-lived and emit high levels of alpha radiation. One isotope of plutonium decays relatively quickly but into americium-241, which itself is a strong alpha emitter. Such alpha radiation is not a major problem outside the body because it can be blocked by many materials including skin. However, if inhaled and lodged in the lungs, these isotopes of plutonium and americium persistently bombard the surrounding tissue with alpha particles that induce mutations, which health physicists believe are guaranteed eventually to cause cancer.

This danger arises especially in MOX fuel production, when plutonium is in the form of an oxide that may be inhaled. Fuel-cycle facilities that process plutonium in metal form pose the additional risk of it catching fire and creating an aerosol that can be inhaled. To reduce the health risk to employees and surrounding communities, MOX plants employ costly hardware – including air purifiers, glove boxes, and automated equipment – and costly procedures such as lengthy shutdowns to clean up spills. These substantially raise the production costs for MOX fuel compared to LEU fuel – by a factor of three or more – even excluding the substantial expense of obtaining plutonium in the first place. Attempting to reduce such fabrication costs, operators have sometimes cut corners, which has backfired by increasing accidents, outages, scandals, and public protest – thereby reducing the output and raising the per-unit cost.

The biggest failure was the UK's British Nuclear Fuel Ltd (BNFL) Sellafield MOX Plant (SMP), which had a planned output of

120 metric tons of heavy metal per year (MTHM/yr). In practice, during its operation from 2001 to 2011, the facility produced a total of only 14 MTHM, an average of barely one MTHM/year, or about one percent of its intended output (see Chapter 4). The two principal causes of this profound failure arose from the safety risk of plutonium: unproven automated techniques to reduce worker exposure, and an unreasonably small facility footprint to reduce the costs of worker-protection measures. The consequences were failed equipment, expensive repairs, and prolonged suspensions of production. Although SMP's troubles could be attributed to experimental technologies and poor design, both of those choices arose from concerns over plutonium's health threat and the costs of mitigating it.

BNFL's preceding and much smaller commercial plant, the MOX Demonstration Facility, also ended in failure, although to a lesser extent. The plant's capacity was eight MTHM/yr. During operation from 1993 to 1999, it produced a total of 20 MTHM, for an average of over three MTHM/yr, or about 40 percent of capacity. However, the plant closed prematurely after revelations that workers had repeatedly falsified quality-control data, which led to an international scandal culminating in $100 million in penalties and the return of unirradiated MOX assemblies from Japan. It is unclear why BNFL failed persistently to monitor quality control, but one possibility is that, as with SMP, the company was attempting to offset the high costs of mitigating plutonium's health risks.

Germany's Alkem Hanau plant underperformed persistently and then closed prematurely in 1991 due to a radiation accident (see Chapter 6). The facility's potential output was 25 MTHM/yr, but from 1972 to 1991, its average annual production was eight MTHM, or about 30 percent of capacity. This shortfall stemmed partly from complications of plutonium's toxicity, including "repair work under difficult glove-box conditions" and "plutonium contamination in the fabrication areas that required time-consuming cleanup." Plutonium's weapons dangers also hindered production due to intrusive EURATOM safeguards inspections and domestic controversy over transport security. In 1991, a plant worker was contaminated by a glove-box accident, and public outrage led to permanent closure of the facility. Such controversy also blocked the opening of a nearly completed follow-on facility, Hanau 1, which was canceled in 1995.

Belgium's P0 plant, operated by Belgonucléaire in Dessel, was relatively successful but closed prematurely due to inefficiency, competition, and vanishing global demand for MOX (see Chapter 2). The plant had a capacity to produce 32 MTHM/yr of MOX fuel rods, which were then combined into fuel assemblies at a neighboring facility owned by FBFC. From 1973 to 2006, the P0 plant produced approximately 600 tonnes of MOX rods, an average of nearly 18 MTHM/yr, or 55 percent of capacity. However, costs were extremely high, mainly due to efforts to address plutonium's health threat. Eventually, P0 could not compete with France's more-efficient MELOX facility, especially as demand declined, so the Belgian plant closed for economic reasons rooted in the hazards and unpopularity of plutonium fuel. Meanwhile, a broken MOX rod at the adjacent FBFC facility in the mid-1990s compelled the shutdown of that facility's MOX and uranium operations, followed by a costly decontamination, and then the expensive construction of a new annex exclusively for MOX assemblies.

