Challenges of plutonium fuel fabrication: explaining the decline of spent fuel recycling

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Abstract: This article presents key findings of the first comprehensive global study of the commercial use of plutonium as fuel for nuclear energy. Research was conducted in all seven countries that have engaged in the commercial production or use of plutonium Mixed-Oxide (MOX) fuel to replace traditional uranium fuel in thermal nuclear power plants: Belgium, France, Germany, Japan, the Netherlands, Switzerland, and the UK. Five of the seven countries already have decided to phase out commercial MOX activities. The price of thermal MOX fuel has proved to be three to nine times higher than traditional uranium fuel. Plutonium fuel also has sparked political controversy, due to safety and proliferation concerns, in four of the six countries where it has been used commercially. The article concludes with lessons for countries that are engaged in, or contemplating, the recycling of plutonium for nuclear energy, including in fast reactors.

Keywords: plutonium; fuel; nuclear; MOX; mixed oxide; reprocessing; reactor; energy; economics; proliferation.

Reference to this paper should be made as follows: Kuperman, A.J. (2019) 'Challenges of plutonium fuel fabrication: explaining the decline of spent fuel recycling', *Int. J. Nuclear Governance, Economy and Ecology*, Vol. 4, No. 4, pp.302–316.

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1 Introduction

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 often proved controversial. This is because plutonium has three big downsides compared to the uranium traditionally used to make nuclear fuel: it is much more likely to cause cancer if inhaled, 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 UK – have engaged in the commercial recycling of plutonium for energy in traditional, thermal nuclear power plants, which rely mainly on 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, and South Korea – are exploring new domestic facilities to recycle plutonium for energy using thermal or fast reactors. In light of the 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, although there have been succinct comparative overviews (Högselius, 2009; Haas and Hamilton, 2007), critiques of MOX (Takagi et al., 1997; Barnaby, 1999), and informative articles and papers on individual national programs, often published by the IAEA, which informed our research.

This article summarises the first comprehensive study of all seven countries that have engaged in the commercial recycling of plutonium for energy in thermal reactors, drawing on field research in each (Kuperman, 2018a). 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 UK.

A major finding of the 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 (see 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, as its sole nuclear power reactor will be closing. 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 (Kuperman, 2018b).

To assess the causes of the overall decline, and the variation in national outcomes, our research project examined 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 Organisations (NGOs) – who provided oral and documentary evidence. We also solicited additional expert feedback on our draft findings.

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

Note: This table covers only past and present activities. The explanations for each country are in the text. Potential initiation of future activities by these or other countries is speculative and not reported in this table.

2 Misperceived necessity

The idea of recycling plutonium for energy took hold in the 1960s based on two assumptions that later proved erroneous: 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 sustain a chain reaction in thermal reactors because it is not fissile – into an energy-producing fissile isotope of plutonium (Pu-239). Since over 99% of uranium is the non-fissile isotope U-238, 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 rely mainly on unmoderated fast (high-energy) neutrons, in contrast to traditional Light-Water Reactors (LWRs) that rely mainly on moderated 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 commercialisation 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, mainly in France, the UK, Japan and Russia (Cochran et al., 2010a).

By this century, most of the world's FBR development programs had failed. Nuclear utilities realised that if they reprocessed their spent fuel, the only way to recycle plutonium commercially would be in MOX fuel for LWRs, which most of them chose not to do. Of the more than 30 countries that have produced commercial nuclear power, utilities in only six have used MOX fuel commercially in thermal reactors. In most of the other countries, utilities decided instead to pursue disposal of their spent fuel as waste, especially after it became clear in the 1970s that global uranium resources were much larger, and the demand for nuclear energy much smaller, than previously anticipated. Starting in 1976, the USA also discouraged worldwide reprocessing of spent fuel, due to concerns that the separation of plutonium would increase risks of nuclear proliferation and nuclear terrorism (Walker, 2001). Nevertheless, the seven countries examined in this article initiated commercialisation of thermal MOX fuel production and/or use.

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 LEU fuel, which necessitated two different refuelling 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 (Takagi et al., 1997; Barnaby, 1999). 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 – radiotoxicity, proliferation, and economics – which have inhibited both the manufacture and use of such fuel.

