Plutonium for Energy?

Explaining the Global Decline of MOX

A Policy Research Project of the
LBJ School of Public Affairs
University of Texas at Austin

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NUCLEAR PROLIFERATION
PREVENTION PROJECT

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The NPPP is neither pro- nor anti-nuclear power. We do hope this book provides insight into how to produce energy safely, securely, and affordably.

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Recycling Plutonium: What Went Wrong?

Alan J. Kuperman

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.

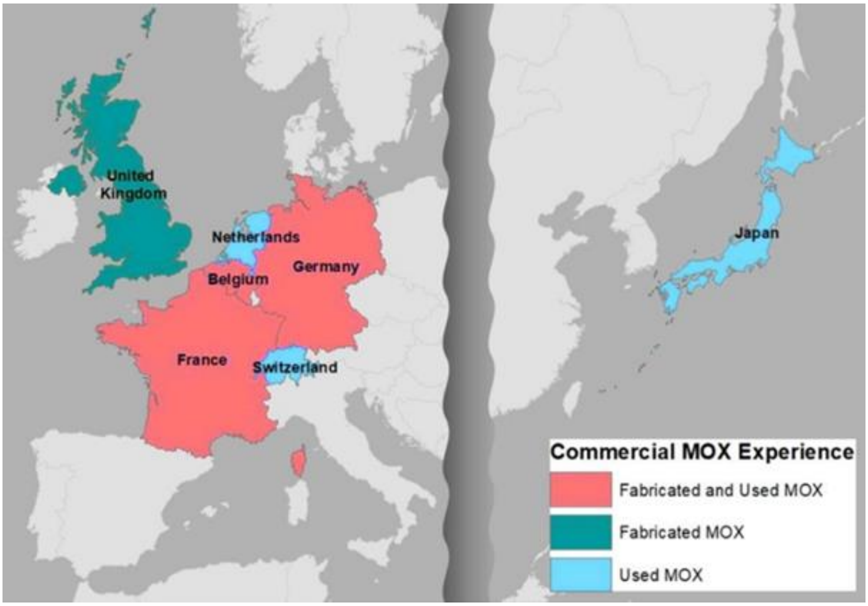
Recycling is typically considered a good thing. It turns garbage into an asset, thereby reducing the need for both raw material and waste disposal. Yet, recycling plutonium from previously used nuclear fuel to make fresh fuel for nuclear energy has proved controversial. This is mainly because plutonium 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.

2

MOX in Belgium: Engineering Success but Politico-Economic Failure

Valentina Bonello

This chapter assesses Belgium's experience with both manufacturing mixed-oxide (MOX) fuel for light-water nuclear reactors, and using such fuel. It is the first such study to focus on Belgium's production and use of MOX fuel, including economic, security, and safety aspects. Field interviews were conducted in France and Belgium in 2018 with officials from Tractebel, Belgonucléaire, Greenpeace, and the University of Liège, and with independent consultants. MOX fuel production and use in Belgium were successes technically but could not compete economically with traditional low-enriched uranium (LEU) fuel. Both production and use of MOX also posed security, safety, environmental, and public acceptance concerns – beyond those of LEU – which contributed to their demise. Based on the Belgian experience, other countries may wish to avoid reprocessing their spent fuel or disposing of their separated plutonium in MOX fuel. Alternative back-end options should be explored that are economically sustainable and do not pose security and safety threats to the local and international community.

This chapter examines in detail Belgium's experience manufacturing and utilizing mixed-oxide fuel (MOX) for light-water nuclear reactors (LWRs), with emphasis on the economic, security, safety, performance, and public acceptance aspects of both production and use of MOX fuel. Previous studies have shown that MOX fuel is less economical and poses more safety, nuclear proliferation, and nuclear terrorism concerns during production and utilization than traditional low-enriched uranium (LEU) fuel. Therefore, it is important to understand why Belgium, among other countries, has pursued MOX fuel utilization, and to assess its experience in retrospect. Ultimately, the account of Belgium's experience using

MOX fuel can be valuable to those countries that are considering pursuing the recycling of spent nuclear fuel into fresh fuel in order to evaluate the implications of their policy choices.

To provide a detailed account of Belgium's experience with MOX fuel, this study proceeds as follows. The first section provides an overview of Belgium's nuclear program, and especially of MOX fuel production and use. The research methods and sources are then summarized. The following section explains Belgium's decision to produce MOX fuel and the economic, security, safety, environmental, and performance aspects of MOX fuel fabrication. Next the chapter examines Belgium's experience using MOX fuel in LWRs, including the reactor licensing and adaptation procedures, and the economic, safety, and security consequences of MOX fuel utilization in Belgium. The subsequent section discusses the impact of MOX fuel on Belgian public opinion of nuclear energy more generally. The report concludes with lessons and recommendations for other countries considering initiating or expanding the closed nuclear fuel cycle.

Belgium's Nuclear Program

Belgium's experience with MOX fuel includes not only its use, but also its fabrication. Belgium has seven nuclear power reactors located at two sites, Tihange and Doel. Three of the seven had some of their spent fuel reprocessed, and the separated plutonium was later recycled in MOX fuel in two of the other reactors.[1] Belgium also hosted the world's first experimental reprocessing plant for civilian spent fuel, in Dessel, owned by an international consortium of OECD countries and private partners, known as Eurochemic. From 1968 to 1974, the facility reprocessed 212 tonnes of Belgian and foreign spent fuel,[2] but this was prior to Belgium starting operation of its first nuclear power reactors. The plutonium separated by reprocessing at Eurochemic was initially destined to manufacture fuel for two German fast reactors, which were co-commissioned by Belgium but never became fully operational.

After domestic reprocessing ended, Synatom, a Belgian public company in charge of managing the country's nuclear fuel cycle,[3] placed two orders in 1976 with France's Cogema for the reprocessing of irradiated fuel from Belgium's first three nuclear power reactors: Tihange-1, Doel-1, and Doel-2. Forty tonnes of Belgian spent fuel were reprocessed at Cogema's La Hague facility in 1981 and 1982. Synatom in 1978 placed a third order from La Hague for the reprocessing of 100 tonnes of spent fuel from the same nuclear reactors, which was completed by 1985. A fourth agreement was signed in 1978 for 530 tonnes of spent fuel produced at the same three reactors from 1979 to 1990, which was reprocessed between 1990 and 2001.[4] A fifth agreement was signed in 1991 for 225 tonnes of spent fuel to be reprocessed between 2001 and 2010. This agreement also included the option to reprocess up to 120 tonnes of spent fuel per year between 2001 and 2015.[5] MOX fuel became Synatom's preferred strategy to utilize the plutonium separated under the reprocessing contracts.

In 1993, however, the Belgian House of Representatives ruled that spent fuel reprocessing and direct disposal were equally acceptable back-end options for spent nuclear fuel, and decided to analyze them in detail over the following five years. Also in 1993, the Belgian government ruled that while the 1978 reprocessing agreements could be fulfilled, Synatom was not allowed to sign any new reprocessing contract without government approval.[6]

As a result, the 1991 agreement was suspended in 1993, and then cancelled in 1998. This was prior to the start of reprocessing under that agreement,[7] so Synatom did not have to pay a financial penalty to Cogema.[8] In 1998, the Council of Ministers reiterated that no new reprocessing contracts could be signed without government approval, thereby extending the moratorium on reprocessing that continues to this day.[9] By 2014, only 16 percent of Belgium's total historical spent power reactor fuel had been reprocessed, while the rest was slated for direct disposal.[10]

According to the International Atomic Energy Agency (IAEA), as of 2015, there was no leftover unirradiated separated plutonium from reprocessing plants in Belgium. The amount of plutonium contained in "unirradiated semi-fabricated or unfinished products at fuel or other fabricating plants or elsewhere" amounted to less than 50 kg (the lowest threshold).[11] The IAEA also reported that Belgium possessed less than 50 kg of plutonium belonging to "foreign bodies," without further detail.

Belgium's MOX production for its domestic LWRs began in 1986.[12] The Belgian Nuclear Research Center (SCK-CEN) and Electrabel, a Belgian energy corporation, were responsible for MOX fuel rod production at Belgonucléaire's P0 plant in Dessel, which operated from 1973 to 2006.[13] The plant could produce 32 tonnes of MOX fuel rods per year, and it ultimately produced approximately 600 tonnes of such rods that were combined into fuel assemblies at other facilities and loaded into 21 nuclear reactors in Belgium and abroad. The country that received the largest amount of P0's MOX was France.

Until 1995, Belgonucléaire also manufactured some of the MOX assemblies made from its fuel rods. Starting in the mid-1980s, however, fabrication of larger MOX assemblies was contracted to *Franco-Belge de Fabrication du Combustible* (FBFC), also located in Dessel. Initially, FBFC fabricated MOX assemblies on its line also used for uranium oxide fuel, but in the mid-1990s this line suffered contamination from a broken MOX rod, which shut down the facility and required costly decontamination. As a result, FBFC constructed a new annex exclusively for MOX fuel, which opened in 1997.[14]

In 2001, FBFC became a wholly-owned subsidiary of the French company Areva. FBFC used MOX rods coming from Belgonucléaire's P0 plant and from the French Cadarache and MELOX MOX plants. In 2005, Areva decided that since the market for MOX fuel had substantially shrunk, it would phase out MOX fuel assembly fabrication in Dessel and instead produce MOX fuel only in France. The last MOX fuel assembly for a Belgian LWR was shipped from FBFC in 2006. In 2011, after suspending LEU assembly production at FBFC, Areva announced its intention to shut down the FBFC facility entirely and thereby end the plant's MOX production, because of "a decrease of demand in Western Europe and an over-capacity on the market."[15] In 2013, the Belgian government approved this decision, and in 2015, FBFC assembled and shipped abroad the last MOX fuel assembly produced in Dessel.[16]

The world's first loading of MOX fuel in an LWR occurred in Belgium in 1963, at the BR-3 prototype power reactor in Mol. The fuel was manufactured by Belgonucléaire. Of the seven commercial nuclear power reactors that eventually operated in Belgium, only two – Doel-3 and Tihange-2 – were licensed for MOX fuel use (in

1994), and the first MOX was loaded in 1995. Belgium exhausted its MOX fuel stocks in 2006, and Doel-3 and Tihange-2 have loaded only LEU fuel since.[17]

Methods

The written sources for this study include documents from Belgonucléaire, which manufactured MOX fuel rods, and from Electrabel and Tractebel – the operator and engineering company, respectively, of Belgium's nuclear power plants. Other publications were obtained from Belgium's government, including the Federal Agency for Nuclear Control, and from experts involved in the safety assessment of the MOX-loaded nuclear reactors. Secondary sources include academic articles and reports from the IAEA and consulting companies.

Interviews were conducted in January 2018 in Paris, France, and in Brussels, Liège, and Mol, Belgium. Interviewees included several industry officials: a chief engineer from Tractebel, specializing in safety, modelling, and nuclear core and fuel studies; a retired MOX fuel expert from Belgonucléaire, now working for his own nuclear fuel consulting company; and an industry official from a Belgian-authorized nuclear consulting agency. Interviews were also conducted with anti-nuclear activists, including a Greenpeace-Belgium representative who worked on plutonium and MOX fuel issues, and a private nuclear energy consultant and analyst. Also interviewed were two professors from the University of Liège, who have expertise in nuclear energy and nuclear engineering.

MOX Fabrication in Belgium

By the late-1980s, it became clear that fast breeder reactors (FBRs) were unlikely to become commercially operational in time to consume the plutonium that Belgium already had separated and contracted to separate from its spent fuel domestically and abroad. Belgium's subsequent decision to produce MOX fuel for thermal reactors was ostensibly based on an economic comparison of back-end options. A 1989 study predicted that reprocessing spent fuel and recycling the separated plutonium in MOX for thermal reactors would be more economical than the alternative of directly disposing of spent fuel, in part due to the expected costs arising from environmental and safety regulation of a waste repository.[18] Moreover, direct disposal was deemed risky because it had not yet been commercially validated.[19]

For previously separated plutonium, the study concluded that recycling it as MOX in thermal reactors would be less expensive than alternative disposition methods. The authors declared, "The storage of plutonium is costly. . . It is clear that it is an advantage for the utilities to put their capital to work rather than to store it with no return."[20] The study also noted that an additional cost of storing plutonium is that some of it decays into americium, which after two to three years must be removed before the plutonium can be used to make MOX.[21]

Direct disposal of plutonium as waste was not evaluated but evidently was perceived to entail both storage costs and opportunity costs from not reusing nuclear material. This indicates that at the time separated plutonium was deemed to have positive economic value, which later proved not to be the case.

In 1993, as noted, the Belgian Parliament decided that reprocessing and direct disposal would be equally acceptable options to deal with spent fuel from Belgian nuclear reactors. The Belgian Parliament authorized the use of MOX fuel in the Belgian nuclear reactors Doel-3 and Tihange-2 but limited it to the plutonium originating from the spent fuel that had already been reprocessed at La Hague under the contracts through 1978.[22] The preceding national and international demonstration of successful use of MOX fuel in LWRs encouraged this decision.[23] The Synatom contracts led to the recycling of 4.8 tonnes of plutonium in 66 tonnes of MOX fuel in Belgian reactors, with an average plutonium content of 7.3 percent.[24]

MOX fuel rods produced in Belgium were designed by the French company Areva (at the time, Fragema), manufactured in Dessel by Belgonucléaire, and then combined into assemblies at the adjacent FBFC. By the end of production, MOX assemblies made in Belgium contained on average 7.7 percent reactor-grade plutonium,[25] and could produce energy for four years like LEU fuel.[26]

During their years of operation, the Belgonucléaire and FBFC plants in Dessel produced MOX fuel not only for Belgian plants, but also for foreign customers.[27] From 1969 to 1972, Belgonucléaire focused exclusively on research and development and on pilot scale fabrication of MOX fuel assemblies, including four assemblies for the Italian commercial boiling water reactor (BWR) Garigliano. From 1972 to 1985, the plant produced a few thousand MOX fuel rods for the SNR-300 and KNK demonstration fast breeder reactors in Germany.[28] During its operation, the Belgonucléaire plant also produced experimental MOX fuel rods for the Dutch Dodewaard LWR and for a Canadian CANDU reactor.[29] Production for the Italian Garigliano BWR occurred between 1973 and 1974, totaling 47 assemblies. Before 1995, P0 also produced experimental MOX fuel rods and assemblies for the Swedish Oskarshamn LWR, the French CAN-Chooz, and the Swiss Beznau PWR power plant.[30] After 1996, about 70 percent of Belgonucléaire's production of MOX fuel was destined for German clients.[31]

Economics of MOX Fabrication

A 1998 Belgonucléaire study estimated the cost of manufacturing MOX fuel by combining the baseline cost of fabricating LEU fuel with the extra expenses arising from handling plutonium.[32] The study did not, however, include the cost of obtaining plutonium by reprocessing spent fuel, although it did include the cost of uranium and enrichment for LEU fuel. The study estimated the cost of manufacturing MOX fuel assemblies as $1,900/kg, compared to only $340-380/kg for LEU fuel assemblies.[33] This meant that MOX fuel was at least five times as expensive as LEU fuel to manufacture, even excluding the substantial cost of obtaining the plutonium via reprocessing. A preceding 1990 Synatom internal study similarly had found that MOX cost five times as much to fabricate as LEU, although the estimated relative total cost of the two fuel types varied significantly depending on assumptions about the price of their heavy-metal inputs.[34] The main cost of producing MOX at Belgonucléaire was not for materials or waste handling but rather plant construction expenses, treated as yearly fixed costs.[35] As a result, any interruption or slowdown in production further increased the per-unit cost of MOX.[36]

Safety concerns associated with plutonium contributed to driving up the cost of MOX fuel fabrication. The upfront investment to start MOX fabrication is ten times higher than for LEU,[37] due in part to the need to install a large and powerful air purification system for plutonium and its decay products. Hubert Bairiot, who worked for Belgonucléaire, reports that the air purification system on the second floor of the P0 fabrication plant required the same footprint as the fabrication floor.[38]

Another way that the radioactivity and toxicity of plutonium drive up the cost of MOX production is that the equipment to handle this material is more expensive than for LEU.[39] Such equipment, including glove-boxes and protection gear, was especially important to protect plant personnel from americium.[40] Plant operators had to use protective shields when working in highly exposed areas. Ultimately, the plutonium that accumulated on the surfaces within the glove boxes represented the highest source of radiological risk for employees.[41] To limit human exposure to radioactive material at P0, the production line was increasingly mechanized and automated during the 1980s and 1990s. Disposing of radioactive waste arising from the production process also increased fabrication costs.[42]

According to an industry official, however, the cost of fuel is only five percent of the total cost of nuclear electricity production in Belgium, which includes the high cost of constructing reactors. Since the final price of electricity for consumers is only twice the cost of producing the electricity, he argued, the fuel cost does not contribute significantly to driving up the price of electricity for consumers.[43] This official argued that MOX helps sustain nuclear energy and thus justifies a small increase in the final price of electricity. However, in light of surpluses of uranium supply and enrichment capacity, MOX fuel is currently not required to sustain nuclear power. Additionally, if MOX costs five times more than LEU to fabricate, then it does significantly increase the cost of producing nuclear electricity, especially after reactor construction costs are fully amortized.[44]

Security and MOX Fabrication

The transport of all radioactive materials in Belgium must be approved and licensed by the Belgian Federal Agency for Nuclear Control.[45] Bairiot described the security measures that applied to the transport of separated plutonium from La Hague to Belgium's

MOX fabrication plant. He says that the cans containing the separated plutonium oxide were placed inside large casks that were loaded into “massive armored” trucks for transport to Belgium.[46] For each transport, the final route was chosen between at least two qualified itineraries and kept secret. Bairiot admitted, however, that the trucks could easily be tracked by simply observing them leaving the reprocessing plant to infer which route they would follow to the Belgonucléaire MOX fabrication facility in Dessel.[47] While in France, an armored vehicle of the French National Gendarmerie would follow the truck. At the border, the Belgian National Gendarmerie would take over and escort the truck to the entrance of the Belgonucléaire process building. The Belgian National Gendarmerie is a domestic military organization that carries weapons, although lighter ones than those available to the army.[48]

Once at Belgonucléaire, the transport casks were unloaded and the cans containing the plutonium oxide were placed individually in safes located in a secured locker room next to the start of the fabrication line. All these operations took place in the hot zone of the fabrication plant, under regulations and surveillance designed to reduce the risk of theft or accident. For security of supply, a stock of separated plutonium sufficient for one year of fabrication was typically kept at the facility.[49] This means that the facility regularly contained more than one tonne of separated plutonium, sufficient for at least 100 nuclear weapons.