France has been more successful at production of thermal MOX, at two successive facilities, but they too have faced economic and safety challenges (see Chapter 3). Commercial production started in 1989, in Cadarache, at the ATPu plant, whose capacity increased gradually from 20 to 40 MTHM/yr of MOX fuel rods that later were combined into assemblies at plants in Belgium or France. In 1995, due to earthquake risk, French safety authorities ordered that the plant cease operations "shortly after 2000," and it did so in 2003. Dangers included that an earthquake could trigger a plutonium fire, criticality accident, or other release of radioactivity. Thus, the premature closure of this MOX plant too can be attributed at least partly to plutonium's safety and weapons risks.

The most successful thermal MOX production plant to date, and the only commercial facility still operating, is France's MELOX. The plant was designed with capacity up to 250 MTHM/yr, but it has never been authorized above 195 MTHM/yr, and in practice it has produced much less. Over the past four years, from 2014 to 2017, MELOX on average has produced under 125 MTHM/yr, or less than half of its original design capacity. Such depressed output stems

mainly from sharply decreased foreign demand (none from Germany since 2015, and only about 10 MTHM/yr combined from the Netherlands and Japan in recent years), while the domestic utility refuses to increase its use of MOX fuel due to high cost. In 2017, MELOX also reported some "technical production difficulties" that may explain a further reduction in output to 110 MTHM.

MOX Fuel in Thermal Reactors

All six countries that have commercially used MOX fuel in thermal reactors discovered that its price was many times that of traditional LEU fuel. The main cause was the increased cost of fuel manufacturing, due especially to plutonium's health threat but also other factors, including small batch size, the challenge of uniformly blending two oxides, and enhanced security for transport. The greatest cost impact was on the activities to fabricate fuel rods. According to an article by Belgian industry officials who led such efforts, "For MOX fuel, the cost of this group of activities is typically 15 to 25 times higher" than for LEU fuel.[4]

Another substantial expense was obtaining the key MOX ingredient, plutonium, by reprocessing spent LEU fuel,[5] but the cost impact on MOX fuel depended on accounting procedures. Typically, the industry considers reprocessing as part of waste management, so the resulting separated plutonium is viewed as a free good for fresh fuel production. In fact, in the nuclear-industry marketplace, plutonium actually has substantial *negative* value, so that owners must pay a high price for someone else to take it (see Chapter 8). Two factors explain this phenomenon: first, there is virtually no market demand for MOX fuel due in part to its high manufacturing cost; second, the alternative disposition pathway, disposal of unirradiated plutonium as waste, is also expensive because of the material's toxicity and security risk.[6] The other main input of MOX fuel is typically depleted uranium, which is abundant as a waste product of enriching uranium, and so has low price. Accordingly, the nuclear industry considers the heavy-metal inputs of MOX fuel to be essentially free, in contrast to those of LEU fuel – natural uranium and enrichment – that have substantial cost. If the high expense of obtaining plutonium via reprocessing is ignored in this manner, the price penalty is less egregious for MOX fuel than for MOX fabrication.

Nevertheless, everywhere it has been used, MOX fuel has proved much more expensive than LEU fuel. Japanese utilities in recent years have paid at least nine times as much for imported MOX fuel as equivalent LEU fuel, according to press reports.[7] If Japan proceeds with its planned domestic fuel-cycle facilities, thermal MOX fuel would cost even more, 12 times as much as LEU fuel, according to the Japan Atomic Energy Commission.[8] In Belgium, a 1998 industry study found that MOX fuel cost at least five times as much to produce as LEU fuel, even ignoring the expense of material inputs for MOX while including them for LEU.[9] In Germany, the cost to produce MOX fuel was three to five times that of LEU fuel, according to experts from government, industry, and civil society.[10] In the Netherlands, a 2010 utility licensing submission to initiate commercial use of MOX fuel portrayed its fabrication cost as five times that of LEU.[11] In the UK, the Department of Energy estimated in 1979 that fabrication costs of thermal-reactor fuel were four times higher for MOX than for uranium.[12] In Switzerland, utilities historically paid about six times as much (inflation-adjusted) for MOX fuel as the current price of LEU fuel.[13]

In France, despite economies of scale, MOX fuel costs four to five times as much to fabricate as LEU fuel, according to industry and other interviewees,[14] due in part to the MELOX plant operating well below capacity.[15] A French government report, in 2000, indicated that the total cost of producing MOX fuel, including obtaining plutonium via reprocessing, was 4.8 times that of LEU fuel.[16] This penalty likely has increased in recent years, as throughput declined at both the reprocessing and MOX fabrication facilities, thereby raising the per-unit production cost.