3 Manufacturing thermal MOX fuel

As detailed below, five of the six fabrication facilities for thermal MOX fuel that ever operated commercially have closed prematurely, and most of them underperformed while they were open. A seventh facility (in Germany) was cancelled after construction, and an eighth (in Japan) is stalled at the early stages of construction. The main underlying cause of this poor track-record is that plutonium is far more hazardous than uranium, leading to high costs and public opposition. Plutonium mostly comprises isotopes that are relatively long-lived but emit significant levels of alpha radiation. One isotope of plutonium, Pu-241, is not an alpha emitter and decays relatively quickly – but into americium-241, which is an especially 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, plutonium and americium isotopes persistently bombard the surrounding tissue with alpha particles that induce mutations, so that at a sufficient dose they are almost guaranteed to cause cancer, as demonstrated in laboratory studies (Oghiso, et al., 1998).

This danger arises especially during MOX fuel production, when plutonium is in the form of an oxide that may 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. As detailed below, 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 may backfire by increasing accidents, outages, scandals, and public protest – thereby reducing the output, which raises 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 tonnes 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 1% of its intended output. 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 (Mann, 2018).

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 about three MTHM/yr or 40% 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 (Mann, 2018). It is uncertain why BNFL failed persistently to monitor quality control at this plant, which had paid high costs to address plutonium's health risks.

Germany's Alkem Hanau plant underperformed persistently and then closed prematurely in 1991 due to a radiation accident. The facility's potential output was 25 MTHM/yr, but from 1972 to 1991, its average annual production was eight MTHM, or about 30% of capacity. This shortfall stemmed partly from complications of plutonium's radiotoxicity, including "repair work under difficult glove-box conditions" and "plutonium contamination in the fabrication areas that required time-consuming cleanup," according to a senior facility official at the time. He reports that production also was hindered by intrusive EURATOM safeguards inspections and domestic controversy over transport security, both arising from plutonium's proliferation concerns. In 1991, a plant worker was contaminated by a glove-box accident, and public outrage led to permanent closure of the facility. Related controversy also blocked the opening of a nearly completed follow-on facility, Hanau 1, which was cancelled in 1995 (Kennedy, 2018).

Belgium's P0 plant, operated by Belgonucléaire in Dessel, closed prematurely due to inefficiency, competition, and vanishing global demand for MOX. The plant had a capacity to produce 32 MTHM/yr of MOX fuel rods, which were then combined into fuel assemblies at a neighbouring 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% of capacity. However, costs were extremely high, due mainly to efforts to address plutonium's health threat (Bonello, 2018). 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 safety hazards of plutonium and reduced global use of MOX 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 (Bonello, 2018).

France has been more successful at production of thermal MOX, at two successive facilities, but they too have faced economic and safety challenges. France's commercial production of MOX 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 (Burns, 2018). Concerns included that an earthquake could trigger a plutonium fire, criticality accident, or other release of radioactivity.

The most successful thermal MOX production plant to date, and the only commercial facility still operating, is France's MELOX. The plant has a nominal capacity up to 250 MTHM/yr, but it has never been authorised above 195 MTHM/yr, and in practice it has produced much less. From 2014 to 2017, MELOX produced on average under 125 MTHM/yr, or less than half its nominal 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 France's domestic utility has not significantly increased its use of MOX fuel, possibly due to high cost. In 2017, MELOX also reported some "technical production difficulties" that may explain a further reduction in annual output to 110 MTHM (Burns, 2018).

4 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 (Kuperman, 2018b). The greatest cost impact initially 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 (Vielvoye and Bairiot, 1991). These activities account for the vast majority of fabrication costs of MOX fuel. By contrast, for LEU fuel, such activities account for only about 20% of fabrication costs, which also include hardware for rods and assemblies, conversion of UF_6 to UO_2, engineering and economic provisions, and transports to and from the plant. (The fabrication costs do not include the inputs of heavy metal, which are uranium and/or plutonium.)

Another substantial expense is obtaining the key MOX ingredient, plutonium, by reprocessing spent LEU fuel, but the resulting impact on the cost of MOX fuel depends on accounting procedures (IPFM, 2015). Reprocessing typically is counted as part of waste management, so the resulting separated plutonium is viewed as a free good for the subsequent production of fresh MOX fuel. Indeed, in the nuclear-industry marketplace, plutonium today actually has substantial *negative* value, so that owners must pay a high price for someone else to take it (Kuperman, 2018c). 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 radiotoxicity and security risk (U.S. Department of Energy, 2018). The other main input of MOX fuel often is depleted uranium, which is abundant as a by-product of enriching uranium and so has a low price. Thus, 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, both in terms of production cost and purchase price. 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 (Energy Monitor Worldwide, 2015). If Japan proceeds with its planned domestic plutonium fuel-cycle facilities, thermal MOX fuel would cost even more, 12 times as much as LEU fuel, according to the Japan Atomic Energy Commission (Atomic Energy Commission Bureau, 2011). 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 (Belgonucléaire, 1998). 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 (Kennedy, 2018). 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 (EPZ, 2010). 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 (Jones, 1984). In Switzerland, utilities historically paid about six times as much (inflation-adjusted) for MOX fuel as the current price of LEU fuel (Kim and Kuperman, 2018). As a result, Swiss utilities contracted for their plutonium to be blended with depleted rather than natural uranium, to minimise the amount of MOX fuel fabrication that they would have to purchase (Bay and Stratton, 1998).