Because U.S.-obligated nuclear material was processed at the Belgian MOX facilities, a 1978 U.S. law required inspections and approval of their security measures. A Belgian nuclear industry official claims this led to systematic improvement of the physical protection system.[50] However, Jan Vande Putte, a spokesperson for Greenpeace-Belgium who worked for years on anti-nuclear campaigns focused on separated plutonium and MOX fuel, says that security measures at the MOX fuel rod and assembly plants were inadequate in light of the proliferation and terrorism risks posed by the plutonium. Each truck transporting fresh MOX rods from the Belgonucléaire plant to the FBFC assembly facility was escorted by only one police car.[51] However, a Belgian industry official who worked on safety and security issues related to MOX says that the Belgonucléaire and FBFC facilities were so close to each other on the same street that these shipments posed little security concern.[52] Yet, Vande Putte notes that the transports were easily tracked by anti-nuclear activists, indicating that terrorists could have done so too. He says it was also easy to monitor trucks transporting separated plutonium from France to Belgium.[53] Moreover, Vande Putte asserts that the gate into the MOX facilities could easily be opened.[54] In light of such reported vulnerabilities, it may be fortunate that the MOX fabrication plant was shut down before Islamist terrorists were discovered in 2015 to be targeting Belgian nuclear facilities.[55]

Safety of MOX Fabrication

Belgonucléaire sought to assure that the performance of MOX fuel was comparable to LEU fuel – yielding the same energy and fuel cycle length, while not affecting operating conditions, equipment requirements, or operational safety.[56] Specifically, MOX fuel assemblies had to be comparable to advanced Fragema LEU assemblies, which contained 3.8-percent uranium enrichment.[57] Ultimately, safety studies showed that the plutonium contained in MOX fuel did not affect the thermal-hydraulic requirements of the assembly.[58]

Because of the presence of plutonium, MOX fuel fabrication poses more safety and environmental risks than LEU fuel fabrication. Specifically, plutonium has much higher alpha and neutron activity, and two times higher gamma activity, than uranium, thereby posing safety risks to the personnel working inside the fabrication plant.[59] Additional radiological risk from MOX arises from the presence of americium, a decay product of plutonium.[60] Pyrophoricity (fire risk) and chemical toxicity are also higher for plutonium than uranium. Extra shielding and other measures are implemented to address these concerns, but the dose rate during normal operations at the Belgian MOX fabrication plant was on average about 50 percent higher than for an LEU fuel fabrication plant, although this depended on the age of the plutonium and the resulting americium buildup.[61]

During the first stages of Belgium's laboratory-scale MOX fuel production, from 1960 to 1969, uranium dioxide and plutonium dioxide were mixed in the form of fine powders, which were extremely volatile and increased the risk of environmental contamination and personnel exposure to plutonium.[62] This method also led to high accumulation of plutonium waste in the plant.[63]

To decrease health risks, in 1967, Belgonucléaire started work on a fabrication method that would blend granulated rather than powdered plutonium and uranium dioxide. However, this new method initially posed different safety risks when the fuel was irradiated. Since the granulated plutonium dioxide could not mix uniformly with the uranium dioxide, irradiation resulted in large fission gas releases. This production process also resulted in MOX fuel that behaved differently from LEU fuel and had unfavorable thermal conductivity. These problems reportedly were eventually resolved by development of the Micronized Master Blend (MIMAS) process, described below.[64]

Greenpeace-International complained to the U.S. Nuclear Regulatory Commission that safety standards at the Belgonucléaire P0 plant were inadequate and lower than at modern MOX fuel fabrication facilities, such as Germany's Hanau 1 plant (which ultimately never opened, as detailed in Chapter 6).[65] According to Greenpeace, the operating license of the Belgonucléaire plant permitted higher concentrations of americium-241, a gamma emitter, than typically allowed internationally.[66] Greenpeace also noted that the handling of plutonium in glove boxes exposed workers to risks not present in newer facilities, where the fabrication process was highly automated.[67]

Technical Challenges of MOX Fabrication

MOX fuel produced at the Dessel plant reportedly performed well in a variety of reactors. The plutonium it contained had been separated by either Cogema or the UK's British Nuclear Fuel Ltd (BNFL). The fuel was successfully inserted in both pressurized and boiling water reactors.[68]

The design of MOX fuel rods, however, presented challenges that did not apply to LEU. MOX fuel releases more gas during fission than LEU fuel, thus requiring a reduction of the axial length of the fuel rod by approximately 10 cm.[69] Moreover, as noted, the production process used by Belgonucléaire from 1974 to 1984 resulted in plutonium-rich agglomerates within the MOX. This lack of homogeneity in the fuel increased uncertainty in MOX fuel assembly design and performance.[70] Moreover, this production process did not satisfy the requirement for potential reprocessing of MOX fuel by dissolution in nitric acid, as that would leave plutonium residues.[71]

In 1984, Belgonucléaire developed the MIMAS process for MOX fuel pellet production, dispersing uranium dioxide and plutonium dioxide into a uranium dioxide matrix. This process ensured that the distribution of the plutonium in the fuel would be homogenous, irrespective of origin or batch size. Thanks to this production process, developed prior to the commercialization of MOX for Belgium's LWRs, there were never any domestic performance problems for MOX fuel, which performed as well as LEU fuel according to published studies.[72] Belgonucléaire's MIMAS-produced MOX also performed well in France, Switzerland, Germany, and the Netherlands. The only reported failure was of two fuel rods in the Swiss reactor Beznau-1, reportedly due to the coolant causing debris and fretting in the assembly, which was not attributed to any flaw in the fuel.[73]

MOX Use in Belgium

The introduction of MOX fuel in Belgian LWRs had the explicit goal of recycling, from 1993 to 2002, some 4.8 tonnes of plutonium that had been separated by reprocessing in France. A Belgian source, who requests anonymity, claims that MOX fuel was also considered the best way to reduce nuclear proliferation concerns, given that the plutonium was already separated,[74] but most nonproliferation experts today oppose MOX fuel. Electrabel, the utility company that runs all seven Belgian nuclear power reactors, decided that MOX fuel would be loaded into two of the seven Belgian nuclear reactors, Doel-3 and Tihange-2, which had the same design and characteristics as France's nuclear reactors already loaded with MOX fuel.[75] By doing so, the utility could best take advantage of France's experience using MOX fuel. Since the original contract with Belgonucléaire to produce 144 MOX fuel assemblies was sufficient to recycle the separated plutonium, Electrabel never applied for authorization to introduce MOX fuel into additional reactors.[76]

Economics of Spent MOX

Although immediately after discharge the residual heat of spent MOX fuel is slightly lower than spent LEU fuel, americium from decay of plutonium makes spent MOX four times hotter than spent LEU in the long run.[77] This significantly increases the volume requirements for permanent disposal of spent MOX fuel compared to spent LEU fuel,[78] and the spent MOX cannot be efficiently recycled further. Moreover, the extra heat and required cooling time for spent MOX may delay Belgium's plan for permanent disposal of all its spent fuel.[79] This is somewhat ironic because reprocessing of spent LEU and recycling of separated plutonium in MOX was touted as simplifying waste management compared to direct disposal of spent LEU fuel.

Public Opinion and MOX

Greenpeace-Belgium highlighted MOX fuel in its anti-nuclear energy campaign.[80] The organization argued that reprocessing of spent fuel in France, and transport of separated plutonium from France to Belgium, raised environmental, proliferation, and terrorism risks.[81] This focus on plutonium impacted Belgian public opinion on nuclear power more generally. In 1998, Greenpeace mobilized Belgian citizens in anti-nuclear campaigns, focused on spent fuel transport from Doel to La Hague. According to Vande Putte, such popular mobilization persuaded the mayors of municipalities along the transit route to press the national government to oppose nuclear energy. In December 1998, Jean-Pol Poncelet, a nuclear engineer who at the time was Belgium's Vice-Prime Minister, Minister of Defense, and Minister of Energy, announced termination of the 1991 Cogema reprocessing contract on grounds that, "At the current state of the information we have concerning economic and ecological aspects, there is no justification to use another time the reprocessing technology."[82] In July 1999, Belgium's newly elected government including the Green Party agreed on a platform calling for the "gradual phasing out of nuclear" energy,[83] which was codified in 2003.[84]

Safety of Using MOX

Unirradiated MOX fuel spontaneously emits neutron, alpha, beta, and gamma radiation. This poses radiological risk to personnel working at power plants. To address this problem, fresh MOX fuel at reactors was stored in pools.[85] Tractebel also evaluated the safety of the power plants' heating, ventilation, and air conditioning systems, optimized the handling process (ALARA), and installed additional monitoring systems for neutron and alpha-particle emissions. It was determined that no other special equipment was required besides emission monitoring and remote video for inspection. According to Tractebel, although the loading of MOX fuel increased the risk of radiological exposure during operations, such impact was considered "minor."[86]

The presence of MOX fuel in the core affects the primary coolant by reducing the activation products, such as cobalt-60, and increasing the presence of tritium via activation in the moderator and diffusion through the cladding.[87] MOX fuel assemblies also lead to higher production of Carbon-14 and potentially higher alpha activity in the moderator if the fuel-rod cladding ruptures.[88] This was not considered a major concern because the cladding had never ruptured in MOX fuel rods loaded in French power reactors.[89]

The safety studies conducted for Doel-3 and Tihange-2 considered four types of accident scenarios. One involved a loss of coolant accident (LOCA) that could lead to excessively high temperature in the rod cladding. However, the studies showed that U.S. NRC safety criteria would be respected and that, in the ten hours following a reactor shutdown, the residual power of MOX fuel assemblies would be lower than for LEU assemblies.[90] The safety study of a LOCA at Tihange-2 predicted a 20- to 40-percent increase of the body radiation dose and a four-percent increase of the inhalation thyroid dose. For this reason, the containment leakage rate of the reactor had to be reduced by 1.24 percent in order for safety standards to be respected.

Since the thermal conductivity of MOX fuel is also 10-percent lower than LEU fuel, the water in the steam line becomes hotter in reactors that include MOX fuel, reducing safety margins and increasing the risk of meltdown.[91] Tractebel's studies showed that MOX fuel did in fact lower the shutdown margin of Doel-3 and

Tihange-2, posing difficulties in the event of a steam-line break, so the steam line was revisited.[92] MOX fuel also presents a harder neutron spectrum than LEU fuel, which negatively affects the performance of the reactor by requiring a higher boron concentration and leading to an undesirably low moderator temperature coefficient of reactivity.[93] Greenpeace's Vande Putte explained that the management of MOX fuel presents more radiological risk because of the higher temperature and increased presence of actinides and volatile products between the fuel pellets.[94] Similarly, Pierre Dewallef, professor of engineering at the University of Liège, cited the concentration of actinides in MOX fuel as a risk factor in an accident scenario.[95]

According to Hubert Druenne of Tractebel Engie, it is not possible to know whether MOX fuel poses more environmental threat than LEU fuel in case of accident.[96] The safety analysis did not examine all radioactive isotopes produced when using MOX fuel. Moreover, the generation of tritium is 25- to 30-percent higher for MOX fuel than for LEU and the deposits of tritium in the rod cladding can be 100 times higher for the hotter portions of the fuel column than the colder ones.[97] The safety analysis determined that more tritium would be dispersed in case of an accident with MOX fuel, but still within safety limits.[98]

Security of MOX Fuel Use

The advent of MOX fuel introduced nuclear-weapons usable material to Belgian power reactors for the first time, but no additional security measures on core re-loading were implemented.[99] In Belgium, the utility is responsible for ensuring the security of the nuclear power plant. Inspectors from Bel V, a subsidiary of the Belgian Federal Agency for Nuclear Control, are present every day at each reactor site.[100] In addition, the utility implements IAEA safeguards, which EURATOM and the IAEA jointly monitor, on all nuclear installations, and which also apply to transport. Fresh MOX fuel assemblies are transported inside of sealed containers, with IAEA or EURATOM present at each loading and unloading. As required by EURATOM, the pool storage area at the reactor site is under permanent surveillance and all routes for the transportation of MOX fuel assemblies are monitored.

EURATOM also has the right to access records upon demand.[101]

Licensing

Electrabel and the architect engineering company Tractebel initiated the evaluation of the safety aspects of MOX fuel in domestic reactors. Framatome, a French company specialized in nuclear reactor equipment and safety, performed the necessary safety studies. Vinçotte Nuclear Safety, a Belgian authorized nuclear consulting agency, was responsible for assessing these studies and presenting its findings to the Belgian Nuclear Safety Commission.[102]

During the feasibility studies, two reload scenarios were considered.[103] The goal was to reduce the negative effects of the increased fast-neutron flux from MOX fuel on the thermo-mechanical behavior of the MOX fuel rods.[104] Economic considerations also impacted the fuel cycle of MOX fuel assemblies in Doel-3. Considering the constraints imposed by MOX fuel assemblies on in-core fuel management, 12-month cycles were deemed more economical than 15- or 18-month cycles.[105]

According to Hubert Druenne, Tractebel intended on loading no more than 25-percent MOX fuel into each reactor core, so that the reactors' control systems would require no modification.[106] In fact, up to 30 percent of the core of an LWR can be loaded with MOX fuel before the reactor requires a modification of the control system.[107] After this threshold, MOX fuel imposes significant constraints on the control system because of the presence of plutonium, which has a larger fast-neutron fission cross-section than uranium-235, thereby increasing the volatility of the reactor's control rods and raising the probability of an accident.[108]

Even at the lower MOX loading, a slight modification of the core nuclear characteristics was required, because plutonium gives MOX fuel a higher absorption rate of thermal neutrons than LEU fuel.[109] Safety studies reported the occurrence of neutron flux gradients and power peaks between LEU and MOX assemblies, which would affect the reactor vessel near the MOX assemblies, causing increased embrittlement of the vessel.[110] In order to minimize this issue and to maintain the neutron flux inside the core as flat as possible, MOX fuel assemblies were loaded at the center of the core during the first two irradiation cycles, but were rotated around the periphery of the core during the last fuel cycles.[111] Alpha decay of MOX fuel also led to helium generation, which increased the gas pressure inside of MOX fuel rods.[112] Nevertheless, rods fabricated at Belgonucléaire were considered adequate to withstand such pressure.[113]

Ultimately, the two Belgian reactors were each licensed to be loaded with a maximum of 37 MOX fuel assemblies.[114] As Doel-3 and Tihange-2 each had 157 assemblies in their cores, the licenses allowed approximately 23.5-percent MOX fuel.[115] For reasons cited above, the percentage of MOX fuel varied with each fuel cycle, but the utility achieved a maximum of 20.3-percent MOX fuel in the cores of Doel-3 and Tihange-2.[116]

Tractebel also commissioned a safety review on the impact of loading MOX. This included an examination of the impact of MOX on fuel and core design, and an analysis of activity release in normal operation and during different types of accidents.[117] The safety authority required an assessment, six months before loading MOX assemblies, to ensure compatibility with LEU in the core.[118] This verification was extremely important, as during irradiation the length of the fuel assembly extends, posing the risk of contact with the internal surface of the pressure vessel and resulting distortion of the assemblies. The maximum length of the fuel assembly had to be predicted to prevent such extension that could compromise the control-rod cluster assembly.[119] The supplier also had to verify the thermal-hydraulic compatibility of the assemblies.[120] However, since multiple suppliers provided fuel assemblies loaded in Belgian nuclear reactors, data submitted to AIB-Vinçotte Nuclear (AVN) included parameters calculated using different statistical methods, which increased the level of uncertainty when assessing the safety of loading MOX fuel into LWRs and required further analysis.[121]

On-site implementation for both reactors started in 1994 and included the training of the reactors' personnel, the installation of an alpha emission monitoring system in the fuel building, and the distribution of neutron dosimeters to the personnel. At the end of the licensing process, a Royal Decree was produced to authorize the loading of MOX fuel. The licensing procedure for Tihange-2 and Doel-3 started in 1989 and ended in 1994. The first loadings of

MOX fuel occurred in March and June 1995 for Doel-3 and Tihange-2, respectively.[122]

Once Doel-3 and Tihange-2 started using MOX fuel, the engineering company observed that the actual measured values for operations were comparable with the calculated values. The discharge assembly burnup was increased to 50,000 megawatt-days per tonne of heavy metal (MWd/tHM), with restriction on the loading positions of MOX fuel. Ultimately, Tractebel deemed the use of MOX fuel in Doel-3 and Tihange-2 as safe as LEU fuel, with negligible impact on the plants' safety and operations.[123] The engineering company also determined that there would be no operational difference for utility companies when using MOX in addition to LEU.

Back-end Plans

Belgium exhausted its MOX fuel stocks in 2006, and since then Doel-3 and Tihange-2 have loaded only LEU fuel. The country no longer has a reprocessing or MOX fuel fabrication facility. By 2025, Belgium intends to phase out nuclear power entirely. Nevertheless, reprocessing and MOX fuel production are not formally banned. The 1993 parliamentary decision imposed only a moratorium on reprocessing. To date, Belgium has not selected a disposal site for permanent disposition of high-level nuclear waste. Therefore, Belgian policymakers still have options on how to deal with the back-end of the nuclear fuel cycle.