MOX proponents downplay such extra expense as marginal to the total cost of producing nuclear energy, which is dominated by construction of the power plant.[17] Prior to completing amortization of such construction, the front-end expense of LEU fuel is estimated to be only five to ten percent of total energy-production costs. When MOX fuel is introduced, it typically substitutes for LEU in about one-third of the core. If the price of MOX fuel is five times that of LEU fuel, then introducing MOX increases front-end fuel expenses by 133 percent but total costs by only 7 to 13 percent. In addition, such costs historically were passed along by regulators to ratepayers, so that utilities suffered little if at all.

However, the extra expense of MOX fuel becomes much more significant after completing amortization of power-plant construction, especially in light of deregulation of modern electricity markets. When a plant is fully amortized, the expense of an LEU-fueled core may rise to about 30 percent of total costs. If MOX is then substituted in one-third of the core and has a price five times that of LEU, the total cost of producing energy rises dramatically – by 40 percent. In a deregulated market, consumers have options and thus cannot be compelled to pay such increased costs, so the power companies face reduced profits or even losses. The widespread abandonment of recycling plutonium in thermal MOX has coincided with the full amortization of older power plants and the deregulation of electricity markets.

Utilities that initiated MOX fuel perceived little alternative at the time. Yet, they harbored concerns about MOX, including cost, safety, operational challenges, regulatory approval, and disposal of spent MOX that emits much more heat and radioactivity than spent LEU in the long run. When utilities initially made such decisions in the 1970s, their countries typically lacked legal or logistical provisions for interim storage of spent fuel, so reprocessing was viewed as the only way to avoid the risk of premature shutdown of their reactors. After the plutonium was separated by reprocessing, the utilities viewed its recycle in MOX as the only feasible disposition pathway. Thus, many nuclear utilities were compelled to initiate MOX fuel despite their misgivings.

More Controversial than Nuclear Energy

The decline of MOX is not merely an economic phenomenon, nor ancillary to a broader global retreat from nuclear power. Recycling spent fuel has repeatedly proved less popular than traditional, once-through use of uranium fuel, due to plutonium's safety and weapons threats. In Germany, anti-nuclear protests escalated in the 1990s, when they started focusing on the environmental and proliferation risks of international shipments for plutonium recycling – especially exports of spent fuel for reprocessing, and imports of high-level waste. Popular outrage spurred a 2002 German law that prohibited the export of spent fuel for reprocessing after 2005, and mandated the phase-out of nuclear energy by 2021 (see Chapter 6). Ironically, the recycling of plutonium, originally conceived as necessary to sustain nuclear power, instead helped to undermine it.

In Japan too, plutonium recycling has proved more controversial than nuclear energy, *per se*, for both domestic and international audiences due to health and security concerns (see Chapter 5). In 1999, Japanese anti-nuclear NGOs successfully persuaded the government, based on safety issues, to reject and return MOX fuel that had been imported for the Takahama-4 reactor, yet they could not shutter the power plant at the time or prevent its restart after the 2011 Fukushima disaster. In 2001, again mainly on safety grounds, Japanese voters blocked the use of MOX fuel in the Kashiwazaki-Kariwa-3 reactor, despite permitting the plant to continue operating with LEU fuel. Also in 2001, a governor withdrew consent for MOX use at the Fukushima power plant due to safety concerns. These three popular revolts against plutonium recycling had the effect of delaying by a decade the start of commercial MOX use in Japan, which exacerbated Japan's plutonium stockpile that now exceeds 47 tonnes. Neighboring countries, including China, South Korea, and North Korea, have expressed strong security concerns about this plutonium accumulation, which is sufficient for more than 5,000 nuclear weapons.[18] Thus, Japan's pursuit of MOX has caused both domestic and international troubles for its nuclear energy program.

In other countries as well, recycling plutonium has proved more controversial than traditional nuclear energy. In Switzerland, a 2003 referendum imposed a moratorium on exports of spent fuel for reprocessing, effective in 2006, yet Swiss voters repeatedly opposed the shutdown of nuclear reactors – until Japan's Fukushima disaster spurred a 2017 vote that phases out nuclear energy by around 2050 (see Chapter 7). In Belgium, in the 1990s, NGO's focused their anti-nuclear campaigns on plutonium's proliferation, terrorism, and environmental risks. These efforts compelled the Belgian government in 1993 to initiate a moratorium

on new reprocessing contracts and to begin reassessing MOX fuel, culminating in the 1998 termination of the last existing reprocessing contract (see Chapter 2). Belgium's Vice-Prime Minister explained in 1998 that, based on the "information we have concerning economic and ecological aspects, there is no justification to use another time the reprocessing technology."[19] This was several years before the government, in 2003, decided to phase out nuclear power entirely, with a target date of 2025.