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, due in part to the MELOX plant operating well below capacity (Burns, 2018). 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 (IPFM, 2015; Charpin et al., 2000). This penalty may have increased in recent years, because throughput has declined at both the reprocessing and MOX fabrication facilities, tending to increase the per-unit production costs of separated plutonium and MOX fuel, but the current penalty would also depend on various other input and production costs for LEU and MOX fuels.

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 (MIT, 2011). Prior to completing amortisation of such construction, the front-end expense of LEU fuel is estimated to be only 5 to 10% of total electricity 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% but total costs by only 7 to 13%. In addition, such costs historically had been 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 amortisation of power-plant construction, especially in light of deregulation of modern electricity markets. When a plant is fully amortised, the expense of an LEU-fuelled core may rise to about 30% of total electricity production 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%. In a deregulated market, consumers have options and thus cannot be compelled to pay such an increase in the price of electricity, so the power companies face reduced profits or even losses. The global decline of recycling plutonium in thermal MOX has coincided with the full amortisation of older power plants and the deregulation of electricity markets.

Some utilities that initiated MOX fuel, including in Switzerland, perceived little alternative at the time but harboured concerns including cost, safety, operational challenges, regulatory approval, and disposal of spent MOX that would emit much more heat and radioactivity in the long run than spent LEU (Kim and Kuperman, 2018). When these utilities opted for MOX in the 1970s, their governments 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, these utilities viewed its recycle in MOX as the only feasible disposition pathway. Thus, some nuclear utilities felt compelled to initiate MOX fuel despite their misgivings.

5 More controversial than nuclear energy

The decline of MOX is not merely an economic phenomenon, or ancillary to a broader global retreat from nuclear power. Reusing spent fuel has repeatedly proved less popular than traditional, once-through use of uranium fuel, due to plutonium's safety and nuclear weapons-related concerns. 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, while mandating a more gradual phase-out of nuclear energy; this occurred well before Japan's Fukushima accident prompted Germany to expedite its nuclear phase-out (Winter, 2013). Ironically, the recycling of plutonium, originally conceived as necessary to sustain nuclear power, instead helped undermine it in Germany.

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. 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, thereby exacerbating the Japanese-owned plutonium stockpile now totalling about 47 tonnes (Acharya, 2018). Neighbouring countries, including China, South Korea, and North Korea, have expressed strong security concerns about this plutonium accumulation, which is sufficient for more than 5000 nuclear weapons (Tajima, 2018; Min-Hyung, 2018). Thus, Japan's plutonium fuel program has sparked both domestic and international protest.

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 continued to support operation of nuclear reactors – until Japan's Fukushima disaster spurred a 2017 vote to phase out nuclear energy by around 2050 (Kim and Kuperman, 2018). In Belgium, in the 1990s, NGOs focused their anti-nuclear energy 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 start a reassessment of MOX fuel, culminating in 1998 with termination of the last existing reprocessing contract. 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," and he also cited proliferation concerns (WISE-Paris, 1999; Bonello, 2018). This was five 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 commercial recycling of plutonium in thermal reactors proceeded, so far without 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 (Guéret, 2017). In the Netherlands, the sole remaining power reactor and the interim waste storage facility are both located 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 its entire 13 years of planned MOX use, which deprived domestic anti-nuclear NGOs and politicians of the opportunity to mobilise public opposition to a potential contract renewal, as had proved effective in other countries. Although the universe of cases is small, the experiences of the Netherlands and France suggest that plutonium recycling may be more likely to succeed politically if either limited in scope or supported by powerful domestic interests.

6 Security risks

Physical security is a concern for fresh MOX fuel, because it contains plutonium that could be used to make nuclear weapons by states or terrorists, according to US national laboratories and other experts in weapons design (Jones, 2018; Goodwin, 2015; Mark, 2009). Although some security procedures at power plants are secret, our research indicates that physical protection at reactors is not significantly bolstered when MOX fuel is introduced. Utilities do, however, handle MOX fuel differently. They try to minimise the storage time of fresh MOX by loading it into the reactor soon after delivery, unlike fresh LEU that may be kept as reserve for possible fuel-supply interruption. They modify worker-safety procedures to address plutonium's higher radioactivity. 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. In addition, some operators 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 (Kuperman, 2018c).