According to a 2009 paper by Van Vliet, et al., spent nuclear fuel storage in pools and dry storage at Belgian nuclear power plants will reach capacity sometime between 2018 and 2022.[124] The study compared two possible scenarios to deal with spent fuel from Belgian reactors: all-reprocessing, or all-direct disposal. The latter scenario would initially require an increase in the interim storage capacity at nuclear power plants in pools or dry casks, entailing an early and significant expense. Ultimately, the amount of spent fuel requiring geological disposal would be 4,700 metric tons of heavy metal, necessitating underground space with a surface area of 15 square kilometers (six square miles). The study says that direct disposal would forego the potential recycling of 10,000 tonnes of uranium that could obviate uranium mining and milling necessary to generate 500 TWH of electricity.[125] In the notional all-reprocessing scenario, only eight square km (three square miles) of surface area would be needed for underground disposal of high-level reprocessing waste. However, this scenario does not explain what would happen to the plutonium separated by reprocessing, for which there is no market. Disposition of such plutonium would also be expensive and require significant underground space, whether directly disposed as waste or recycled once as MOX fuel. In addition, the Belgian Government, under its 1998 decision, would need to grant approval for any potential reprocessing contract.[126]

Summary of Findings

MOX fuel production in Belgium posed economic, security, safety, and performance concerns that did not arise from LEU fuel production. Belgium's first two MOX production processes increased risks to worker safety and fuel performance, before a third technology succeeded at producing MOX reliably. Belgian manufacturers complied with minimum international security standards, but critics argue that physical security measures at the fabrication plants were inadequate.

Synatom opted in 1976 to contract for reprocessing of Belgium's spent power-reactor fuel, despite the risks and potential alternatives. Faced with the resulting separated plutonium, Synatom opted to recycle it in MOX, perceived at the time as the most cost-effective disposal method. Although no modification was required to the control rods, because MOX was capped at 23.5 percent of the core, the fuel management had to be modified, shortening the refueling cycle. Eventually, the performance of reactors with partial MOX cores matched that of entirely LEU-fueled reactors. However, in retrospect, reprocessing spent fuel and recycling plutonium in MOX fuel increased the costs of nuclear power and complicated efforts to permanently dispose of high-level nuclear waste.

It appears that no additional security measures were implemented for nuclear reactors using MOX fuel. Nuclear industry officials interviewed did not seem concerned by the security risks of fabricating and using MOX fuel in Belgium. By contrast, Greenpeace successfully aroused segments of the Belgian public to the security, proliferation, and environmental concerns associated with recycling spent fuel and transporting separated plutonium for MOX fuel. The closed fuel cycle for MOX thus exacerbated Belgian public opposition to nuclear power, which influenced the 1999 government call to phase out nuclear energy entirely, as codified in 2003 and scheduled to be completed by 2025.

Conclusion

Recycling plutonium from spent LEU into fresh MOX fuel for thermal reactors is extremely expensive. In Belgium, MOX fuel cost five times as much to produce as LEU fuel, even excluding the high price to obtain plutonium via reprocessing. Belgium quickly realized this and halted further reprocessing of its spent fuel to avoid wasting more money. By 2014, only 16 percent of Belgium's total historical spent nuclear power-reactor fuel had been reprocessed. That percentage obviously has since declined, as such spent fuel continues to be produced but the last reprocessing occurred in 2001.

Security concerns about separated plutonium and fresh MOX fuel were not taken seriously initially by the Belgian government, as financial considerations prevailed. Belgonucléaire maintained a stockpile of more than one tonne of separated plutonium, sufficient for at least 100 nuclear weapons, at a civilian facility whose security measures were inadequate according to several interviewees. The stated excuses include false claims – such as that it would be hard if not impossible to produce a nuclear bomb from reactor-grade plutonium, and that no sub-state actor could separate plutonium from fresh MOX fuel.

Based on the Belgian experience, it appears that MOX fuel cannot compete economically with LEU fuel. If a country already has separated plutonium, there are likely cheaper options to dispose of it than fabrication, irradiation, and disposal of MOX fuel, as the U.S. government has determined in recent studies.[127] Security is the other major concern with a MOX program. Unless and until both the economic and security issues can be addressed, MOX fuel should not be considered a viable option to dispose of surplus plutonium.

Endnotes

[1] Doel-1 and -2, and Tihange-1, had some of their spent fuel reprocessed until 2001. The separated plutonium was used in two other reactors, Doel-3 and Tihange-2, or sold for use in other countries. Michel De Valkeneer and Christian Dierick, "Spent fuel management in Belgium," *Nuclear Europe Worldscan* 5-6 (2001), 24. "National Programme for the Management of Spent Fuel and Radioactive Waste," First edition, Kingdom of Belgium, October 2015, Courtesy translation, https://economie.fgov.be/sites/default/files/Files/Energy/National-programme-courtesy-translation.pdf, 19.

[2] This included 181.5 tonnes of natural and low-enriched uranium spent fuel, plus 30.6 tonnes of fuel elements from European pilot reactors, from which the facility separated 677 kg of plutonium and 1,363 kg of highly enriched uranium. See, http://www.eurochemic.be/eng/proces.html.

[3] From 1983 to 1994, Belgium owned 50 percent of Synatom. After that time, Belgium retained veto power over any decision running counter to national energy policy. http://synatom.be/en/about-us/a-brief-history/.

[4] "Fifth meeting of the Contracting Parties to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management," National Report, Kingdom of Belgium, October 2014, 11 http://www.belv.be/images/pdf/2015-jointconv-public.pdf. Jean Van Vyve and L. Resteigne, "Introduction of MOX fuel in Belgium NPPs – From feasibility to final implementation," in *Fuel management and handling: proceedings of the International conferences organized by the British Nuclear Energy Society and held in Edinburgh on 20-22 March 1995* (London: British Nuclear Energy Society, 1995), 133.

[5] "Management of irradiated fuels in Belgium," FOD Economie, K.M.O. http://economie.fgov.be/en/consumers/Energy/Nuclear_energy/Management_of_irradiated_fuels_in_Belgium/#.WfeOm8aZMdU (accessed October 30, 2017).

[6] "Belgium" (Updated 2016), IAEA Country Nuclear Power Profiles, https://www-pub.iaea.org/mtcd/publications/pdf/cnpp2013_cd/countryprofiles/Belgium/Belgium.htm (accessed October 30, 2017).

[7] "Belgium" (Updated 2016), IAEA Country Nuclear Power Profiles.

[8] "Belgium cancels reprocessing contract!" *Wise World Service Information on Energy,* December 18, 1998, https://wiseinternational.org/nuclear-monitor/504/brief.

[9] "Historique de la gestion des combustibles irradiés en Belgique," SPF Economie, January 15, 2018, https://economie.fgov.be/fr/themes/energie/sources-

denergie/nucleaire/gestion-des-combustibles/historique-de-la-gestion-des. "Belgium" (Updated 2016), IAEA Country Nuclear Power Profiles.

[10] "National Programme for the Management of Spent Fuel and Radioactive Waste," 19.

[11] "Information circular: Communication Received from Belgium Concerning its Policies Regarding the Management of Plutonium," IAEA, May 18, 2016, 3-4.

[12] "Management of irradiated fuels in Belgium," FOD Economie, K.M.O., http://economie.fgov.be/en/consumers/Energy/Nuclear_energy/Management_of_irradiated_fuels_in_Belgium/#.WfeOm8aZMdU (accessed October 30, 2017).

[13] Yvon Vanderborck and Jean Van Vliet, "Safety of the Belgonucleaire MOX fabrication plant," in *Nuclear Materials Safety Management Volume II,* ed. Leslie J. Jardine and Mikhail M. Moshkov (St. Petersburg: Springer-Science + Business Media B.V., 1998), 63. "Belgium" (Updated 2016), IAEA Country Nuclear Power Profiles.

[14] Author's email exchange with Hubert Bairiot, May 2018.

[15] "Areva: layoffs and restructuring," *Wise World Service Information on Energy,* November 11, 2011, https://wiseinternational.org/nuclear-monitor/736/areva-layoffs-and-restructuring.

[16] "Dessel: a new step forward with the dismantling of the site," Framatome, October 19, 2017, http://www.framatome.com/EN/businessnews-841/dessel-a-new-step-forward-with-the-dismantling-of-the-site.html. Geert Cortenbosch, "Establishing decommissioning plans and the decommissioning of the fuel facility FBFC in Belgium," Bel V, Presentation to Eurosafe Forum 2016, 2016. https://www.eurosafe-forum.org/sites/default/files/Eurosafe2016/Seminar3/3.02_Presentation_FBFC_Eurosafe percent202016.pdf.

[17] Under its nuclear phase-out program, the Belgian Government plans to shut down both reactors by 2022.

[18] Hubert Bairiot and Gérard Le Bastard, "Recent progress of MOX fuels in France and Belgium," International Atomic Energy Agency, 1988, 460.

[19] Bairiot and Le Bastard, "Recent progress of MOX fuels," 462.

[20] Bairiot and Le Bastard, "Recent progress of MOX fuels," 463.

[21] Bairiot and Le Bastard, "Recent progress of MOX fuels," 463-464.

[22] Jean Van Vliet, et al., "Reprocessing and MOX in Belgium: past experience and future possibility," BNS Conference on Nuclear Fuel Management in the Belgian NPPs, 2009, 2-3.

[23] Albert Charlier and Nadine Hollasky, "Introduction of mixed oxide fuel elements in the Belgian cores," Brussels, 1994, 335.

[24] Van Vliet, et al., "Reprocessing and MOX in Belgium," 6.

[25] Charlier and Hollasky, "Introduction of mixed oxide," 338.

[26] "Dessel: a new step forward with the dismantling of the site."

[27] An anonymous source says that Belgonucleaire produced 600 tons of MOX for foreign customers.

[28] P. Deramaix, et al., "Experience and trends at the Belgonucleaire plant," Belgonucléaire, 2000, 169.

[29] Hubert Bairiot, interview with author, January 11, 2018.

[30] Bairiot, interview, January 11, 2018.

[31] Frank Barnaby, "Annex I. MOX production standards and quality control at Belgonucléaire and the implications for reactor safety in Fukushima-1-1" in "Greenpeace comments regarding the Nuclear Regulatory Commission's (NRC) scoping process in preparation for the completion of the Plutonium (MOX) Fuel Environmental Impact Statement (EIS)," ed. Damon Moglen, Washington DC, May 21, 2001, 8.

[32] Belgonucléaire, "Comparison of MOX & U Fuel Assembly Costs," 1998, 3.

[33] Belgonucléaire, "Comparison of MOX & U Fuel Assembly Costs," 3.

[34] Pierre Goldschmidt, email to Alan Kuperman, July 30, 2018. Goldschmidt was director general of Synatom at the time of the November 1990 study. He says that if plutonium was assumed to be free, and combined with depleted uranium (presumably also assumed to be free or almost so), then the total cost of MOX fuel was estimated to be only slightly higher than that of LEU fuel. For this to be true, the combined uranium and enrichment costs for LEU fuel would need to be about four times higher than the LEU fabrication costs. By contrast, according to a 2017 U.S. study, the combined modal uranium and enrichment costs are about half those of LEU fabrication. See, "Advanced Fuel Cycle Cost Basis – 2017 Edition," INL/EXT-17-43826, Prepared for U.S. Department of Energy Fuel Cycle Options Campaign, NTRD-FCO-2017-000265, September 29, 2017, p. x, https://fuelcycleoptions.inl.gov/2017%20Cost%20Basis%20Report/2017%20Advanced%20Fuel%20Cycle%20Cost%20Basis_1.pdf.

[35] D. Haas, "MOX fuel fabrication experience at Belgonucleaire," International Atomic Energy Agency, 1997, 80.

[36] Haas, "MOX fuel fabrication experience at Belgonucleaire," 80.

[37] Bairiot, interview, January 11, 2018.

[38] Bairiot, interview, January 11, 2018.

[39] Pierre Dewallef, interview with author, January 12, 2018.

[40] Hubert Bairiot, et al., "LWR MOX Fuel Experience in Belgium and France with Special Emphasis on Results Obtained in BR-3," Centre d'Etudes Nucléaires de Saclay, Service de Documentation, Commisariat à l'Energie Atomique, 1986, 3.

[41] Bairiot, et al., "LWR MOX Fuel Experience in Belgium and France," 4.

[42] Deramaix, et al., "Experience and trends at the Belgonucleaire plant," 176.

[43] Author's interview with an industry official, January 9, 2018.

[44] The cost of producing MOX would also be reduced after full amortization of the construction costs of the fabrication facility, but that would not obviously translate into a reduced price for MOX, especially for foreign customers if the fabricator has a monopoly.

[45] "Information Générales sur le Cycle du Combustible Nucléaire Belge," SPF Economie, P.M.E., December 2014.

[46] Hubert Bairiot, email to author, April 1, 2018.

[47] Bairiot, email to author, April 1, 2018.

[48] Bairiot, email to author, April 1, 2018.

[49] Bairiot, email to author, April 1, 2018.

[50] Belgian nuclear industry official who requests anonymity, personal communication, July 18, 2018.

[51] Jan Vande Putte, interview with author, January 12, 2018.

[52] Author's interview with a Belgian nuclear industry official, January 9, 2018.

[53] Vande Putte, interview, January 12, 2018.

[54] Vande Putte, interview, January 12, 2018.

[55] Steve Mufson, "Attacks Stoke New Fears About Nuclear Security," *Washington Post*, March 26, 2016.

[56] Charlier and Hollasky, "Introduction of mixed oxide," 337.

[57] Charlier and Hollasky, "Introduction of mixed oxide," 337.

[58] Charlier and Hollasky, "Introduction of mixed oxide," 337.

[59] Bairiot, interview, January 11, 2018.

[60] Bairiot, et al., "LWR MOX Fuel Experience in Belgium and France," 3.

[61] Bairiot, interview, January 11, 2018.

[62] Bairiot, interview, January 11, 2018.

[63] Deramaix, et al., "Experience and trends at the Belgonucleaire plant," 170.

[64] Deramaix, et al., "Experience and trends at the Belgonucleaire plant," 170.

[65] Barnaby, "Annex I. MOX production standards," 18.

[66] Barnaby, "Annex I. MOX production standards," 18.

[67] Barnaby, "Annex I. MOX production standards," 19.

[68] Deramaix, et al., "Experience and trends at the Belgonucleaire plant," 169.

[69] Hubert Druenne, interview with author, January 5, 2018.

[70] Haas, "MOX fuel fabrication experience at Belgonucleaire," 78.

[71] Bairiot, interview, January 11, 2018.

[72] Haas, "MOX fuel fabrication experience at Belgonucleaire," 77-78. Bairiot and Le Bastard, "Recent progress of MOX fuels," 465.

[73] Haas, "MOX fuel fabrication experience at Belgonucleaire," 83.

[74] Belgian source who requests anonymity, interview with author.

[75] Druenne, interview, January 5, 2018.

[76] Druenne, interview, January 5, 2018.

[77] Druenne, interview, January 5, 2018.

[78] Druenne, interview, January 5, 2018.

[79] Vande Putte, interview, January 12, 2018.

[80] Mycle Schneider, interview with author, January 3, 2018.

[81] Vande Putte, interview, January 12, 2018.

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

[83] "Belgium gets new government," *Agence France Presse*, July 11, 1999.

[84] "Belgian parliament backs plan to phase out nuclear plants," *Agence France Presse*, January 16, 2003.

[85] Charlier and Hollasky, "Introduction of mixed oxide," 338, 342.

[86] Belgian source who requests anonymity, interview with author.

[87] Charlier and Hollasky, "Introduction of mixed oxide," 338, 342.

[88] Charlier and Hollasky, "Introduction of mixed oxide," 338, 342.

[89] Charlier and Hollasky, "Introduction of mixed oxide," 338, 342.

[90] Charlier and Hollasky, "Introduction of mixed oxide," 338, 341.

[91] Pierre Dewallef, interview with author, January 12, 2018.

[92] Druenne, interview, January 5, 2018.

[93] Charlier and Hollasky, "Introduction of mixed oxide," 340.

[94] Vande Putte, interview, January 12, 2018.

[95] Dewallef, interview, January 12, 2018.

[96] Druenne, interview, January 5, 2018.

[97] Bairiot et al., *LWR MOX Fuel Experience in Belgium and France*, 11.

[98] Druenne, interview, January 5, 2018.

[99] Belgian source who requests anonymity, interview with author.

[100] "Qui contrôle nos installations nucléaires?" Forum Nucléaire, https://www.forumnucleaire.be/theme/la-surete/surete-et-controle-des-centrales-nucleaires (accessed April 13, 2018).

[101] Hubert Druenne, email to author, April 16, 2018.

[102] Charlier and Hollasky, "Introduction of mixed oxide," 335.

[103] The first consisted of "reload by quarter core, annual cycle of 11,000 MWd/T, 8 MOX assemblies, nominal operating conditions, UO2 assemblies

enriched to 3.8 percent." The second included "reload by third of core, extended cycles of 15,000 MWd/t, 12 MOX assemblies, uprated power operating conditions (+4 percent), UO2 assemblies enriched to 4.5 percent." See, Charlier and Hollasky, "Introduction of mixed oxide," 338.

[104] Charlier and Hollasky, "Introduction of mixed oxide," 338. Belgian source who requests anonymity, interview with author. The design burnup for the two reactors was 45,000 MWd/tHM, and spent fuel was placed into pool storage on site once discharged. Each MOX fuel assembly was designed to produce the same energy as an LEU assembly. Tihange-2 had a 15-month cycle length and one-third of the core was replaced after each cycle. The cycle length for Doel-3 was 12 months, with one-quarter of the core replaced after each cycle.

[105] Druenne, email to author, April 16, 2018.

[106] Druenne, interview, January 5, 2018.

[107] Dewallef, interview, January 12, 2018.

[108] Dewallef, interview, January 12, 2018.

[109] Bruce B. Bevard, et al., "The Use of MOX Fuel in the United States: Bibliography of Important Documents and Discussion of Key Issues," Oak Ridge National Laboratory, 2000, 3.

[110] Charlier and Hollasky, "Introduction of mixed oxide," 338, 343.

[111] Druenne, interview, January 5, 2018.

[112] Bairiot et al., "LWR MOX Fuel Experience in Belgium and France," 7.

[113] Bairiot et al., "LWR MOX Fuel Experience in Belgium and France," 7.

[114] Belgian source who requests anonymity, interview with author.

[115] Luc Vanhoenacker, "Belgian Experience in Steam Generator Replacement and Power Uprate Projects," Tractebel Engineering, October 2012, 6.