Only in two countries, France and the Netherlands, has the recycling of plutonium in thermal reactors proceeded without, so far, provoking decisive public opposition. In France, a strong industry-government alliance has fended off Greenpeace and Green Party efforts to highlight the environmental risks of reprocessing and the security risks of plutonium transport (see Chapter 3).[20] In the Netherlands, the sole power reactor and the waste facility are both in the country's southwest along the border with Belgium, which is the transport route to and from the French reprocessing and MOX plants, so few Dutch residents are affected by imports and exports for plutonium recycling. The Dutch nuclear utility also signed a single contract for the entire 13 years of planned MOX use, which deprived domestic anti-nuclear NGOs and politicians of the opportunity to mobilize public opposition to a potential contract renewal, as had proved effective in other countries. The experiences of France and the Netherlands suggest that plutonium recycling is more likely to succeed politically if backed by powerful domestic interests or circumscribed to avoid public scrutiny.

Security Risks

This book also raises serious concerns about the adequacy of physical security for fresh MOX fuel containing plutonium that could be used to make nuclear weapons. Although some security procedures at power plants are secret, our case studies indicate that physical protection at reactors is not significantly bolstered when MOX fuel is introduced. Utilities do try to minimize the storage time of fresh MOX by loading it into the reactor soon after delivery, unlike fresh LEU that may be kept as reserve in case of fuel-supply interruption. Reactor operators also modify worker-safety procedures to address plutonium's higher radioactivity. In addition, they comply with international safeguards requirements for more frequent monitoring and inspection of fresh MOX, compared to fresh or spent LEU, to address potential state-level diversion. Some operators also say that, because fresh MOX fuel contains plutonium, they guard it more rigorously than fresh LEU and in the same manner as spent LEU fuel, which also contains plutonium.

None of these measures adequately addresses the threats from terrorists or criminals. Fresh MOX poses a much greater sub-national security risk than spent LEU because it lacks high radioactivity that could deter theft and processing to obtain the plutonium for weapons. Reactor operators and government officials appear to believe that the large mass of a fresh MOX fuel assembly (hundreds of kilograms) and its storage in a reactor pool or vault are sufficient to prevent theft. They do not appear to guard this unirradiated plutonium as nuclear weapons-usable material, which it indisputably is. In the event of a concerted terrorist attack, that could prove disastrous.

Additional security is applied to ground transports of fresh MOX fuel, which often traverse hundreds of miles. However, such measures typically are limited to use of an armored shipping truck, escorted by a few national police vehicles in radio communication to a central command. If attacked by terrorists armed with the types of weapons that they have used in the past – including shaped charges, armor-piercing ammunition, and rocket-propelled grenades – such a shipment might be susceptible to breach and theft. This vulnerability is exacerbated by the transport vehicles using routine and predictable routes, which include bottlenecks and stops that present ideal opportunities for attack.[21] A single MOX fuel assembly for a pressurized water reactor usually contains more than 30 kg of plutonium, sufficient for at least three nuclear weapons. Moreover, each MOX shipment may include a dozen or more of these assemblies to reload the reactor, and such transports occur weekly in France. Another vulnerability, until the recent development of integrated facilities, was the transport of MOX rods to other plants that combined them into fuel assemblies (see Chapters 2 and 3).

Even more dangerous in France are shipments of separated plutonium oxide from the reprocessing plant to the MOX

fabrication facility – each containing up to 250 kg of plutonium, sufficient for at least two-dozen nuclear weapons.[22] These shipments occur twice weekly, traveling over 600 miles. Security also has been called into question at the French reprocessing and MOX plants, which each contain tonnes of separated plutonium, sufficient for hundreds or thousands of nuclear weapons. The managing director of the fuel-cycle firm, Orano, testified in 2018 that doubling the company's spending on security would add only about 0.2 percent to the French price of electricity.[23] In light of the enormous potential consequences of terrorist theft of weapons-usable plutonium, such an increased security investment would appear prudent.