However, such measures may not be adequate to address the threats from terrorists or criminals (Mark et al., n.d.; Guéret, 2017). Fresh MOX poses a much greater sub-national security risk than spent LEU because it lacks very high radioactivity that could deter theft and processing to separate plutonium for use in nuclear 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 regard it as nuclear weapons-usable material. In the event of a concerted terrorist attack, that could prove catastrophic.

Additional security is applied to ground transports of fresh MOX fuel, which often traverse hundreds of miles. Such measures typically include an armoured shipping truck and escort by a few national police vehicles in radio communication to a central command. However, if attacked with the types of weapons that international terrorists have used in the recent past – including shaped charges, armour-piercing ammunition, and rocket-propelled grenades – such a shipment might be susceptible to breach and theft. This vulnerability is exacerbated by nuclear transport vehicles using routine and predictable routes, which include bottlenecks and stops that present ideal opportunities for attack (Guéret, 2017). A single MOX fuel assembly for a pressurised water reactor usually contains more than 30 kg of plutonium, sufficient for at least three nuclear weapons. Each MOX shipment may include a dozen or more of these assemblies to reload the reactor, and such transports occur weekly in France (Burns, 2018). Another vulnerability, until the recent development of integrated fuel manufacturing facilities, was the transport of MOX rods to other plants that combined them into fuel assemblies.

Even more concerning 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. Such shipments occur weekly, each traveling over 600 miles (Burns, 2018). Security also has been called into question at the French reprocessing and MOX plants, each containing tonnes of separated plutonium, sufficient for hundreds or thousands of nuclear weapons. The managing director of the French fuel-cycle firm, Orano, testified in 2018 that doubling the company's spending on security would add only about 0.2% to the French price of electricity (Knoche, 2018). In light of the enormous potential consequences of terrorist theft of weapons-usable plutonium, such an increased security investment could be prudent.

Surprisingly, some non-US government and industry officials have claimed that reactor-grade plutonium cannot be used to make nuclear weapons, decades after this myth was disproved. 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" (Nuclear Control Institute, n.d.). Belgian officials in recent years have expressed similar sentiments (Bonello, 2018). 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" (Republic of France, 2017).

Such claims appear to confuse LWRs – which rely on fission by thermal neutrons, so that only certain isotopes of plutonium can sustain a critical chain-reaction – with nuclear weapons, which rely on fast neutrons, so that all plutonium isotopes can sustain a super-critical chain-reaction. Reactor-grade plutonium of any isotopic composition can be used to make reliable nuclear weapons, as has been documented repeatedly, including by US nuclear weapons laboratory officials (Jones, 2018; Goodwin, 2015; Mark, 2009). 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 injection of tritium. Swiss interviewees, to their credit, implicitly acknowledged this risk from reactor-grade plutonium by revealing that their government and military supported the reprocessing of spent fuel in part to help establish a nuclear-weapons option (Kim and Kuperman, 2018).

7 Lessons for East Asia and beyond

This article 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 the two countries contemplating the start of large-scale MOX fuel use in thermal reactors: China and the UK. Third are the countries – including India, South Korea, Russia and China – pursuing the recycling of plutonium from spent fuel using alternative technologies such as fast reactors and pyro-processing that may nevertheless pose similar risks from plutonium's radiotoxicity, weapons capability, and resulting costs.

The first lesson is that reusing spent nuclear fuel for energy is very expensive due to the high costs of addressing plutonium's health and security threats at fuel-cycle facilities. Second, the ostensible benefits of recycling plutonium – energy security and waste management – are unlikely to compensate for such financial costs. This applies not only to MOX in thermal reactors but also to alternative technologies, including fast reactors, based on recent scholarly assessments (National Research Council, 1996; Krall and Macfarlane, 2018). Third, the security measures applied to recycling of plutonium may be inadequate in light of several concerns: the indisputable feasibility of making nuclear weapons from reactor-grade plutonium, the declared objective of some terrorist groups to acquire and use nuclear weapons, and the demonstrated ability of such groups to stage sophisticated attacks as on September 11, 2001. Fourth, reusing spent fuel is currently unnecessary for sustained and efficient production of nuclear energy, in light of the world's plentiful supplies of uranium and enrichment. Accordingly, there appears to be little justification for incurring the substantial economic, security, and safety risks of recycling plutonium. Fifth, countries that continue to pursue plutonium fuel, despite its high cost and lack of obvious compensating benefits, may be suspected by other countries of having ulterior motives, which could threaten international peace and security (Tajima, 2018).