[116] Belgian source who requests anonymity, interview with author. Reactor safety regulations are contained in the Belgian Regulation for the Protection of Labour, applicable to pressure vessels, electrical installation, and lifting equipment. The Royal Decree of February 28, 1963, on the Belgian Regulation for the Protection against the Danger of Ionizing Radiations, regulates the nuclear aspects of the reactors.

[117] Belgian source who requests anonymity, interview with author.

[118] Nadine Hollasky, "Belgian Licensing Requirements: Mixed Cores and Control Rods Insertion Problem Aspects," Specialist meeting on nuclear fuel and control rods: operating experience, design evolution and safety aspects, November 1996, 374-375.

[119] Hollasky, "Belgian Licensing Requirements," 374-375.

[120] Hollasky, "Belgian Licensing Requirements," 374-375.

[121] Therefore, they also present statistical uncertainties that, according to AVN, cannot be statistically combined, but need "to be considered in a

deterministic and penalizing way" (Hollasky, "Belgian Licensing Requirements," 374-375, 379). Uncertainty also applies to the departure for nucleate boiling (DNB), which reduces the safety margin. The DNB is an important parameter, as it represents "the point at which the heat transfer from a fuel rod rapidly decreases due to the insulating effect of a steam blanket that forms on the rod surface when the temperature continues to increase." See "Departure from nucleate boiling (DNB)," U.S. NRC, Nuclear Regulatory Commission, https://www.nrc.gov/reading-rm/basic-ref/glossary/departure-from-nucleate-boiling-dnb.html (accessed March 01, 2018.). As a result, AVN imposed a four-percent design limit on DNB ratio. In addition, the neutronic compatibility of LEU and MOX fuel had to be ensured. This included verifying the reactivity during various operational conditions, and comparing the isotopic composition, moderator temperature, and Doppler coefficients. Finally, fuel behavior was observed to ensure that the fuel rod would not incur cladding rupture or other damage during operations.

[122] Belgian source who requests anonymity, interview with author.

[123] Belgian source who requests anonymity, interview with author.

[124] Van Vliet, et al., "Reprocessing and MOX in Belgium," 8.

[125] Van Vliet, et al., "Reprocessing and MOX in Belgium," 12.

[126] Van Vliet, et al., "Reprocessing and MOX in Belgium," 4, 13.

[127] 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.

3

MOX in France: Reassessment as Foreign Customers Fade

Kingsley Burns

France is the world's most prolific country in both the fabrication and use of mixed-oxide (MOX) plutonium-uranium fuel for light-water nuclear reactors. This chapter explores France's historical experience with MOX, current practice, and future scenarios. It focuses on safety and security concerns, economic considerations, and waste management. Field interviews were conducted in France in 2018 with current and former officials of the company that fabricates MOX fuel (Orano), the atomic energy commission (CEA), the domestic utility (EDF), and independent nuclear experts. MOX fuel has been a technological success, achieving parity with traditional low-enriched uranium (LEU) fuel in burnup and performance. However, MOX does not appear economically competitive with LEU. Perpetuation of the program is driven instead by the lack of alternative disposition options for spent LEU fuel besides reprocessing, which creates separated plutonium that must be recycled as MOX under current policy. Sharp drops in foreign demand for French reprocessing and MOX fabrication since 2000 have created excess capacity, and EDF is now the only major customer for these services. Accordingly, the French government is reassessing the future of the nuclear fuel cycle and conducting a study of whether the planned deep geological repository for high-level reprocessing waste could also accommodate spent fuel, which could obviate future reprocessing.

Plutonium is controversial as a civilian fuel because it is highly toxic and can be used to make nuclear weapons. Although many countries have attempted to launch MOX fuel programs, France is the only one that continues to operate both commercial reprocessing and MOX fabrication facilities for thermal reactors. This chapter examines France's initial motivations for MOX use, its experience producing and using MOX, and the future of MOX in

France. It finds that France initially turned to MOX for light-water reactors (LWRs) when it became apparent that a previously expected generation of fast reactors would not come to fruition. This decision was heavily influenced by the "sunk cost" of investments in reprocessing facilities that would otherwise have gone unused. French nuclear firms then invested to expand the reprocessing and MOX fabrication facilities in expectation that lucrative foreign contracts would continue.

However, a drop in foreign demand from 2000 onward has left these facilities with excess capacity, and the French utility EDF is now the only major customer. Although France has 24 of its 58 power reactors licensed to burn MOX fuel, these reactors have been loading less MOX than they are licensed to use, and France's stockpile of unirradiated plutonium continues to grow. As of 2016, France reported holdings of around 65 tonnes (metric tons) of domestic-owned plutonium and 16 tonnes of foreign-owned plutonium. This stockpile presents serious security concerns, as it is sufficient for approximately 10,000 nuclear weapons. A fourth-generation fast reactor (ASTRID) is under development, but estimates suggest that commercial fast reactors will not come online until at least the 2040s, so they are not a viable near-term solution to the growing plutonium stockpile.

France's reprocessing and MOX industries have reached a major turning point. The country's two main nuclear firms are under severe financial strain and are both pursuing high-stakes foreign projects to remain solvent. French energy policy, which has long supported the recycling of spent fuel, is shifting away from nuclear. President Emmanuel Macron's administration is solidifying its approach to a 2015 law that would potentially force the closure of many reactors that currently burn MOX fuel.

The next section of this chapter is a brief history of France's MOX program. Following that are detailed sections on MOX fabrication, domestic use of MOX in LWRs, and reprocessing – including current status and future plans for each. Topics covered included safety and security concerns, economic considerations, and waste management. The chapter closes with lessons from the French experience with MOX.

Why MOX?

France started pursuing reprocessing technologies in the late 1950s in anticipation of a new generation of fast breeder reactors that would require separated plutonium.[1] Although the breeder program was slow to develop and eventually suspended, France remained committed to its policy of reprocessing spent fuel. This decision was influenced by contracts to reprocess foreign spent fuel that had helped to pre-finance the UP3 facility at La Hague, in northern France, which opened in 1990. In the absence of commercial breeder reactors, the French began recycling their own separated plutonium by loading pressurized water reactors (PWRs) with partial MOX fuel cores in 1987.

France is the dominant country in the fabrication and use of MOX, and is one of only three countries currently operating a commercial-scale reprocessing program for civilian spent fuel.[2] France began reprocessing spent LWR fuel in 1976, and its commercial fabrication of MOX originated in 1989 in Cadarache, in southern France. France first investigated the use of MOX fuel in the mid-1970s in the Centrale Nucléaire des Ardennes PWR. These experiments were conducted as part of the Commission of the European Communities (CEC) research program on plutonium recycling in LWRs. The trials involved irradiation of four "island" assemblies in 1974, and two full-MOX lead test assemblies in 1975 – both of which contained fuel rods produced by France's Atomic Energy Commission (CEA) at its Cadarache plant. After these early trials, French research on plutonium fuels turned to fast reactors, thereby ending the CEC research program.[3]

France's first commercial MOX assemblies in the 1970s were primarily produced from French plutonium by Belgonucleaire at its P0 plant in Dessel, Belgium, but France's domestic MOX fabrication capabilities developed quickly. The UP2 reprocessing plant at La Hague began handling exclusively LWR spent fuel in 1987, and CEA's Cadarache facility began fabricating MOX fuel rods on a commercial basis in 1989. The MOX fuel rods were combined into fuel assemblies elsewhere – first by FBFC at Dessel in Belgium, then at Cogema's new MELOX plant starting in the early 1990s. MELOX, France's second and current MOX fabrication plant, is located at the Marcoule nuclear site, also in southern France. It began commercial operations in 1995 with an initial authorized annual capacity of 101 tonnes of heavy metal (MTHM), equivalent to 115 tonnes of uranium oxide and plutonium oxide.

In addition to fulfilling domestic contracts, France has engaged in reprocessing and MOX fabrication for several European countries and Japan. From 1997 to 1999, Cadarache produced MOX fuel for German and Swiss utilities, and from 2000 to 2003 exclusively for German reactors. MELOX began producing MOX for EDF in 1995, and for Japanese customers in 1999. Contracts for German MOX customers were transferred to MELOX when Cadarache closed in 2003, and those contracts ended in 2015. Today, the main facilities in the MOX fuel cycle are the UP2-800 and UP3 reprocessing plants at La Hague, which have a combined authorized capacity of 1,700 MTHM/year, and the MELOX fabrication facility, which has a current authorized capacity of 195 MTHM/year.

Methods

This study relies heavily on primary source material, including documents produced by the nuclear industry, government, and regulators. The research also included a series of interviews in 2018 with subject matter experts from the French nuclear industry conducted in France and primarily in English. Interview subjects were current and former officials of the company that fabricates MOX fuel (Orano, formerly Areva and Cogema), the regulatory authority (CEA), and the domestic utility (EDF). Interviewees also included two independent nuclear consultants and a nuclear journalist. Greenpeace-France is very active on this topic but did not respond to interview requests.

MOX Fabrication

France's first MOX fabrication facility was the government-owned *Atelier de Technologie du Plutonium* (ATPu), located at CEA's Cadarache nuclear studies center near Marseille. ATPu was built in 1961, and its two production lines primarily produced fast breeder reactor (FBR) fuel for the next 30 years. In 1989, the facility was authorized to produce MOX fuel for LWRs. At the time, the largely government-owned EDF had a contract to purchase about 17 tonnes of MOX per year, and the plant was expected to have a capacity of 20 tonnes per year, although it initially did not achieve this level.[4] The authorization did not include any limits on production quantities, which were controlled by the operator's safety reports. Subsequent facilities included production caps in their authorization decrees under the "Basic Nuclear Installation" regulatory scheme established in 1963.

Abandoning a request to build a third production line for its new LWR MOX fuel, CEA instead converted one of its two FBR lines. The government-owned Cogema assumed control of operations in 1991, and then modified the other production line in the mid-1990s to produce both FBR and LWR fuel.[5] This raised the plant's maximum annual capacity to 30 MTHM/year, assuming no FBR fuel was being fabricated.[6]

In 1996, nearly all MOX production for EDF was transferred to the new MELOX plant, although a few fuel rods for EDF were still produced at Cadarache. By contrast, MOX for German and Swiss customers continued to be produced at Cadarache, where throughput reached 40 MTHM/year by 1999. In 1995, safety authorities demanded that the Cadarache MOX plant be closed "shortly after 2000" in light of serious earthquake risk. The facility ceased operations in 2003, and the remaining production of MOX for Germany was shifted to MELOX.[7] Decommissioning of Cadarache began in 2007, and was completed in 2017.

MELOX

MELOX received its initial installation license, the *Décret d'Autorisation de Création* (DAC), in May 1990, and it produces both MOX fuel rods and assemblies. The DAC authorized the plant to fabricate fuel rods containing 101 MTHM/year.[8] The MELOX plant initially was conceived as a small facility, designed to accommodate workers displaced by the closure of other facilities, including the nearby UP1 reprocessing plant in Marcoule. Cogema had planned a large MOX fabrication facility at La Hague but never pursued it, so MELOX was eventually designed for high throughput, theoretically up to 250 MTHM/year.[9] Since then, the actual throughput has been constrained mainly by regulators, and more recently by lack of demand, but not typically by technical limitations.

Japan's planned growth of MOX use in the late 1990s – which still has not transpired (see chapter 5) – led Cogema to pursue increasing MELOX's capacity. In 1997, the company applied for a license amendment for a new line at MELOX to produce MOX for boiling water reactors (BWRs), in expectation of Japanese contracts. Authorization was granted in July 1999, despite significant opposition from the Environment Minister, who was from the Green Party. Although the new BWR line effectively added up to 50 MTHM/year of additional production capacity, the facility license still capped throughput at 101 MTHM/year.[10]

By the early 2000s, a series of setbacks compelled Cogema to reconsider its rosy estimates of global MOX demand. EDF's MOX use did not rise as expected because only 20 French reactors, not 28, were licensed for MOX. In Germany, domestic politics inhibited the delivery of spent fuel to France for reprocessing. Japanese customers temporarily halted their MOX purchase contracts over disputes about quality control. As a result, Cogema decreased MELOX's book capacity from 250 to 195 MTHM/year and took a €184 million write-down on its 2001 finances.[11]

Cogema's 1999 license application to increase MELOX's annual output cap to 195 MTHM remained politically stalled three years later, so the company proposed a compromise, offering to close Cadarache and transfer its production capacity (roughly 40 MTHM/year) to MELOX.[12] The government authorized a public inquiry in January 2003, and then accepted the deal, granting MELOX a license in September 2003 for 145 MTHM/year.

Cogema continued to pursue increased throughput at MELOX in anticipation of the shutdown in Belgium of facilities that produced MOX fuel rods at Belgonucleaire's P0 plant and assemblies at FBFC (see Chapter 2). Fabrication of MOX assemblies for Germany would be shifted from Belgium to MELOX. In 2004, Cogema reapplied for a license for 195 MTHM/year, finally receiving it in 2007.[13] However, MELOX has persistently operated well below that limit.

In 2008, the head of Areva's Recycling Business Unit said that MELOX could not reach its licensed capacity because too many different kinds of fuel assemblies were being manufactured. He estimated that the plant realistically could fabricate 130 to 150

MTHM per year, depending on the type of fuel being produced. At the time, MELOX had contracts for around 30 MTHM of annual exports, plus domestic production.[14] Areva adjusted its production targets after the 2011 Fukushima disaster, saying that MELOX would aim to produce 150 MTHM/year – just over 75 percent of its licensed capacity.[15]

Since then, Areva's annual reports show that MELOX's throughput has fallen even further. This is due mainly to declining demand, not production problems, since the company points out that it has honored all contracts. Recent annual output is summarized in Table 1.

Table 1
MELOX Output Declines in Recent Years

Year	**MTHM**	**Notes**
2014	134	
2015	125	Ended fabrication for Germany.
2016	124	Resumed fabrication for Japan.
2017	110	Output constrained by technical problems.

After the restart of Japanese contracts in 2016, Areva had predicted that MELOX would increase production to 130 MTHM in 2017.[16] However, production problems reduced annual output by 20 tonnes to 110 MTHM.[17] In its mid-2017 earnings report, Areva attributed this shortfall to "technical production difficulties" that also affected the La Hague reprocessing plant.[18] Areva has not released details, but experts suggest a link to MELOX's loss of 80 workers through "voluntary departures" under Areva's restructuring plan.

Jean-Philippe Madelaine, who took over as MELOX's director in early 2018, refused in a press interview to draw a direct connection between the staff cuts and the production shortfall, but conceded that, "when you have a mass of somewhat important departures, you have a latency period."[19] The production problems are inopportune for MELOX, whose management is pursuing contracts to export its technology. Madelaine's 2018 goals include "strengthening [MELOX's] status as a reference plant for recycling unit projects in Japan, China, and the United Kingdom."[20] The company hopes to restore output to 130 MTHM in 2018.[21]

Economics

The high cost of reprocessing to obtain separated plutonium is generally not included in MOX fuel costs and is instead categorized as spent fuel management. Even when plutonium is counted as free, however, France's MOX fabrication cost is approximately four to five times higher than for LEU – a figure confirmed by multiple interviewees, including in industry. The higher cost to fabricate and deliver MOX fuel can be attributed to several main factors: more stringent radioprotection requirements for plutonium; the need to blend plutonium and uranium; and tighter security for transportation – of plutonium to the fabrication plant, and of fabricated fuel to the reactors.[22] According to a French government report in 2000, the total cost of producing MOX fuel, including reprocessing to obtain the plutonium, was 4.8 times that of LEU fuel.[23]

France's shift of MOX production from the smaller Cadarache to the larger MELOX plant enabled economies of scale but also imposed substantial fixed costs. The net effect on cost depends on output: if production is high, the cost per unit is lower at MELOX; but if production drops, the cost per unit increases. Jürgen Krellmann, a former executive at both the Cadarache and MELOX fabrication facilities, claims that in his experience the costs at MELOX were approximately 20 percent lower than at Cadarache.[24] However, a 1991 study predicted that the costs per unit at such a large plant could be up to three times higher if it ran below capacity, as MELOX has.[25]

In 2001, as noted, Cogema utilized an accounting maneuver to make future MOX production appear more profitable. The company slashed MELOX's book capacity from 250 to 195 MTHM/year, which imposed an enormous, one-time loss of €184 million in net revenue but reduced future annual costs for amortizing the plant's construction. Areva's chairman claimed this would enable the company to "improve the profitability of MOX fuel."[26] Cogema's Fuel Business Unit director further claimed that the write-down and MELOX technical improvements would bring MOX prices within "a few tens of percent" of LEU costs in the medium term. However, there is no sign today that MOX prices have dropped, and they are still believed to be hundreds of percent higher than LEU.[27]

Waste Management

The MELOX plant was designed to minimize wasted production. Its MIMAS process ostensibly reincorporates production scraps and sub-spec product, together known as "chamotte," back into the main product flow.[28] The plant has some onsite storage capacity for such chamotte but sends the excess to the La Hague reprocessing facility, along with any defective output that cannot be reincorporated into the production process.