Remarkably, some foreign government and industry officials still claim that reactor-grade plutonium cannot be used to make nuclear weapons, despite this myth having been punctured for decades. Japan's former ambassador to the UN Conference on Disarmament, Ryukichi Imai, declared in 1993 that, "reactor grade plutonium . . . is quite unfit to make a bomb."[24] Belgian officials have expressed similar sentiments (see Chapter 2). In France, an October 2017 government report claimed that, "Using plutonium in MOX fuel enables . . . significantly degrading the isotopic composition of the remaining plutonium, so this technology is non-proliferating."[25]

Such claims appear to confuse LWRs – which rely on fission by thermal neutrons so that only certain isotopes of plutonium can sustain a chain-reaction – with nuclear weapons, which rely on fast neutrons so that all plutonium isotopes can sustain a chain-reaction. Reactor-grade plutonium of any isotopic composition can be used to make reliable nuclear weapons, as documented repeatedly by government and independent experts.[26] The critical mass of such plutonium remains small; additional heat can be conducted away or dealt with by delaying insertion of the pit or using a levitated core or heat-resistant explosive for implosion; and pre-initiation can be addressed by faster assembly or addition of tritium. Swiss interviewees, to their credit, implicitly acknowledged this risk from reactor-grade plutonium by revealing that their government and military supported the recycling of spent fuel in part to help establish a nuclear-weapons option (see Chapter 7).

Lessons for East Asia and Beyond

This book provides lessons for at least three groups of states. First are the two countries planning to continue long-term commercial use of MOX fuel in thermal reactors: France and Japan. Second are three countries contemplating the start of large-scale use of MOX fuel in thermal reactors: China, the UK, and the United States (in the last case to dispose of plutonium originally produced for nuclear weapons). Third are other countries – including India, South Korea, Russia, and China – pursuing the recycling of spent fuel with alternative technologies such as fast reactors and pyroprocessing that may pose similar concerns from plutonium's toxicity, weapons capability, and associated expense.

The first lesson is that recycling spent nuclear fuel for energy is extremely expensive due to the high costs of addressing plutonium's safety and health threats at fuel-cycle facilities. Second, the ostensible benefits of recycling plutonium – energy security and waste management – are too marginal, at best, to compensate for such enormous costs. This applies not only to MOX in thermal reactors but also to alternative technologies, including fast reactors, based on recent authoritative studies.[27] Third, the security measures applied to recycling of spent fuel are inadequate in the face of several concerns: the nuclear-weapons capability of reactor-grade plutonium, the stated objective of some terrorist groups to acquire and use nuclear weapons, and the demonstrated ability of such groups to stage sophisticated attacks as on 9/11. Fourth, recycling spent fuel is unnecessary for sustained and efficient production of nuclear energy, considering the world's plentiful supplies of uranium and enrichment. Accordingly, there is no justification for incurring the substantial economic, security, and safety risks of plutonium recycling. Fifth, countries that continue to pursue plutonium fuel, despite its high cost and lack of compensating benefits, may be suspected by other countries of having ulterior motives, which could undermine international peace and security.

These lessons give rise to recommendations for each of the three groups of states specified above. The two countries planning to continue the uneconomical and risky use of thermal MOX, France and Japan, should instead phase it out as quickly as their domestic politics will permit. France has powerful and entrenched pro-plutonium interests in government and industry. Yet, the national utility realizes that recycling plutonium raises the cost of electricity, which explains why it has not increased use of MOX fuel despite domestic surpluses in the four requirements: separated plutonium, reprocessing capacity, MOX fabrication capacity, and reactor capacity to use MOX. Even if safety and security concerns do not compel France to reevaluate its MOX program, the economic penalty likely will eventually do so.

Japan's pro-plutonium lobby is not quite as formidable because the country does not yet operate commercial reprocessing and MOX fabrication facilities. Instead, the strongest pressure for recycling may come from local communities – adjacent to reactors and the incomplete reprocessing and MOX plants – who fear being stuck with spent nuclear fuel. To address this concern, Japan's government should invest in expanding dry-cask storage of spent fuel, while explaining the safety and reliability of this technology to such communities and compensating them for serving as temporary waste-storage sites prior to completion of a geological repository. The government also should use part of its sizeable reprocessing fund – which holds contributions from utilities to manage nuclear waste – to pay the UK to take title to the 22 tonnes of its plutonium in that country, thereby cutting Japan's stockpile nearly in half. Since most of Japan's domestic plutonium is in forms that cannot currently be used in its reactors, the government instead should dispose of that material as waste, in cooperation with the United States, which has a similar disposal program.[28] The rest of Japan's plutonium – two tonnes at home and 15.5 tonnes in France – should be dispositioned relatively quickly as a combination of MOX and waste, which could enable Japan to eliminate its plutonium stockpile in as little as five years.[29]