These lessons give rise to recommendations for each of the three groups of states specified above. The two countries planning to continue the uneconomic and risky use of thermal MOX, France and Japan, could instead choose to phase it out – as rapidly as their domestic politics would permit. France has powerful and entrenched pro-plutonium interests in government and industry. Yet, its national utility appears to be aware that recycling plutonium raises the cost of electricity, which could explain why it has not significantly increased the use of MOX fuel despite domestic surpluses in all four factors required to do so: separated plutonium, reprocessing capacity, MOX fabrication capacity, and reactor capacity to use MOX. Even if safety and security concerns do not compel France to re-evaluate its MOX program, the economic penalty eventually may do so.

Japan’s pro-plutonium lobby is less 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 Japan’s reactors or to its incomplete reprocessing and MOX plants – who fear being stuck with spent nuclear fuel if it is not reused. To address this concern, one possibility would be for Japan’s government to invest in expanding dry-cask storage of spent fuel, while explaining the safety and reliability of this technology to these communities and compensating them for serving as temporary waste-storage sites prior to completion of a geological repository. The government also could use part of its sizeable reprocessing fund – which contains contributions from utilities to manage nuclear waste – to pay the UK to take title to the 22 tonnes of Japan’s plutonium that is in the UK, 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 could dispose of that material as waste, in cooperation with the USA, which has a similar disposal program (Von Hippel and Mackerron, 2015). The rest of Japan’s plutonium – two tonnes at home and 15.5 tonnes in France – could 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 (Kuperman and Acharya, 2018).

The two countries contemplating initiating large-scale MOX use in thermal reactors – China and the UK – should recognise that this option is uneconomic and unnecessary. The US Government recently reached such a decision, after wasting billions of dollars on partial construction of a MOX fabrication plant that soared in cost before being abandoned, and Washington now plans instead to dispose of surplus weapons plutonium as waste (Gardner, 2018). 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 (Mann, 2018). As a result, the UK has title to a domestic stockpile of 110 tonnes of separated civil plutonium, dwarfing the 3.2 tonnes of plutonium in that country’s nuclear weapons arsenal. Officially, the government’s preferred option for its civil plutonium is to recycle it in MOX fuel, despite the domestic absence of either a MOX fabrication facility or reactors licensed to use MOX fuel. The UK could choose to end this fiction and instead dispose of its plutonium as waste (Von Hippel and Mackerron, 2015). China has not yet created a surplus of separated plutonium, but it has negotiated with Orano about construction in China of both reprocessing and MOX fabrication plants. China has successfully mimicked many aspects of Western industrialisation, but doing so in this case could be ill-advised, considering how costly and risky thermal MOX has proved in the West.

Finally, countries such as India, South Korea, Russia, and China are pursuing the recycling of plutonium for energy using alternative technologies. Russia has stockpiled nearly 60 tonnes of civilian separated plutonium (IAEA, 2018) and recently shipped the first MOX fuel elements to its BN-800 fast reactor (IPFM Blog, 2019). In theory, fast reactors could fission more plutonium and other actinides in their fuel, thereby reducing the long-term heat and radioactivity of high-level nuclear waste. Pyro-processing could avoid separating pure plutonium and thus – compared to traditional reprocessing – might reduce somewhat the nuclear-terrorism risk of a closed fuel cycle. However, experts have demonstrated that these purported benefits of pyro-processing and fast reactors have been exaggerated (National Research Council, 1996; Krall and Macfarlane, 2018; Acton, 2009; Lyman, 2002). Such technologies cannot overcome plutonium's three fundamental risks that have bedevilled previous efforts to reuse spent fuel: safety, nuclear weapons, and cost. Accordingly, as such countries pursue alternative fuel cycles, they would be advised to examine the historical track record of plutonium fuel, in thermal reactors, to understand its commercial failures. In so doing, they might realise that their proposed approaches to obtaining plutonium and fabricating it into reactor fuel would face similar challenges – in addition to the substantial hurdle of commercialising fast reactors, which have failed both technically and economically almost everywhere that they have been attempted (Cochran, et al., 2010b).

The reprocessing of spent nuclear fuel to extract plutonium is an excellent way to produce nuclear weapons. To date, however, it has proved to be an inefficient, dangerous, and unnecessary way to produce electricity. Unless and until there are major improvements in the safety, security, and economics of recycling plutonium, spent reactor fuel should instead – after temporary cooling in pools – be transferred to interim dry storage, in preparation for eventual permanent disposal in geological repositories.

Acknowledgements

This research was supported by a grant from the John D. and Catherine T. MacArthur Foundation.

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