In 2015, the National Agency for the Management of Radioactive Waste (ANDRA) reported that 234 tonnes of unirradiated MOX was stored at La Hague by the end of 2013 – the first time it had reported this material separately.[29] In a 2018 report, two former French government nuclear engineers calculated that this represented 7.2 percent of France's historical MOX production. Based on the 2013 statistics, the report's authors extrapolate that by 2018 there were 20.4 tonnes of plutonium in unirradiated MOX stored at La Hague.[30] These estimates are supported by Orano's managing director, Philippe Knoche, who testified in 2018 that La Hague holds roughly 20 tonnes of unirradiated plutonium in MOX and other forms besides separated plutonium.[31] Independent experts claim that the vast majority of this unirradiated MOX is being held in La Hague's storage pools.[32] Consistent with this assertion, an Areva official estimated that only "a few fresh assemblies here and there" had been reprocessed.[33]

Security of Fuel Facilities and Transportation

Risks of nuclear terrorism and nuclear proliferation are likely increased by France's policy to reprocess spent fuel and recycle the resulting plutonium in MOX fuel. This practice exposes nuclear weapons-usable, separated plutonium to potential theft or diversion during transport and while at the reprocessing and MOX fabrication facilities. By contrast, the alternative of a once-through nuclear fuel cycle would avoid the separation of plutonium, which would remain protected from theft initially by the radiation barrier in spent fuel and subsequently by the geological barrier in a repository. Interestingly, France actively rejects this logic, claiming that the closed fuel cycle instead reduces proliferation risks. A typical, October 2017 government report asserts that "using plutonium in MOX fuel enables consumption of about one-third of the plutonium, while significantly degrading the isotopic composition of the remaining plutonium, so this technology is non-proliferating."[34] In reality, it is well documented that reactor-grade plutonium, such as that separated from France's spent fuel, can be used to make reliable nuclear weapons.[35]

Separated plutonium must be transported approximately 1,000 km (more than 600 miles) by road from La Hague to MELOX. Until 2003, each shipment typically consisted of a single truck carrying around 140 kg of plutonium oxide. Starting in August 2003, the transports have comprised a two-truck convoy carrying around 280 kg of plutonium oxide every seven to ten days.[36]

France has adopted security categories that are slightly more restrictive than IAEA recommendations for lower-risk materials,[37] but as in the IAEA guidelines, two or more kilograms of plutonium constitute "Category 1" material, which is subject to higher levels of physical security. Transports of Category 1 and 2 materials, except for spent fuel, require a police escort under French law.[38] In 2010, Areva's transport contractor paid the National Gendarmerie €450,000 for security escort of non-irradiated nuclear transports including the plutonium shipments, or around €2,650 per transport. An audit revealed that this payment covered only 10 percent of the actual cost, leaving the Gendarmerie to pay around €4 million.[39]

Watchdog groups have questioned the security of the plutonium shipments, warning that they are vulnerable to theft or intentional environmental dispersal.[40] Each truck carries nine transport casks in what appears to be a standard-size shipping container. Security escorts generally comprise two vans carrying lightly armed gendarmes. Greenpeace activists have been able to follow the convoys and map their routine pathways and stops.[41] At a 2018 French parliamentary hearing on the security of nuclear installations, Orano's managing director announced that the firm would work to increase its protection of nuclear transports. He pledged additional security on plutonium shipments by the end of 2018, and a near-term plan to make the convoy routes less predictable.[42]

Orano's fuel-cycle facilities also incur significant security costs. Knoche says the firm's annual security expenses are stable at around €300 million, and that they accounted for five percent of the annual operating costs at MELOX and La Hague. Spending on security could be doubled, he says, while adding only around 0.2 percent to the domestic price of electricity.[43] This is presumably because at fuel-cycle facilities the operating costs are a fraction of the construction costs, and at reactors the fuel costs are a fraction of the construction costs. In light of the huge quantities of nuclear-weapons usable plutonium at La Hague and MELOX, doubling security spending could well be justified, especially if it only raised the price of electricity by a small fraction of one percent.

MOX Use at French LWRs

France has 58 nuclear power reactors, all operated by a single utility, EDF. Of these reactors, 24 are currently authorized to use MOX fuel. EDF initially licensed 16 reactors to use MOX in the mid-1990s. Four additional reactors (Chinon B1, B2, B3, and B4) were authorized for MOX use in July 1998, bringing the total to 20.[44] Two more reactors (Gravelines-5 and -6) received MOX authorization in November 2007.[45] The final two reactors (Blayais-3 and -4) were authorized for MOX in May 2013, and the loading of such fuel is now proceeding.[46] The reactors chosen for MOX fuel were all 900MWe PWRs in the same family, providing EDF the benefit of a standardized program without substantial variation between reactors.

The legality of using MOX fuel in a French reactor is dependent on the reactor's authorization decree (DAC). The first 16 reactors that were "MOX-ified" included a mention of plutonium fuel in their initial authorization decrees.[47] Because of a policy shift in the early 1980s intended to conserve plutonium for fast reactor startup, plutonium fuel was not included in the authorization decrees for the last 900MWe reactors or the 1300MWe reactors.[48]

If a reactor's initial decree does not include permission for plutonium as fuel, it can be difficult to gain authorization after the fact. Modifying the decrees requires a public inquiry along with environmental impact and risk studies, which can take several years. EDF's request to use MOX fuel in Blayais-3 and -4, for example, required just over three years to be approved.[49]

When EDF began licensing reactors for MOX in the 1990s, it hoped to expand such fuel to 28 of its 34 reactors in the 900MWe class.[50] So far, as noted, it has sought authorization for only 24 of the reactors, and used MOX in just 22 of them (an industry source says the other two will soon be loaded with MOX for the first time). In the late 1990s, industry experts attributed such delays to limitations on MOX production capacity.[51] Today, instead, they blame the expense of modifying the decrees, the high price of MOX fuel, the low price of uranium, and the increased plutonium content of MOX fuel – which taken together leave little incentive to MOX-ify new reactors. What is indisputable is that France has significant surpluses of spent fuel, reprocessing capacity, separated plutonium, MOX fabrication capacity, and authorized reactor capacity to irradiate MOX. This demonstrates that EDF is not maximizing its potential to use MOX fuel domestically.

Economics of Using MOX

Ironically, studies in the 1980s predicted that MOX fuel could cost less than comparable LEU fuel. These analyses compared MOX fabrication costs against the LEU fuel supply chain (purchasing milled natural uranium, conversion, enrichment, and fabrication). Most such studies assumed plutonium was free, because reprocessing costs were assigned to waste management rather than to fuel fabrication. In practice, however, even assuming no-cost plutonium, MOX fuel has proved to be much more expensive than LEU fuel, due to sharp decreases in the costs of uranium and enrichment services, and increases in MOX fabrication costs.

A 1989 OECD study, for example, found that MOX would become economically attractive to utilities if uranium prices exceeded $50/kg, or approximately $178/kg in 2018 dollars.[52] As of early 2018, however, the spot price for uranium was only about $49/kg, meaning that the price of uranium would need to more than triple in order to make MOX fuel competitive.

Nuclear industry officials refuse to divulge specific cost figures or detailed contract information, but there is broad consensus that France's MOX production is a "high-cost operation."[53] EDF officials estimate that MOX fuel is about three to four times as expensive to produce as LEU fuel, a ratio that they have long hoped to reduce.[54] In the late 1990s, EDF aimed to increase the burnup of MOX to improve its economics, but the burnup of LEU has also increased.

Two financial developments in the early 2000s significantly worsened the MOX program's economics. By 2001, EDF had fully amortized its original nuclear power-plant construction expenses. That adjustment changed the distribution of costs for nuclear energy generation, increasing fuel's contribution from about five percent to an average 30 percent of the cost, which led to an even greater focus on possible fuel cost savings.[55] A second financial adjustment occurred in 2001, when EDF fully amortized its stake in the Georges Besse II uranium enrichment plant. This effectively decreased the cost of enriching uranium, reducing by more than 25 percent the cost of LEU fuel, thereby increasing the price penalty for MOX. EDF's deputy fuel director, in 2001, called it "the biggest accident that is happening to MOX" in France.[56]

Today, French nuclear industry officials concede that the use of MOX fuel is not based on economics. "MOX probably doesn't make financial sense for utilities," said one nuclear official in an interview, adding that the picture might improve once uranium returned to a "normal price." Other officials insist that the economic burden of MOX is manageable. For example, a former Areva executive said in an interview that there is "no economic justification for MOX, and no reason to denounce MOX for economics."[57]

Although French energy policy considers plutonium a valuable resource – which is part of the justification for the reprocessing and MOX recycling programs – EDF has assigned its plutonium stocks a zero book value. Indeed, one former EDF official said plutonium should have been listed with negative value, but that wasn't possible politically.[58] Areva's foreign customers confirm that separated plutonium has a negative value, which they must pay if they want third countries to take their plutonium, and France by law cannot hold it indefinitely (see Chapter 8).[59]

MOX proponents point to waste management benefits, such as reducing the quantity of stored spent fuel, and "optimiz[ing] the high-level waste scenario" by vitrifying waste.[60] An industry official also predicts that such recycling eventually will provide economic benefit, since "nobody knows the cost of [the] once-through" fuel cycle, including the proposed geological repository and associated safety measures.[61] However, recycling plutonium also adds costs on the back-end since spent MOX has much higher long-run heat and radiation and thus must cool for 100 years in a storage pool – much longer than spent LEU – before it can be disposed with efficient density in a permanent repository.

Energy Transition Law

In August 2015, France enacted an energy transition law that includes restrictions on nuclear power generation. Under the law, France must reduce the contribution of nuclear to no more than 50 percent of the country's energy supply by 2025, and EDF is responsible for planning the drawdown. An industry report assessed that the change would require the closure of approximately 18 nuclear power reactors, depending on the approach taken by EDF.[62] Because the 24 reactors authorized to use MOX fuel include some of the oldest in France's fleet, it is likely that they would be among the first to close. Doing so without introducing alternative plutonium disposition methods would increase France's already substantial stockpile of separated plutonium.

Nuclear industry officials hope that the Macron administration will relax the drawdown. In 2017, then-Minister of Environment, Nicholas Hulot, announced that the 2025 deadline was not achievable, postponing it by at least five years.[63] However, there are no signs that the 50-percent goal itself is being abandoned, which would require a statutory change. The only other way to avoid closure of reactors would be if overall national energy consumption increased by 50 percent using non-nuclear power sources, which is unlikely.

Modifying Reactors for MOX Fuel

MOX use in LWRs has required several modifications to the reactors and their operations. Because the plutonium in MOX fuel hardens the neutron spectrum, it necessitates additional neutron poisons to control the reaction and provide shutdown capacity. As the percentage of plutonium increases, reactors require higher levels of boron in the water and/or additional (or more efficient) control rods. Unlike reactors in several other countries that avoided extra control rods – by employing MOX with a low percentage of plutonium, cores with a low percentage of MOX, or high concentrations of enriched boron – the French 900MWe reactors employed additional rod cluster control assemblies (RCCAs). When MOX was initially introduced, each reactor required four additional RCCAs, raising the total from 53 to 57.[64] When the plutonium content of the fuel was increased in 2007 to achieve MOX parity with LEU fuel, another four RCCAs were added, for a total of 61,[65] the maximum possible for the existing pressure vessel heads.[66] This means that the plutonium content in the core cannot safely be increased significantly further – by boosting either the MOX percentage in the core or the plutonium percentage in the MOX.

MOX Parity with LEU

Since the early days of large-scale MOX usage in the 1990s, EDF's goal was to make MOX fuel perform as similarly as possible to LEU fuel. The "MOX parity" fuel management program, implemented in the early 2000s, increased the burnup of MOX fuel assemblies to match that of the adjacent uranium fuel assemblies in a reactor. Higher burnup made the price of MOX less uncompetitive with uranium fuels. However, the main economic benefits of MOX parity are two others, according to EDF: higher plant availability, due to synchronizing the refueling of MOX and LEU; and increased operational flexibility because MOX fuel can be replaced by LEU in case of "disruption in the supply chain."[67]

To address safety concerns of higher burnup MOX identified by the French government's Institute for Radiological Protection and Nuclear Safety (IRSN), EDF modified the assemblies. It switched to a different cladding material (M5), which was more corrosion-resistant than the original Zircaloy.[68] In addition, fission gas pressure was mitigated through improved pellet manufacturing methods that minimized "clumps" of plutonium.

Following the changes to fuel design, MOX parity management was licensed in December 2006, and slowly rolled out across the 900 MWe reactor fleet from 2007 to 2014.[69] To reach parity with 3.7-percent LEU, the MOX assemblies have an average plutonium content of 8.65 percent. The core is managed in one-year cycles, with one-quarter reload each cycle. Each reload contains 12 MOX assemblies and 28 LEU assemblies. Both have a maximum assembly discharge burnup of 52,000 megawatt-days per tonne of heavy metal (MWd/tM), with an average discharge burnup of 48,000 MWd/tM.[70]

Environmental and Safety Impact of Using MOX

MOX use in LWRs reportedly has caused no appreciable difference in radioactive release during normal operations. EDF data from a group of six reactors from 2002 to 2004 shows similar levels of gaseous and liquid waste release for MOX and LEU fuel, with the release attributed mainly to fuel-rod leakage.[71] To license MOX fuel for higher burnup as part of the MOX parity scheme, the Directorate for the Safety of Nuclear Installations (DSIN) required a wide range of safety analyses. Specific concerns were highlighted for analysis and ultimately resolved, including the impact of curium-244 in vitrified high-level waste and potentially higher tritium levels in reactor effluents due to the augmented boron levels in the moderator.[72]

Security at Reactor Sites

MOX use has necessitated additional security measures at reactor sites, particularly during MOX handling operations, but few details are available, due to classification. EDF representatives describe modified procedures for MOX transport vehicles entering reactor sites, as well as a "protected zone" for storage of fresh MOX assemblies. Upgrades include the installation of sensor cameras to observe the storage pool, restricting employee access to the fuel area, and ensuring that doors and fuel handling equipment are locked and alarmed.[73] The cost of these changes was characterized by a former EDF official as marginal, because they only required "small adaptations within the physical protection of the plant."[74]

The bulk of the security costs at reactors comes from protection measures not exclusively linked to the presence of MOX fuel. EDF's director of the reactor fleet, Philippe Sasseigne, says the utility has spent around €700 million on improvements to plant security since 2001. He cites an additional cost of €100 million per year for the gendarmes assigned to reactor sites, and another €100 million annually for the rest of the security force.[75]

Fuel Performance

France's MOX fuel performance has been generally successful and similar to that of LEU. This success was likely aided by France's collaboration with Belgonucléaire, whose experience and process technologies were the foundation of France's MOX efforts.[76] France's nuclear industry considers MOX a mature fuel, after 40 years of operating experience and performance modeling. Compared to LEU fuel, MOX has demonstrated higher fuel temperature, due to increased reactivity, and higher rod internal pressure at end of life resulting from higher fission gas release and helium production.[77] Power ramp tests in the early 1990s showed better pellet-clad interaction in MOX fuel than LEU fuel. Improvements in neutronics calculations have yielded good consistency between predicted values and those measured during core startup tests.[78]

Failure rates for MOX fuel have been on par with those of LEU fuel. From the beginning of MOX use through 2010, EDF reported six MOX fuel assembly leakages. Five of the failures were attributed to debris in the water, and one failed assembly was not examined.[79] The debris issues have reportedly been mitigated by adding a trap in the bottom of the MOX fuel assemblies.[80] EDF has reported no significant impact from MOX on reactor operation, except that the refueling outage duration is slightly longer for cores that include irradiated MOX fuel due to its higher long-run decay heat.[81]

Politics of MOX Use

French experts generally agree that public opinion has little influence on domestic nuclear energy strategy or regulation. One former EDF executive described the country's "very powerful atomic lobby" as able to wield significant influence over government policy, sometimes over the objections of the utility.[82] Another EDF official noted the "strong political and governmental consensus, including with industrial actors such as CEA, EDF, Cogema, and Framatome," favoring pro-nuclear national policies.[83]

This political power of France's nuclear industry is illustrated by the history between the Socialist and Green parties. The two parties have long struggled over nuclear energy, with waste and MOX the two major points of contention. In 1997, they agreed on a pre-election platform that called for a moratorium until 2010 on both new nuclear reactors and the manufacture of MOX fuel. Attempting to implement this policy after taking office in 1999, that year the Environment Minister, Dominique Voynet of the Green Party, challenged Cogema's application for a new production line at MELOX. However, at the urging of the nuclear industry, the Socialist-led government granted the license.[84]

In 2011, the MOX program was again the focus of a political battle between the Green party, the Socialist party, and the French nuclear industry. The two political parties signed and announced a pre-election draft platform indicating their intention to end reprocessing and MOX production and to convert those facilities into "centers of excellence for waste treatment and dismantling."[85] The final platform, however, deleted the MOX paragraph. The Greens blamed the Socialist Party for unilaterally modifying the agreement under pressure from Areva, which intervened on the reported grounds of "serious economic, social, industrial, and environmental concerns, which would also lead to the disappearance of French leadership in the civil nuclear sector."[86]

In 2013, the Green Party was yet again frustrated when the Socialist-led government granted EDF a license to use MOX fuel in the Blayais power plant near Bordeaux. Noël Mamère, the deputy mayor of a nearby community, spoke out against the move that he blamed on the Socialists. He viewed it as a political rather than technical decision, alleging that it was "a way to protect the MOX industry, which we are the only country in the world to want to continue." He further characterized the decision as proof that in France the nuclear lobby is stronger than politicians and is "able to impose its law on the President of the Republic and the Prime Minister."[87]

Future MOX Use Plans

The 1300 MWe series reactors were not originally able to accommodate MOX fuel because of limited ability to insert more control rods. In the 1990s, however, a Westinghouse design issue led to new pressure-vessel heads that included openings for additional control rods. It is now technically possible to extend MOX use to the 1300 MWe reactors, and feasibility studies have been conducted.[88] Re-licensing a reactor to use MOX fuel is costly, however, and would require additional safety studies, public inquiries, and physical modifications. As noted, EDF has little incentive to incur such costs to increase MOX use while uranium fuel prices remain low.