The three countries contemplating the start of large-scale MOX use in thermal reactors – China, the UK, and the United States – should instead concede that this option is uneconomical and unnecessary. The U.S. government appears to have reached such a decision, after wasting billions of dollars on partial construction of a MOX fabrication plant that soared in cost, and now plans instead to dispose of surplus weapons plutonium as waste.[30] The UK has reprocessed its spent fuel for more than half a century, but for economic and other reasons has never commercially recycled the resulting plutonium in reactors (see Chapter 4). The result is a domestically owned UK stockpile of 110 tonnes of separated civil plutonium, which dwarfs the 3.2 tonnes of plutonium in the country's nuclear weapons. Officially, the government's preferred option for this civil plutonium remains to recycle it in MOX fuel, despite the domestic absence of either a MOX fabrication facility or reactors licensed to use MOX. The UK should end this fiction and instead dispose of its plutonium as waste.[31] China is in the best position of the three countries, because it has yet to create a surplus of separated plutonium, but it is now negotiating with Orano about construction in China of both reprocessing and MOX fabrication plants. Although China has successfully mimicked western industrialization, doing so in this case would be ill-advised, given that thermal MOX has proved a costly and dangerous blunder in the west.

Finally, other countries such as India, South Korea, Russia, and China are pursuing the recycling of plutonium for energy using alternative technologies. In theory, fast reactors can consume more plutonium and other actinides in their fuel, thereby reducing the long-term heat and radioactivity of high-level waste. Pyroprocessing can avoid separating pure plutonium and thus – compared to traditional reprocessing – may reduce somewhat the nuclear-terrorism risk of a closed fuel cycle. However, scholars have demonstrated that these purported benefits are highly exaggerated.[32] Such technologies cannot overcome plutonium's three fundamental risks that have bedeviled previous efforts to recycle spent fuel: safety, weapons, and cost. Accordingly, as these countries pursue their alternative technologies, they would be well advised to examine the international experience with thermal MOX to understand why it failed. In so doing, they might realize that their proposed approaches to recycling plutonium for energy would face similar challenges, in addition to the hurdle of commercializing fast reactors that have failed both technically and economically almost everywhere that they have been tried.[33]

The reprocessing of spent nuclear fuel to extract plutonium is an excellent way to produce nuclear weapons. However, the history detailed in this book demonstrates that it is an inefficient, dangerous, and unnecessary way to produce electricity. Unless and until there are major improvements in the safety, security, and economics of spent fuel recycling, the answer to the question posed by this book – "Plutonium for Energy?" – will remain a resounding no.

Endnotes

[1] Informative articles and papers do exist on individual national programs, and they are cited in this book's case chapters. There are also at least two brief comparative national studies: Per Högselius, "Spent nuclear fuel policies in historical perspective: An international comparison," *Energy Policy* 37, 1 (2009): 254-263, and D. Haas and D. J. Hamilton, "Fuel cycle strategies and plutonium management in Europe," *Progress in Nuclear Energy* 49, 8 (2007): 574-582. A Japanese NGO in the 1990s assessed the safety, security, and economics of MOX, but not in a comparative national framework. See, Jinzaburo Takagi, et al., *Comprehensive social impact assessment of MOX use in light water reactors* (Tokyo: Citizens' Nuclear Information Center, 1997), http://www.cnic.jp/english/publications/pdffiles/ima_fin_e.pdf. A shorter critique from that era is Frank Barnaby, "How Not to Reduce Plutonium Stocks: The Danger of MOX-fuelled Nuclear Reactors," Corner House Briefing 17, December 30, 1999, http://www.thecornerhouse.org.uk/resource/how-not-reduce-plutonium-stocks.

[2] Thomas B. Cochran, et al., *Fast Breeder Reactor Programs: History and Status* (International Panel on Fissile Materials, 2010).

[3] J. Samuel Walker, "Nuclear Power and Nonproliferation: The Controversy over Nuclear Exports, 1974–1980," *Diplomatic History* 25, 2 (2001): 215-249. This U.S. policy was a reaction to India's 1974 "peaceful nuclear explosion," which demonstrated that plutonium separated from ostensibly peaceful spent fuel could be used to make a nuclear weapon. The policy employed coercive leverage by threatening to withhold permission for reprocessing of spent fuel that was subject to U.S. consent rights, as it originated in the United States or was irradiated in reactors based on U.S. technology.