France's current hopes for additional nuclear energy rest with the European Pressurised Reactor (EPR), an innovative design created by Areva and Siemens in the 1990s and early-2000s. The country's first EPR is under construction as unit 3 at Flamanville, scheduled to open in 2020. Areva in particular has touted the EPR's ability to use a 100-percent MOX core, which would allow for an "optimized, homogeneous" MOX fuel. Current MOX fuel assemblies contain fuel rods with varying levels of plutonium distributed across three distinct zones to compensate for power variations between MOX and LEU fuel. A full MOX core would allow for uniform fuel rods containing higher levels of plutonium. As Areva notes, an EPR using a full MOX core would recycle the plutonium produced by eight additional EPRs using LEU.[89]

A former EDF executive, however, downplayed the idea of a full MOX core in the EPR. He said there were no plans for 100-percent MOX use, which would require further technical and safety studies. Loading the reactors with 50-percent MOX would give the operator more flexibility and allow for swaps with LEU fuel if there were any issues with MOX supply.[90]

Because it is a new build, the delayed and still incomplete Flamanville EPR includes provisions for MOX fuel in its initial authorization decree. However, EDF has sought final authorization for LEU fuel only, while retaining "the idea of obtaining [authorization] afterwards for MOX."[91] Before the reactor could use MOX fuel, EDF would need to conduct additional safety studies and receive approval from France's Nuclear Safety Authority (ASN).[92] There are no signs that EDF intends to load the reactor with MOX in the near future, and fact sheets from EDF and Framatome list the fuel as LEU.[93]

Historically, EDF undertook research and development to enable MOX fuel to match the burnup of LEU fuel. This included increasing the average plutonium content of MOX fuel assemblies, improving the oxide composition of the fuel to reduce fission gas release, and modifying the designs of the rod and assembly structure.[94] However, MOX fuel in the LWR fleet has not advanced beyond a maximum burnup of 52,000 MWd/tM, while the EPR is designed to be capable of higher burnup between 60-70,000 MWd/tM.[95] The current objective for MOX fuel is to maintain its existing burn-up capacity even while switching to plutonium that has a lower percentage of fissile isotopes due to its having been separated from higher-burnup spent LEU fuel. In October 2017, ASN authorized the use of MOX fuel with an average plutonium content of 9.08 percent, which EDF is expected to implement soon.[96] The utility also has studied the feasibility of MOX with an average plutonium content of 9.2 percent and expects to require a further increase to 9.54 percent within 20 years' time.[97]

Reprocessing

France's first reprocessing facility, UP1, opened at the Marcoule nuclear complex in 1958, and was dedicated to producing weapons-grade plutonium for military use. The La Hague reprocessing facility, by contrast, was built specifically to reprocess power-reactor fuel. The first reprocessing line built at La Hague, UP2, began operating in 1967 and was dedicated to reprocessing fuel from Magnox-style, natural-uranium gas-graphite (UNGG) reactors.[98]

The UP2 plant's history with LWR fuel can be divided into three phases: after a slow startup beginning in the late-1970s, Cogema invested in building capacity during the 1990s, only to be faced with overcapacity after the loss of foreign contracts in the 2000s. La Hague started reprocessing oxide fuels in 1976 with the construction of a High Activity Oxide (HAO) head-end for the UP2 production line. The modified plant, known as UP2-400 or UP2-HAO, had difficulty reaching its nominal annual capacity, which accordingly was reduced from 800 to 400 MTHM, then further to 250 MTHM, before being restored to 400 MTHM in 1987.[99] Several factors contributed to the low initial throughput, including delayed deliveries of foreign spent LWR fuel and logistical complications from the plant's mixed workload of LWR, UNGG, and FBR fuel.[100]

La Hague's capacity expanded substantially in the early 1990s. The UP3 plant added an additional 800 MTHM/year of reprocessing capacity for LWR fuel. Because the new production line was funded almost exclusively by foreign reprocessing clients, particularly Germany and Japan, it was contractually dedicated to reprocessing only foreign fuel for approximately the first 10 years of operation.[101] UP3 was originally expected to begin operating in 1987 but was delayed until 1990.

In addition, a new UP2-800 plant was introduced in 1994. Though it shared some facilities temporarily with UP2-400 until that plant closed, the new line had capacity on par with UP3, being licensed for 800 MTHM/year. In 2003, the licensed annual throughput for each plant (UP2-800 and UP3) was raised to 1,000 MTHM, although their combined throughput was capped at 1,700 MTHM.[102] Actual throughput peaked in the late 1990s at around 1,650 to 1,700 MTHM annually.

However, in 2000, La Hague lost most of its foreign contracts that had accounted for almost half its work. Since 2001, La Hague's annual throughput has been only 920 to 1,170 MTHM.[103] In 2008, EDF signed a contract with Areva to increase reprocessing of domestic spent fuel from 850 to 1,050 MTHM/year by 2010. Although La Hague still has a handful of small foreign contracts, EDF remains its only substantial customer and in 2015 accounted for 90 percent of La Hague's throughput.[104] In 2016, La Hague reprocessed only 1,118 MTHM of spent fuel, or about 66 percent of its licensed capacity.

The reduced throughput at La Hague is mainly attributed to loss of foreign contracts. However, performance issues also have arisen, compelling Areva to admit in its 2012 annual report that, "Without investment in additional capacity, productive capacity is currently around 1,250 metric tonnes." Throughout 2017, Areva (now Orano) reported technical issues affecting performance at both La Hague and MELOX. Environmental concerns also have mounted in recent years (see Appendix 4).

Economics of Reprocessing

Nuclear industry officials characterize France's reprocessing facilities as a sunk cost for the MOX program. "If you have reprocessing [plants] anyway, the marginal cost of processing spent LEU is low," said a former Areva official.[105] By contrast, he said, building new reprocessing facilities just to make MOX would not make sense financially. Another industry official highlighted the importance of economies of scale, stating that a new reprocessing facility "might not make sense in a small country."[106]

When the UP3 contracts were signed with foreign customers in the mid-1980s, reprocessing at the UP2 plant was billed at a fixed rate of around 5,600 French francs per kilogram of heavy metal (kgHM), roughly $800 at the time. The UP3 contracts, however, called for customers to pay the actual operating costs plus a 25-percent markup, in addition to the construction costs of the plant. In 1986, this total cost to foreign utilities was estimated at around $1,000 per kgHM,[107] much of which they paid up-front and only later recovered through a surcharge to their electricity ratepayers.[108]

La Hague will require substantial additional funding when its facilities eventually are shut down and decommissioned. The UP2-400 plant was officially closed in 2004, and work continues on dismantling its workshops. In 2010, Areva estimated the costs of decommissioning UP2-400 at €2.5 billion, but in 2013 it revised that upward to €4 billion including the packaging of waste.[109]

Spent MOX

Although the plants now operating at La Hague were designed to reprocess spent LEU fuel from LWRs, Areva has demonstrated the ability to reprocess fuels of varying composition including spent MOX fuel. In the 1990s, Areva conducted two research campaigns at the UP2-400 plant, reprocessing about 10 MTHM of spent MOX. These were followed by four campaigns at UP2-800 from 2004 to 2008 that reprocessed about 60 MTHM of spent MOX.[110] In total, 73 MTHM of spent MOX was reprocessed at

La Hague from 1992 to 2008, including under contracts for German and Swiss clients.[111] France now has about 2,000 MTHM of spent MOX,[112] meaning it has reprocessed only a tiny fraction – much less than five percent – of the MOX fuel it has irradiated. By contrast, it has reprocessed tens of thousands of MTHM of spent LEU, and currently stores 11,400 MTHM of domestic spent LEU.[113]

Reprocessing spent MOX required several operational modifications because La Hague was not optimized for the high plutonium content: typically five to six percent in spent MOX, compared to only one percent in spent LEU. During reprocessing, the MOX stream was diluted with uranium to reduce criticality dangers during the extraction and vitrification processes.[114] This process was inefficient, doubling the normal throughput time for spent fuel at La Hague.[115]

Areva also has demonstrated the ability to reprocess more than one generation of MOX – that is, reprocessing spent MOX fuel produced with plutonium separated from spent MOX fuel. However, recycling plutonium becomes more difficult and costly with each cycle, due to the reduced percentage of fissile isotopes in the plutonium. A 2014 French parliamentary report noted that, "in the absence of a fast neutron reactor, this uranium, for the most part U-238, and this plutonium, with an isotopic composition enriched in even elements, cannot be the subject of a second recycling in a PWR under conditions of acceptable safety."[116] An Areva recycling executive explained that the first recycling has acceptable performance, but to achieve a second reprocessing cycle the separated plutonium must be mixed with higher quality plutonium extracted from "first-cycle" fuel. The firm's engineers have demonstrated the technical ability to achieve even a third cycle in LWRs, but further extending recycling would require the use of even higher-grade plutonium separated from low-burnup LWR fuel.[117]

Despite the technical feasibility and available plant capacity, France has chosen not to pursue sustained reprocessing of spent MOX fuel. There is broad agreement among nuclear experts that producing MOX from plutonium separated from spent MOX is more complex and costly than alternative disposition. According to Krellmann, who worked at both of France's MOX plants, it likely would be less expensive to dispose of spent MOX as waste.[118]

In 2007, EDF reclassified its spending on spent MOX fuel as long-term waste management, rather than a reprocessing liability, despite France's legal mandate to reprocess all spent fuel.[119] In 2008, the utility explained that, "without prejudging how Generation IV type reactors will develop, liabilities concerning [spent MOX] are now estimated according to a prudent scenario of long-term interim storage and direct disposal."[120] In a 2011 AREVA presentation, the slide on reprocessing of spent MOX focuses instead on interim storage solutions to preserve the spent MOX fuel for a future generation of reactors, or until the "implementation of definitive solutions."[121] Routine reprocessing of spent MOX would also produce much more separated plutonium than France is able to dispose of at this time, since spent MOX contains five to six times as much plutonium as spent LEU.

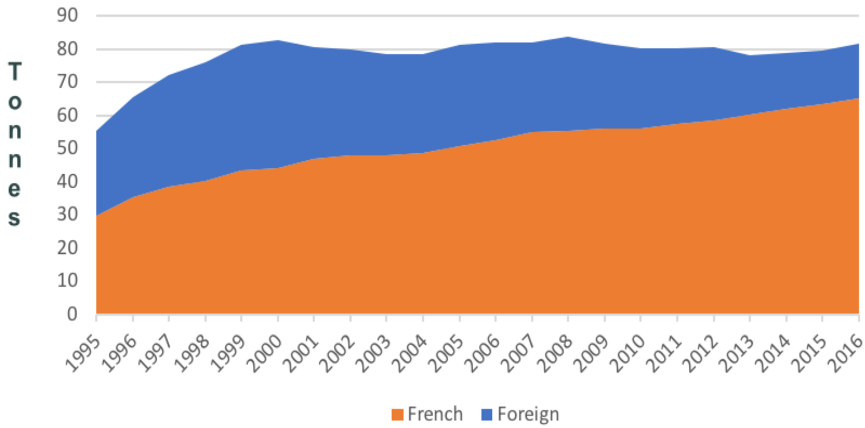
A former EDF executive says the utility avoids reprocessing spent MOX because it wants to maintain the reliable fuel cycle that it has today. He also claims that the utility's strategy is to store spent MOX until fast reactors are "economically needed." He speculates that in 50 to 100 years, a rise in the cost of uranium might spur the need for fast reactors on economic grounds.[122]

Stockpiles of Plutonium

The total amount of unirradiated plutonium in France, combining domestic-and foreign-owned, has stayed relatively constant for two decades at about 80 tonnes. However, the foreign-owned stockpile has been shrinking, as France exports fresh MOX fuel but does not reprocess much new foreign spent fuel.[123] By contrast, the domestic-owned stockpile has grown by an average of 1.5 tonnes annually for the last two decades, reaching 65.3 tonnes at the end of 2016, the most recent year reported to the IAEA (see Figure 1 and Appendix 3).

EDF manages its plutonium stocks under an "equal flows" policy, sometimes called the "flux adequation policy."[124] This calls for separating only as much plutonium as can be recycled through MOX fuel. EDF also claims there is no stockpile of domestic separated plutonium beyond a three-year buffer for MOX fabrication, reportedly to ensure uninterrupted production of such fuel even if reprocessing were temporarily disrupted.[125]

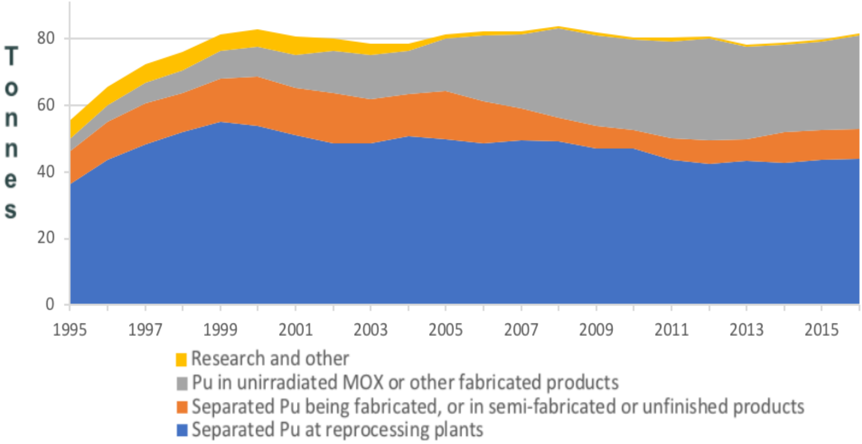
Figure 1. Civil Unirradiated Plutonium in France by Ownership



Source: IAEA Reports: INFCIRC/549/Add.5/[1-21]. See Appendix 3.
Note: Includes separated plutonium and unirradiated MOX in various forms.

Independent experts rightly question whether the equal flows policy is being implemented, given that France's stockpile of domestic-owned, unirradiated plutonium has doubled in the last 20 years. Yves Marignac of WISE-Paris suggests that this growth can be attributed to large quantities of scrap and sub-spec MOX not being reused in the production process.[126] That is, France separates a certain amount of plutonium each year at La Hague from domestic spent fuel, then sends that same amount to MELOX, knowing that a significant fraction (perhaps 10 to 20 percent) will be returned to La Hague as unusable MOX, thereby increasing France's stockpile of unirradiated plutonium. This would explain France's inventory reports to the IAEA, which show a steady increase in the stockpile of plutonium in unirradiated MOX (see Figure 2 and Appendix 3). In 2016, this category equaled 28.1 tonnes of plutonium in scrap MOX and fresh MOX outside the fabrication facility. In 2018, France reported holding 267 MTHM of unirradiated scrap MOX,[127] equivalent to more than two years of nationwide demand for MOX fuel, at 120 MTHM per year. This amount of unirradiated scrap MOX contains more than 20 tonnes of plutonium, assuming its average plutonium content exceeds 7.5 percent.

Figure 2. Civil Unirradiated Plutonium in France by Category



Source: IAEA Reports: INFCIRC/549/Add.5/[1-21]. See Appendix 3.
Notes: Includes both domestic- and foreign-owned plutonium in France. Unirradiated MOX includes scrap and sub-spec.

Stockpiles of Spent Fuel

The backlog of spent fuel awaiting reprocessing in France also continues to increase gradually, in 2015 reaching 14,070 tonnes, some 355 tonnes higher than in 2010. The majority of the net growth comes from spent MOX and spent re-enriched reprocessed uranium fuels, neither of which is currently reprocessed. By contrast, the backlog of spent LEU fuel was virtually unchanged during those five years, decreasing by 0.1 percent.[128] However, the vast majority of the total backlog is spent LEU, which by itself would require 10 years of reprocessing at La Hague's current throughput rate, even excluding the additional spent fuel that would arise during that time.

The increasing backlog of spent fuel means that La Hague's storage pools are filling up. According to official data, released by Orano in 2018, the pools have an authorized capacity of 13,990 MTHM and by the end of 2016 already contained 9,778 tonnes.[129] However, independent experts claim the situation is much worse, because the effective storage capacity is limited by empty BWR fuel racks (for previously expected foreign fuel that never arrived), water treatment systems, and space reserved for shuffling assemblies. According to Yves Marignac, the pools have only about 650 tonnes of available capacity, equal to about four years of growth in La Hague's spent fuel backlog based on current rates of reprocessing and reactor discharges. But if reprocessing were interrupted for any reason, the pools would reach capacity in less than six months, he estimates.[130]

In the wake of Japan's Fukushima disaster, ASN refused EDF's request to dense-pack its storage pools at reactor sites. EDF then requested that Areva build a storage pool at La Hague specifically for spent MOX fuel, which has a higher heat load and thus is more of a burden in reactor pools. In 2014, however, Areva decided the costs were too high, leaving EDF to seek another solution for its mounting spent fuel inventories.[131] In February 2018, EDF confirmed that it was working on a proposal for a new central storage pool at one of its reactor sites, because it worried that the pools at La Hague could be full by 2030. The proposal, due in 2019, is expected to request a new pool with capacity for 8,000 tonnes of spent fuel.[132]

Areva also has proposed a new facility at La Hague to facilitate reprocessing fuel with high fissile content, particularly MOX and research-reactor fuel. The Polyvalent Fuel Treatment Facility, or *l'installation de traitement des combustibles particuliers* (TCP), entails a shearing and dissolution workshop to process both irradiated and non-irradiated fuel. Studies were in progress as of 2017, but even if the facility gets the go-ahead, it could not launch until at least the 2020s. The TCP would allow Orano to process these specialized fuels with less impact on La Hague's throughput, because its design includes buffer tanks for operational flexibility in integrating its output into the main reprocessing flow. Executives at Orano also envision the TCP as an integral part of demonstrating a future fast-reactor closed fuel cycle, claiming it would allow them to extract plutonium from spent MOX to manufacture startup FBR cores, and then to reprocess the resulting spent FBR fuel.[133]

Direct Disposal of Spent Fuel

ANDRA was charged with studying the potential for direct disposal of spent fuel, in a report that was delivered to the Minister of Energy in 2018.[134] Nuclear experts point out that disposal of spent MOX would present particular challenges due to its increased heat. They estimate that if cooled in a pool for the same time as spent LEU, each spent MOX assembly would require as much volume as four or five spent LEU assemblies in a geological repository to allow for appropriate thermal density. Alternatively, Greenpeace's Yannick Rousselet says that spent MOX would have to cool for 100 years in a storage pool, much longer than spent LEU, prior to burial.[135]

Analysis

French nuclear firms have invested in expansive reprocessing and MOX fabrication facilities since the 1980s, based on the expectation of lucrative foreign contracts. A drop in foreign demand from 2000 onward, however, has left them with excess capacity, and the French utility EDF is now the only major client, contracted to buy 120 tonnes of MOX fuel annually. To produce this MOX without risk of interruption, Orano claims to need a three-year buffer of plutonium, or roughly 30 tonnes, yet France's stockpile of domestic-owned, unirradiated plutonium reported in 2016 was around 65 tonnes. Explaining most of this difference, France held about 28 tonnes of plutonium in the form of fresh or unusable MOX, and the vast majority of that is domestic-owned since the MOX production was mainly for EDF. Thus, the amount of French-owned unirradiated plutonium not in fabricated MOX – at La Hague, MELOX, or CEA in 2016 – was probably about 37 tonnes. France's latest official figures, from August 2018, provide confirmation, reporting 37 tonnes of domestic-owned unirradiated plutonium in various forms – 26 tonnes of separated material, nine tonnes in the process of MOX fabrication, and two tonnes at CEA facilities. This is in addition to an undisclosed quantity of domestic-owned fresh MOX and unusable MOX, which in recent years has averaged about 28 tonnes.[136] This means that the MOX production pipeline entails about 26 tonnes of separated plutonium and nine tonnes being fabricated, for a total of 35 tonnes of working stock.