[4] A. Vielvoye and H. Bairiot, "Economic optimization of MOX fuel," *Nuclear Europe Worldscan*, 11, 1/2 (1991): 13. For MOX fuel, these activities incur the vast majority of fabrication costs. By contrast, for LEU fuel, such activities incur only about 20 percent of fabrication costs, which also include hardware for rods and assemblies, conversion of UF6 to UO2, engineering and economic provisions, and transports to and from the plant. Fabrication costs do not include heavy-metal inputs.

[5] *Plutonium Separation in Nuclear Power Programs: Status, Problems, and Prospects of Civilian Reprocessing Around the World* (International Panel on Fissile Materials, 2015).

[6] In 2018, the proposed U.S. "dilute and dispose" plan was estimated to cost about $500,000 per kilogram of plutonium. Although quite expensive, that is less than one-third the estimated cost of disposition via MOX fuel, which is more than $1,600,000 per kilogram of plutonium. U.S. Department of Energy, "Surplus Plutonium Disposition Dilute and Dispose Option Independent Cost Estimate (ICE) Report," April 2018, https://s3.amazonaws.com/ucs-documents/global-security/dilute-and-dispose-independent-cost-estimate-4-18.pdf. In Europe, the negative market price for plutonium is tens of thousands of dollars per kilogram (see Chapter 8).

[7] See Chapter 5. "MOX imports have cost at least ¥99.4 billion, much higher than uranium fuel," *Energy Monitor Worldwide*, February 23, 2015.

[8] Atomic Energy Commission Bureau, "Estimation of Nuclear Fuel Cycle Cost," November 10, 2011, http://www.aec.go.jp/jicst/NC/about/kettei/seimei/111110_1_e.pdf.

[9] See Chapter 2. Belgonucléaire, "Comparison of MOX & U Fuel Assembly Costs," 1998, 3.

[10] See Chapter 6. Jurgen Krellmann, interview with Kelli Kennedy, Marseilles, France, January 4, 2018. Dr. Christoph Pistner, interview with Kelli Kennedy, Darmstadt, Germany, January 10, 2018. Dr. Klaus Janberg, interview with Kelli Kennedy, Dusseldorf, Germany, January 6, 2018. Wolfgang Heni, Interview with Kelli Kennedy, Darmstadt, Germany, January 12, 2018. Wolfgang Heni, "Physical, Technological, Ecological, and Economic Aspects for The Optimization of the Nuclear Fuel Cycle," Peter the Great St. Petersburg Polytechnic University, 1994.

[11] See Chapter 8. EPZ, "Milieueffectrapportage Brandstofdiversificatie," July 2010, Figure 2.9.1.

[12] Peter Jones, *The Economics of Nuclear Power Programs in the United Kingdom* (New York: St. Martin's Press, 1984): 55.

[13] See Chapter 7. Former nuclear operator employee who requests anonymity, interview with Harry Kim, January 10, 2018. As a result, Swiss utilities contracted for their plutonium to be blended with depleted rather than natural uranium, to minimize the amount of MOX fuel fabrication that they would have to purchase. H. Bay and R. Stratton, "Use of Mixed Oxide Fuel in a Pressurized Water Reactor Experience of NOK, Switzerland," International Topical Meeting on Safety of Operating Reactors, American Nuclear Society, San Francisco, CA, 1998, 293.

[14] See Chapter 3.

[15] Vielvoye and Bairiot, "Economic optimization of MOX fuel," 15, observes that, "MOX fuel fabrication plants must operate at or near nominal capacity to maintain reasonable manufacturing costs."

[16] *Plutonium Separation in Nuclear Power Programs*, 138 (footnote 16), www.fissilematerials.org/library/cha00.pdf, which analyzes Jean-Michel Charpin, Benjamin Dessus, and René Pellat, "Economic forecast study of

the nuclear power option," Report to the Prime Minister, July 2000, Appendix 1.

[17] Estimated as about three-quarters of the total cost. See, "The Future of the Nuclear Fuel Cycle," MIT, April 2011, 21.

[18] Yukio Tajima, "Japan's 'plutonium exception' under fire as nuclear pact extended; Beijing and Seoul question why US allows only Tokyo to reprocess," *NIKKEI Asian Review*, July 14, 2018, https://asia.nikkei.com/Politics/International-Relations/Japan-s-plutonium-exception-under-fire-as-nuclear-pact-extended. Lee Min-hyung, "NK slams Japan's plutonium stockpiling," *The Korea Times*, August 5, 2018, https://www.koreatimes.co.kr/www/nation/2018/08/356_253381.html.