EDF's claim of balanced flows means that the same amount of plutonium that is separated each year at La Hague from French spent fuel is sent to MELOX to make MOX for French reactors. This is consistent with its contracts for reprocessing and MOX fabrication: 1,050 tonnes of reprocessed spent LEU yields roughly

10 tonnes of separated plutonium annually, which is about what is required for 120 tonnes of MOX at an average plutonium content of 8.65 percent. However, this cannot explain the consistent growth in France's stockpile of unirradiated domestic-owned plutonium. In reality, it appears that a non-trivial percentage of MELOX's 120-ton output actually is sub-spec or scrap MOX that is not reincorporated into the production process, so that more plutonium is separated from spent fuel than is fabricated into usable MOX. Each year, EDF has 10 tonnes of plutonium separated from its spent fuel, and the same amount sent to MELOX to make MOX, knowing that a significant fraction (perhaps 10 to 20 percent) will be returned to La Hague in unusable unirradiated MOX, thereby increasing France's stockpile of unirradiated plutonium. Obviously, this is not a balanced flow, but instead a persistently higher production than consumption of plutonium, and the main cause appears to be inadequate domestic demand for MOX.

After nearly 30 years of commercial MOX use, EDF has never reached its original target to use such fuel in 28 reactors. In fact, only 22 of the 24 reactors licensed for MOX have used such fuel. Moreover, Orano's domestic reprocessing and MOX fabrication facilities are both operating well below capacity. This indicates that EDF is not maximizing its potential MOX use, which is consistent with claims by independent experts and a former EDF official that the utility does not particularly want to use MOX fuel.[137]

If EDF really wanted to implement balanced flows, it could ask Orano to send another 1.75 tonnes of plutonium from La Hague to MELOX annually, to enable additional annual production of usable MOX fuel containing 1.5 tonnes of plutonium. If EDF did so, then France's stockpile of domestic unirradiated plutonium would cease growing. However, EDF would have to pay several times more for the additional MOX fuel than the cost of the LEU fuel that it would displace, so EDF does not do so, but France continues to perpetuate the myth of balanced flows. While EDF might prefer not to use any MOX fuel, it appears locked into the MOX fuel program at its current level, due to the government's recycling requirement and political pressure to subsidize a financially struggling Orano.

Corinne Lepage, France's former Environment Minister, remarked in her 1998 memoir that, "EDF doesn't like MOX fuel, which is difficult to use and which, above all, costs an arm and a leg since it is now the only justification for the costly plutonium industry. But does EDF have a choice? Is the use of MOX not imposed on it by the Direction de la Sûreté Nucléaire (DSN)? And we can clearly see how essential it is that [DSN] remains under the control of the nuclear lobby."[138]

Finally, Areva's claims about the waste management benefits of spent fuel reprocessing are somewhat misleading (see Appendix 4). The reduction in radiotoxicity "by a factor of 10" seems to refer to the fact that plutonium is removed from the spent fuel. While this may reduce the radioactivity of the resulting vitrified high-level waste, the separated plutonium does not disappear. Rather than a real reduction in radioactivity, this merely pushes off the problem until the plutonium is eventually disposed of at a later date – unless new reactors are developed that can consume a considerable portion of the plutonium. The General Administrator of CEA admitted as much in 2014 when he told the National Assembly that "the first problem to tackle . . . is the plutonium one: if it is not multi-recycled, the problem remains unresolved."[139]

Conclusion

France's MOX program has been technologically successful, and MOX fuel has achieved parity with LEU in burnup and performance, at least in Generation II reactors. Though it is industrially mature, MOX remains several times more expensive than LEU. Thus, France's continued use of MOX is driven not by economics but several other factors: politics, lack of an alternative disposal method for spent fuel, and hopes for lucrative foreign contracts.

France's reprocessing and MOX industries have reached a major turning point. The country's two main nuclear firms – Orano and EDF – are under severe financial strain and pursuing high-stakes foreign projects to remain solvent. Government inquiries are currently in progress on the future of France's fuel cycle and a pilot program for deep geological disposal of spent fuel.[140] Independent experts and industry officials agree that building new reprocessing facilities in other countries to enable MOX use does not make sense. In France, ongoing development of a geological repository may well offer more economical options for direct disposal of spent fuel.

Appendix 1
Milestones in French MOX History

1962: ATPu at Cadarache begins producing fuel with plutonium

1966: UP2 plant at La Hague begins reprocessing various fuels

1968: Pilot MOX plant in Belgium

1973: Belgonucleaire P0 MOX plant opens at Dessel

1974: MOX used in Chooz A

1978: Cadarache begins producing fuel for fast reactors

1983: France decides to commercially utilize MOX in thermal reactors

1987: UP2 plant at La Hague shifts to LWR spent fuel reprocessing exclusively

1987: Permission to load MOX in 16 reactors (900 MWe PWR)

1987: MOX loaded in St. Laurent B1 plant (fabricated by Belgonucleaire in P0)

1988: 2 MOX batches loaded

1989: 3 MOX batches loaded (4 reactors total)

1989: Cadarache begins producing MOX for LWRs

1990: UP3 begins reprocessing at La Hague

1991: Cogema takes over Cadarache Pu activities

1994: 7 reactors loaded with MOX to date, 4 reach core equilibrium

1995: MELOX begins producing MOX for EDF

1995: DSIN requests Cogema prepare a plan to close Cadarache's ATPu fabrication facility by 2000 due to seismic risks

1997: MELOX first year of production with licensed capacity of 101 MTHM

1999: MELOX produces first MOX fuel for Japanese customers

2003: MELOX authorized for 145 MTHM

2003: German clients transferred to MELOX from Cadarache, which closes

2004: UP2-400 plant closed

2004: MELOX license request for 195 MTHM capacity

2006: MOX parity license granted (rolled out across reactors from 2007 to 2014)

2007: MELOX receives license for 195 MTHM capacity

2013: First MOX production for Dutch EPZ at MELOX

2015: End of MELOX production for German customers

2016: MELOX resumes production for Japanese customers

Appendix 2
Evolution of MOX Fuel Management

EDF's in-core fuel management for MOX fuel has evolved through three major phases. Most changes to MOX management came as a response to modifications in LEU fuel management and burnups:

1987 – 1994 (Start of Commercial MOX Use)

- LEU: 3 cycles. MOX: 3 cycles.
- Reload: 36 LEU assemblies, 16 MOX assemblies.
- Average burnup: 37,500 MWd/tM.

1994 – 2007 (Hybrid Management)

- LEU: 4 cycles, MOX: 3 cycles.
- Reload: 28 LEU assemblies, 16 MOX assemblies.
- Average burnup – LEU: 45,000 MWd/tM, MOX: 37,500 MWd/tM.
- In 1995, all reactors licensed for MOX were permitted to operate in load-follow mode, following a five-year demonstration in the Saint-Laurent reactors. This permits them to rapidly change their power output in response to changing demand, as LEU-fueled reactors already had been licensed to do.[141]

2007 – Present (MOX Parity)

- LEU: 4 cycles. MOX: 4 cycles.
- Reload: 28 LEU assemblies, 12 MOX assemblies.
- Average burnup: 48,000 MWd/tM.

Appendix 3
Inventories of Civil Unirradiated Plutonium, 1995-2016

Year	Separated Pu at reprocessing plants	Pu being fabricated into MOX	Pu in fresh MOX, scrap, sub-spec	R&D and other	TOTAL	Foreign-owned	Domestic-owned	Annual growth in domestic-owned
1995	36.1	10.1	3.6	5.5	55.3	25.7	**29.6**	
1996	43.6	11.3	5.0	5.5	65.4	30.0	**35.4**	5.8
1997	48.4	12.2	6.3	5.4	72.3	33.6	**38.7**	3.3
1998	52.0	11.8	6.8	5.3	75.9	35.6	**40.3**	1.6
1999	55.0	13.0	8.2	5.0	81.2	37.7	**43.5**	3.2
2000	53.7	14.8	9.2	5.0	82.7	38.5	**44.2**	0.7
2001	51.1	14.1	9.9	5.4	80.5	33.5	**47.0**	2.8
2002	48.7	15.0	12.7	3.5	79.9	32.0	**47.9**	0.9
2003	48.6	13.3	13.2	3.5	78.6	30.5	**48.1**	0.2
2004	50.7	12.7	12.8	2.3	78.5	29.7	**48.8**	0.7
2005	49.8	14.4	15.9	1.1	81.2	30.3	**50.9**	2.1
2006	48.6	12.7	19.6	1.2	82.1	29.7	**52.4**	1.5
2007	49.5	9.7	22.1	0.9	82.2	27.3	**54.9**	2.5
2008	49.3	7.1	26.6	0.8	83.8	28.3	**55.5**	0.6
2009	47.1	6.8	27.2	0.7	81.8	25.9	**55.9**	0.4
2010	47.0	5.5	27.1	0.6	80.2	24.2	**56.0**	0.1
2011	43.5	6.6	29.1	1.1	80.3	22.8	**57.5**	1.5
2012	42.4	7.1	30.6	0.5	80.6	22.2	**58.4**	0.9
2013	43.2	6.6	27.7	0.6	78.1	17.9	**60.2**	1.8
2014	42.6	9.5	26.0	0.7	78.8	16.9	**61.9**	1.7
2015	43.6	8.9	26.7	0.5	79.7	16.3	**63.4**	1.5
2016	43.8	9.2	28.1	0.5	81.6	16.3	**65.3**	1.9

Source: Compiled from IAEA Reports: INFCIRC/549/Add.5/[1-21].
Notes: Figures in tonnes, rounded to 100 kg. In addition to these domestic inventories, a minimal quantity of French-owned, unirradiated plutonium may be held abroad. Since 1996, France has reported that category to be under 50 kg, the lowest threshold.

Appendix 4
Reprocessing and the Environment

French nuclear industry officials cite the ability to concentrate, vitrify, and simplify the storage of high-level waste as a main benefit of reprocessing.[142] According to figures frequently cited by Areva, reprocessing reduces waste volume by a factor of five and waste radiotoxicity by a factor of ten due to removal of plutonium.[143] Of course, the plutonium does not disappear and must also be disposed of eventually, but France's 2006 waste management law imposed a strict definition of radioactive waste that explicitly excludes any material ostensibly intended for future reuse. Accordingly, most official French statistics for radioactive waste exclude plutonium-containing products, including spent MOX fuel.[144]

Independent experts note that the cited volume of high-level and long-lived intermediate-level reprocessing waste excludes both the additional volume required to package this waste and the much larger volume of low-level waste generated by reprocessing. In addition, the historical volume of waste arising from reprocessing was much larger, prior to recent process improvements including the "ACC" compaction facility commissioned in 2002.[145] This facility compacts the empty hulls and end pieces left over after de-cladding spent fuel assemblies. According to Areva and IRSN, the compaction reduces the volume of this type of structural waste by 80 percent.[146]

The required volume for a geological repository is determined not only by the volume of waste but also by its heat output. IRSN found that the high- and intermediate-level waste from reprocessing, fully packaged, would yield around 26 percent savings in repository volume compared to packaged spent LEU fuel.[147] Similarly, the U.S. Department of Energy found that a reprocessing and thermal recycle program could result in around 27 percent less high-level waste by volume sent to a repository than a once-through fuel cycle.[148]

Neither of these estimates, however, includes the full range of reprocessing waste requiring disposal. Although high-level waste and long-lived intermediate-level waste are the two categories France plans to send to a deep geological repository, it is estimated that around 84 percent of the waste volume from reprocessing is short-lived intermediate- or low-level waste.[149] This waste has a maximum half-life of 31 years and is currently stored at two surface storage facilities.[150]

Scholars and environmental groups also raise concerns about the security of spent fuel storage pools, particularly those at La Hague, which are the largest in the world. Of particular concern is the risk of environmental contamination from fires caused by loss of cooling water. These concerns were heightened in the wake of the September 11, 2001 terrorist attacks, which highlighted the risk of plane crashes, and the 2011 Fukushima accident that illustrated the dangers from draining a spent fuel pool. Areva points to security measures including a no-fly zone and French Air Force radar coverage over La Hague, in addition to physical protection from surrounding buildings. French officials also argue that much of the spent fuel at La Hague has been in storage long enough to reduce its heat load, which presumably reduces the risk of a fire in the event of an accidental or terrorist-induced draining of pool water.[151]

Endnotes

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[111] Orano, "Rectificatif d'Orano à Reporterre," February 15, 2018, http://www.orano.group/FR/home-199/rectificatif-dorano--reporterre.html (accessed March 15, 2018).

[112] France had 1,840 MTHM of unreprocessed spent MOX at the end 2016, and that inventory grows by more than 100 MTHM annually. See ANDRA, "National inventory of material and radioactive waste - 2018 edition: synthesis report," 44, https://www.andra.fr/sites/default/files/2018-08/Andra-Synthese-2018-web.pdf. In 2013, the inventory was 1,540 MTHM, according to Ministry for the Environment, Energy and the Sea, and Nuclear Safety Authority, "French National Plan for Radioactive Materials and Waste Management (PNGMDR)," February 25, 2017, 73.

[113] ANDRA, "National inventory of material and radioactive waste - 2018 edition: synthesis report," 36. It also stores 30 MTHM of foreign spent fuel, presumably including LEU and MOX.

[114] Lelièvre, et al., "Polyvalent fuel treatment facility".

[115] Brueziere, interview, January 10, 2018.

[116] "Rapport au Nom de L'office Parlementaire D'évaluation des Choix Scientifiques et Technologiques sur L'évaluation du Plan National de Gestion des Matières et des Déchets Radioactifs," Assemblée nationale, September 18, 2014, http://www.assemblee-nationale.fr/14/rap-off/i2226.asp (author's translation).

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[118] Krellmann, interview, January 5, 2018.

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[121] Gros, "Reprocessing / Recycling of Used Fuels."

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[144] Schneider and Marignac, "Spent Nuclear Fuel Reprocessing in France."

[145] Schneider and Marignac, "Spent Nuclear Fuel Reprocessing in France."

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4

MOX in the UK: Innovation but Troubled Production

W. Neal Mann

This chapter is the first comprehensive history of the development, production, and use of mixed oxide (MOX) fuel in the United Kingdom. Field interviews were conducted in the UK in 2018 with current and former employees of the government (including British Nuclear Fuels Ltd, and the Nuclear Decommissioning Authority), industry officials, and independent experts. Both of the now-closed commercial fabrication plants – the MOX Demonstration Facility (MDF), and the larger Sellafield MOX Plant (SMP) – are analyzed in detail, covering engineering design, production, economics, security, safety, and environmental impacts. In addition, all UK power reactor types are evaluated for their technical and economic suitability for MOX fuel. MOX production in the UK had mixed success. Some innovative processes were demonstrated, including a dry pelletizing process, but quality-control data problems and design flaws hampered output, especially for the SMP that over its lifetime achieved only one percent of its intended capacity. Despite producing MOX fuel for foreign customers, the UK never used MOX fuel in its own reactors on a commercial basis. This resulted primarily from the higher cost of MOX fuel but also the prospective expenses of retrofitting reactors and safety licensing. Due to reprocessing its spent nuclear fuel but not utilizing MOX, the UK has accumulated an enormous stockpile of over 110 tons of separated civilian plutonium (excluding foreign-flagged plutonium). The nominal UK policy is eventually to recycle this plutonium in MOX. However, this would be expensive, requiring a new MOX fabrication provider and subsidies to reactor operators to use MOX fuel rather than more economical low-enriched uranium (LEU) fuel.

The United Kingdom produced mixed oxide (MOX) fuel with recycled plutonium at various scales from the 1960s through the 2000s. MOX fuel was originally designed and produced for the fast breeder reactor program of the UK Atomic Energy Authority (AEA). MOX development shifted to thermal reactors after fast reactor funding was severely cut in 1988. Most of the MOX fuel has been produced at the Sellafield site in northwest England.

Commercial MOX production began with the opening of the MOX Demonstration Facility (MDF) at Sellafield in 1994. It produced MOX pellets that were inserted into customer-provided fuel rods and assemblies for light-water reactors (LWRs). MDF produced fuel assemblies for three utilities in Switzerland, Germany, and Japan, utilizing mostly manual processes in glove boxes. In 1999, it was revealed that the quality assurance checks for two batches of fuel for Japan had not been carried out, and instead data had been copied from previous work, leading the Japanese customer to return the batch that had been delivered. Nearly simultaneously, the UK Nuclear Installations Inspectorate (NII) began an in-depth examination of safety practices at the plant. As a result, MDF halted production in 1999.

The Sellafield MOX Plant (SMP) was authorized in 1991 as a scaled-up, follow-on to MDF. Despite this, the SMP design was significantly different than MDF, and it used an unproven automation technology for rod fabrication, among other attempted innovations. Unlike MDF, SMP produced not just MOX fuel pellets, but also fuel rods and assemblies. SMP's design throughput was 120 tonnes of heavy metal per year (MTHM/yr). It was completed in 1997 but did not start operations until 2001 due to a delayed authorization for discharges. When it did open, its throughput was downgraded to 72 MTHM/yr. By 2005, the target throughput had been lowered again to 40 MTHM/yr. Actual total production during its lifetime was only 13.8 MTHM from 2001 through 2011, an average of barely 1.2 MTHM/yr. The highest annual throughput was 4.8 MTHM/yr – in fiscal year 2010.