[19] WISE-Paris, "Belgium: Scheduled End to Reprocessing and to MOX Use," January 21, 1999, http://www.wise-paris.org/index.html?/english/ournews/year_1999/ournews0000990121.html. He also cited nuclear proliferation concerns as a primary rationale, according to Jan Vande Putte, interview with Valentina Bonello, January 12, 2018.

[20] *Sécurité nucléaire: le grand mensonge*, film documentary, directed by Éric Guéret, *ARTE*, 2017.

[21] *Sécurité nucléaire: le grand mensonge.*

[22] Each shipment contains up to 280 kg of plutonium oxide (see chapter 3).

[23] "Audition de M. Philippe Knoche, directeur général d'Orano (ex-Areva)," Commission d'enquête sur la sûreté et la sécurité des installations nucléaires, March 8, 2018.

[24] Nuclear Control Institute, "The Plutonium Threat," http://www.nci.org/new/nci-plu.htm.

[25] Republic of France, "Sixième rapport national sur la mise en œuvre des obligations de la Convention commune," October 2017, 36, which states, "l'utilisation du plutonium dans les combustibles MOX permettant de consommer environ un tiers du plutonium, tout en dégradant significativement la composition isotopique du plutonium restant, fait que cette technologie n'est pas proliférante."

[26] Gregory S. Jones, *Reactor-Grade Plutonium and Nuclear Weapons* (Arlington, VA: Nonproliferation Policy Education Center, 2018). Bruce T. Goodwin, "Reactor Plutonium Utility in Nuclear Explosives," Lawrence Livermore National Laboratory, November 6, 2015. Past skeptics had highlighted the potential difficulties of making a reliable nuclear weapon from plutonium separated from spent MOX fuel; see Bruno Pellaud, "Proliferation aspects of plutonium recycling," *C. R. Physique* 3 (2002): 1067–1079. Only about one percent of the world's civil separated plutonium was derived from spent MOX.

[27] National Research Council, *Nuclear Wastes: Technologies for Separations and Transmutation* (National Academy Press, 1996): 3. Lindsay Krall and Allison Macfarlane, "Burning waste or playing with fire? Waste management considerations for non-traditional reactors," *Bulletin of the Atomic Scientists* 74, 5 (2018): 326-334.

[28] Frank von Hippel and Gordon MacKerron, *Alternatives to MOX: Direct-disposal options for stockpiles of separated plutonium* (International Panel on Fissile Materials, 2015). The two countries already have a bilateral mechanism that could promote such technical cooperation, known as the U.S.-Japan Plutonium Management Experts Group. See, U.S. National Nuclear Security Administration, "Prevent, Counter, and Respond – A Strategic Plan to Reduce Global Nuclear Threats, FY 2017 – FY 2021," Report to Congress, March 2016, 2-4.

[29] Alan J. Kuperman and Hina Acharya, "Japan's Misguided Plutonium Policy," *Arms Control Today* (October 2018): 16-22, https://www.armscontrol.org/act/2018-10/features/japan's-misguided-plutonium-policy. Alan J. Kuperman, "How not to reduce Japan's plutonium stockpile," *Kyodo News*, op-ed, July 13, 2018, https://english.kyodonews.net/news/2018/07/f91d38319475-refiling-opinion-how-not-to-reduce-japans-plutonium-stockpile.html.

[30] Timothy Gardner, "Trump administration axes project to generate power from plutonium," *Reuters*, May 13, 2018.

[31] von Hippel and MacKerron, *Alternatives to MOX*. Such disposal could be facilitated by international technical cooperation under an existing multilateral initiative that includes the UK, France, Japan, and the United States, known as the International Plutonium Management Roundtable. See, U.S. Department of Energy, "Departmental Response: Assessment of the Report of the SEAB Task Force on Nuclear Nonproliferation," October 2015, 12-13.

[32] National Research Council, *Nuclear Wastes.* Krall and Macfarlane, "Burning waste or playing with fire?" James M. Acton, "The myth of proliferation-resistant technology," *Bulletin of the Atomic Scientists* 65, 6 (November/December 2009): 49-59. Edwin S. Lyman, "The Limits of Technical Fixes," in *Nuclear Power & the Spread of Nuclear Weapons*, eds. Paul Leventhal, et al. (Dulles, VA: Brassey's Inc., 2002): 167-184.

[33] The exception is Russia, although its most successful fast reactor, the BN-600, still suffered 14 sodium fires at its steam generator from 1980 to 1997. See Thomas B. Cochran, et al., "It's Time to Give Up on Breeder Reactors," *Bulletin of the Atomic Scientists* 66, 3 (2010): 50-56.