The UK Nuclear Decommissioning Authority (NDA) was founded in 2005, taking over responsibility for SMP from British Nuclear Fuel Ltd (BNFL). NDA commissioned a report from Arthur D. Little to investigate the causes of its poor performance. This 2006 report, eventually released in redacted form, concluded that there were no fuel-quality issues.[1] Instead, unplanned outages and production bottlenecks had led to the very low production rate. A strategic review was launched in 2008 to determine the best path forward. In 2010, ten Japanese utilities financed a plant refurbishment, with Chubu Electric as the first customer. Areva was contracted to replace the fuel rod fabrication line, and work was begun in late 2010. However, the Fukushima Daiichi nuclear accident in 2011 led the Japanese utilities to cancel their agreement with SMP, resulting in SMP's closure in late 2011.

The UK's Magnox and advanced gas-cooled reactors (AGRs) have used MOX fuel for experimental purposes only. The Sizewell B pressurized water reactor (PWR) has never used MOX fuel. Several new LWRs have been proposed in the UK, and while the various designs are technically capable of MOX use, none is being assessed or constructed in anticipation of utilizing such fuel. Future use of MOX fuel in the UK would require either retrofitting and restarting SMP, building a new MOX fabrication plant, or purchasing MOX fabrication services from a foreign facility.

Methods

This chapter seeks to answer two overarching questions: why did the UK struggle to produce MOX fuel for thermal-spectrum nuclear reactors on a large scale, and why has the UK never adopted MOX fuel for use in its own thermal reactors? Answering these questions required a qualitative method because much of the quantitative data, such as detailed engineering designs and customer data, remains commercially confidential or is otherwise not publicly available. However, quantitative data and analysis were used whenever possible to confirm qualitative findings.

The research process began with a literature review of publicly-available documents on MDF, SMP, and MOX use in UK reactors. This led to potential interviewees and additional documents to review. Interviewees were chosen based on their expertise in nuclear fuel-cycle issues. A variety of perspectives were sought on MOX fuel production, nuclear power, nuclear fuel cycles and waste management, nuclear safety, nuclear security and weapons nonproliferation, nuclear licensing and regulation, and government oversight. Experts or interested parties included current and former employees of Areva, BNFL, British Energy, and the Nuclear Industries Association; government officials from the NDA, the Office for Nuclear Regulation, and the former NII; university professors; members of the UK Government's Committee on Radioactive Waste Management (CoRWM); and the citizens group Cumbrians Opposed to a Radioactive Environment (CORE). Most interviews were conducted in person, in the UK, during February 2018. One interview was conducted over the telephone, and several others via e-mail.

This research was supplemented by a variety of documentary sources, including press releases, news articles, periodicals, technical conference proceedings, presentations, reports, books, Parliamentary documents (including Hansard, Written Questions and Answers, and committee reports), legal cases, and websites. Some materials were difficult or impossible to find due to age, confidentiality, or the dissolution of the original company (e.g., BNFL was disbanded and some functions rolled into the NDA). Some sources were found through the UK Government Web Archive,[2] or the Internet Archive Wayback Machine.[3]

MOX Fabrication

MOX fuel production in the UK started in the 1960s, and the early experiences directly led to MDF. The Prototype Fast Reactor (PFR), the second fast reactor built by the UK AEA, used oxide fuel pellets fabricated at Dounreay, Scotland.[4] It used fuel assemblies with MOX pellets in the center and depleted uranium dioxide breeding pellets above and below the driver fuel.[5] Plutonium was recovered from used PFR fuel at a reprocessing plant in Dounreay,[6] and then MOX fuel was fabricated at the B33 plant at Sellafield. Over 20 tonnes of MOX fuel was produced for the PFR.[7]

In addition, nearly three tonnes of MOX fuel was produced at B33 for thermal reactors through the 1970s.[8] These included experimental loadings for the prototype steam-generating heavy water reactor (SGHWR) and the Windscale advanced gas-cooled reactor (WAGR). These UK thermal reactor fuel assemblies achieved respectable burnups – 10 to 20 megawatt-days per kilogram heavy metal (MWd/kgHM) – with relatively low plutonium content under two percent.[9] The rest of the early thermal reactor MOX fuel produced at B33 was for experimentation and demonstration in LWRs in continental Europe, including Vulcain in Belgium and Kahl in West Germany.[10] In 1979, the UK Department of Energy estimated that thermal reactor MOX fuel fabrication costs were likely four times higher than uranium-only fuel fabrication costs.[11]

The plutonium for the thermal reactor fuel was obtained at the B204 reprocessing facility at Sellafield. This facility was originally designed to reprocess Magnox metallic fuel, but an oxide-fuel-compatible head end was added in 1969. This allowed AGR fuel to be reprocessed, as well as fuel from Canada, Germany, Italy, Japan, Spain, and Switzerland.[12] About 90 tonnes of spent oxide fuel was reprocessed at B204 through its closure in 1973.

MOX Demonstration Facility (MDF)

Although the UK's original reason for producing MOX fuel was to recycle plutonium in fast reactors, this motivation vanished with the curtailment and eventual demise of the UK fast reactor program in the late-1980s and early-1990s. A European agreement had also shifted 1990s fast reactor fuel fabrication to France, leaving the AEA MOX fuel plant redundant.[13] During the mid-1980s, other European companies – primarily Belgonucléaire (Belgium), Cogema (France), and Siemens (Germany) – started successfully selling MOX fuel fabrication services for LWRs.

The UK's Layfield inquiry of 1983 to 1985 considered the benefits and risks of building new domestic PWRs. In 1985, BNFL started a development program aimed at building a commercial thermal MOX fuel fabrication plant, including for the expected future domestic PWRs.[14] However, UK reactor development fell short of expectations when only one PWR was authorized for construction in 1987 at Sizewell B.[15] Accordingly, by 1989, BNFL instead argued that the MOX program was aimed primarily at foreign reprocessing customers.[16] In 1990, BNFL publicly announced plans for the MDF and the much larger SMP.[17] MDF was designed to produce either PWR or boiling water reactor (BWR) fuel assemblies, but the focus was on PWRs because of BNFL's Westinghouse fuel license.[18]

Design

BNFL collaborated with the UK AEA on the MDF project, signing a formal agreement in January 1991.[19] MDF was built inside the former UK AEA plutonium laboratories (B33), already set up for plutonium handling.[20] The PFR's MOX fuel had been manufactured in the same building, but an extension was added that allowed finished fuel assemblies to be stood up vertically.[21] In addition, the design of MDF borrowed from BNFL's then-new Springfields Oxide Fuels Complex (OFC), an LEU fuel plant. In 1989, BNFL approved a capital cost of £10 million for MDF,[22] and by the next year the estimated cost had increased to £15 million.[23]

MDF consisted of a single production line for fuel pellets, rods, and assemblies for PWRs or BWRs.[24] The production process was similar to other MOX plants at the time: mix powders, create pellets, load pellets into rods, and insert rods into assemblies. One significant difference between MDF and other MOX fabrication facilities was the introduction of the short binderless route (SBR) pellet production process.[25] BNFL had previously investigated a gel precipitation process for MOX pellets utilizing sintering and vibrocompaction.[26] The SBR process brought several improvements over other processes: short milling times, fully-contained powder flow, and no liquid waste production.[27] These improvements were enabled by using high-speed attritor mills followed by spheroidizers. This milling process produced finer, more homogeneous powders, and did so more quickly, than typical ball mills used elsewhere. Because the SBR process was relatively new, MDF was built to gain additional production experience and to expedite in-reactor testing of the new fuel.[28]

Production and Economics

Commissioning of uranium and plutonium operations started in 1993, and BNFL took full ownership and control of MDF in 1994.[29] Commercial production ended in late-1999 due to the data falsification scandal detailed below. When first announced, MDF had a planned throughput of five MTHM/year.[30] This was later uprated to eight MTHM/year, or about 20 PWR fuel assemblies annually.[31] Over six years, MDF actually produced a total of about 18 MTHM (44 PWR fuel assemblies), for an average throughput of three MTHM/year (about seven PWR fuel assemblies per year), servicing three customers. Production was typically done in batches of eight fuel assemblies for one customer at a time.

The first and largest customer was the Swiss utility Nordostschweizerische Kraftwerke (NOK), for which MDF produced

24 fuel assemblies in at least two batches – in 1994 to 1995, and in 1997 – for the Beznau dual-unit PWR power plant.[32] German company PreussenElektra had four fuel assemblies manufactured for its Unterweser PWR power plant during 1995 to 1996. Japan's Kansai Electric Power Company (KEPCO) of Japan, starting in 1997, had sixteen fuel assemblies manufactured for Units 3 and 4 of its Takahama four-unit PWR power plant. These final sixteen assemblies were never used due to the data falsification scandal.

Security, Safety, and Environment

Despite its successes, MDF is perhaps best known for its role in the MOX pellet inspection data falsification scandal that broke in 1999. For its Swiss and German customers, MDF's quality assurance process included two quality control checks: an automated inspection of all pellets followed by a visual inspection. Pellets could be rejected at either stage. KEPCO requested a third quality control check, or "overinspection," of five percent of each lot by hand, with measurements manually typed into a spreadsheet.[33] However, in violation of this requirement, MDF personnel in some cases failed to conduct the manual inspection and instead simply copied data from previous batches. The NII ultimately concluded that the pellets with falsified measurements met specifications and were safe to use.[34] Nevertheless, the failure of the quality assurance process was a significant blow to BNFL's reputation and compelled the company's CEO John Taylor to resign.[35] The eight fuel assemblies that had already been delivered to KEPCO, but never irradiated, were returned to BNFL in 2002. Those and the other eight unirradiated MOX assemblies that SMP had fabricated for KEPCO were ultimately contracted to be reprocessed at the La Hague facility in France.[36]

In February 2000, BNFL admitted that additional records of pellet production had been falsified.[37] These were for pellets manufactured in 1996 for the Unterweser power plant in Germany. Although reported after the Takahama data falsification, the Unterweser data falsification actually occurred three years prior to the other case. This suggests systemic problems with quality control, given that it occurred during production for at least two of MDF's three customers, in two separate campaigns that were three years apart. In the Unterweser case, quality control checks were performed but subsequently "lost due to a computer error."[38] The shift supervisor noted this, but the next shift copied a previous data set to fill in the missing data.[39] BNFL's admission of the falsification prompted German officials to remove the four offending MOX fuel assemblies and temporarily ban importing fuel from BNFL.[40] The offending pellets had been irradiated from 1997 through early-2000 without evidence of fuel problems.[41]

In an unrelated incident, the Swiss Federal Nuclear Safety Inspectorate (ENSI) revealed in 1999 that three MDF-produced fuel assemblies contained damaged fuel rods when removed from the Beznau-1 reactor. These fuel assemblies had been supplied in 1996. A BNFL spokesman said that the problem was "a fairly common occurrence with no safety implications."[42] The Swiss customer NOK continued to use the MOX fuel in the late-1990s despite these revelations.[43] NOK also continued to use its MDF-supplied MOX fuel in 2000 after the Takahama and Unterweser data falsification incidents were revealed, concluding that other inspection tests were adequate to ensure the fuel's safety.[44]

MDF stopped producing MOX fuel pellets, rods, and assemblies for commercial use after the data falsification scandals. Although the government eventually allowed MDF to reopen after its concerns were addressed, BNFL chose not to resume commercial production,[45] on grounds that it would have been "politically hazardous."[46] However, MDF did reopen in a supporting role for its successor by producing small quantities of fuel pellets in 2002 as benchmarks for SMP's new production lines.[47]

Worker safety and dose minimization were important parts of MDF's design. Leak-proof glove boxes were intended to prevent internal exposure to workers in the fuel pellet and rod manufacturing areas, while fixed and personal air samplers were used to monitor internal dose hazards.[48] External gamma and neutron dose to workers were minimized by shielding on glove boxes and other equipment.[49]

Sellafield MOX Plant (SMP)

SMP was conceived together with MDF but designed for much larger-scale production. SMP was an annex to the Thermal

Oxide Reprocessing Plant (THORP), which serviced mainly foreign customers. The large MOX fabrication plant was expected to enhance the reprocessing business by enabling the return of foreign materials in the acceptable form of MOX fuel rather than as separated plutonium dioxide.[50] SMP was never intended to deal with UK-owned separated plutonium.[51]

BNFL presented a business case for the SMP's originally planned output of 120 MTHM/yr. It noted that despite low uranium prices and the curtailment of fast-reactor programs, in 1989 Belgonucléaire and Cogema were projecting that MOX fuel demands for LWRs in Europe would exceed 300 MTHM/yr around 1995.[52] This greatly exceeded the existing European MOX fabrication capacity of 170 MTHM/yr, so if the demand growth projections were right, BNFL had an exciting business opportunity.

The UK Environment Agency was required to determine if SMP's operation was "justified" – meaning that expected benefits of the ionizing radiation exceeded the expected costs – before the plant could open. However, BNFL delayed submitting its application until after construction had started.[53] By 1997, the agency commissioned an independent assessment of SMP's business case by PA Consulting Group, which used more optimistic assumptions than BNFL to estimate that the most likely net present value of profit was £230 million.[54] A key difference between the BNFL and PA analyses was in the market scope. BNFL considered producing MOX only for its existing reprocessing customers, while PA added potential new customers, assuming that BNFL would capture 25 percent of an additional global demand of 90 to 120 MTHM of MOX annually. On this basis, PA estimated that SMP would have contracts of 90 MTHM/yr in 2000, and 120 MTHM/yr in 2005.[55]

With a positive outlook from the PA report, the government provisionally declared in 1999 that SMP's operation was justified, only a few months before the data falsification incident at the demonstration MDF plant came to light. Around the same time, Prof. Gordon MacKerron of the University of Sussex questioned PA's market forecast for MOX fuel. He pointed out that if the actual MOX fuel demand were significantly lower than expected, SMP would be uneconomical.[56]

The public spotlight on MOX fuel after the MDF data falsification incident, along with BNFL revising its business case for SMP, led the government to commission a new independent evaluation by Arthur D. Little Ltd in 2001.[57] This study too concluded that the net present value of SMP would very likely be positive over a range of scenarios. However, it also envisioned six downside scenarios based on delays in production or demand, unexpected lower throughput, or a complete project shutdown.

Both independent assessments treated the construction of SMP itself as a sunk cost, so that only future operating costs and revenues were evaluated. This meant that the economic analyses had a positive bias because they assumed that the plant's initial capital costs would never have to be recovered. Greenpeace and Friends of the Earth sought an injunction against SMP's startup because of this perceived shortcoming in the economic case.[58] The plant's capital cost climbed from £300 million in 1998, to £470 million by 2001,[59] and £490 million by 2006.[60] By 2013, two years after SMP ceased production, the cumulative capital and operating expenses exceeded £1.4 billion.[61]

Design

SMP (building B572) was located adjacent to the THORP reprocessing facility (building B570), so it could receive plutonium oxide directly, minimizing transport. SMP was designed by BNFL Engineering Ltd and was roughly cubic with dimensions of 20 meters on each side, yielding a footprint of only 400 square-meters. This was significantly smaller than Cogema's MELOX plant, which had a footprint of 5,600 square-meters and was two stories high.[62] A planning application was submitted to local authorities in 1992, and the plant was essentially complete by 1997.[63]

SMP's design adopted the short binderless route pelletizing process from MDF and the cushion transfer system from the Springfields OFC fuel plant.[64] Because SMP was intended for foreign customers, the plant needed to process plutonium powders with varying compositions and to create fuel assemblies of multiple designs for various reactors.[65] The plutonium at SMP had a greater concentration of Pu-238 than at MDF because it was separated from higher-burnup foreign LWR fuel.[66] Thus, SMP had to deal with higher radiation levels, as well as higher heat loads due to alpha heating, compared to MDF.

SMP was expected to produce PWR and BWR fuel assemblies, but it was also designed to produce AGR and fast-reactor fuel pellets.[67] Novel automated processes had to be developed for handling the plutonium dioxide powder canisters from THORP and for building the fuel assemblies.[68] These were not tested first at MDF, the ostensible "demonstration" facility.

SMP was touted as "the most up to date, flexible, and automated MOX fuel fabrication plant in the world," near the end of its construction in 1996.[69] In practice, however, SMP suffered from several design flaws that led to production being far below its original design throughput of 120 MTHM/yr. The size and shape of the building – which led to cramped manual access to gloveboxes and a vertically-oriented powder-mixing stage – likely contributed to some of SMP's production troubles.[70] Another fundamental problem was the lack of buffer capacity between production stages. Initial designs had included buffer storage within or between stages.[71] However, after the plant's first budget of £380 million was rejected, the buffers were removed during redesign.[72] This caused the production stages to be tightly linked: if one part of the plant was shut down for maintenance or repairs, the entire plant soon became idled.

The two rod fabrication lines also did not work as designed. One line was set up to produce rods for PWRs, and the other for BWRs. Each line consisted of a set of seven gloveboxes connected to a revolving carousel. The carousel would move rods from one glovebox stage to the next. As with the lack of buffers between major stages of production, the lack of buffer capacity within the rod fabrication lines meant that a work stoppage within one glove box would quickly stop production in the preceding processes.

Fuel assembly fabrication, the final stage of production, also suffered its share of problems. PWR and BWR fuel assemblies have somewhat different designs, to the point that the European Commission recognized them as being in two separate product markets.[73] SMP had one fuel assembly line for PWRs and another for BWRs. The PWR fuel assembly line pulled whole rows of rods into a fuel assembly skeleton. By contrast, the BWR fuel assembly line pushed rods individually into a fuel assembly skeleton. The BWR "pushing" process turned out to be much more difficult than the PWR "pulling" process and led to plant backups.[74]

SMP also challenged the boundaries of automated production at the time. Many of these processes were located inside gloveboxes that normally were covered with Jabroc shielding material.[75] Workers needed approval to remove the shielding to see inside gloveboxes,[76] which may have led to additional delays during frequent outages.

The production lines were set up to produce one type of fuel assembly at a time. After fuel batches were completed for one customer's order, the plant had to be reconfigured for the next customer's order.[77] Not only was this reconfiguration time-consuming and expensive, but a delay in production for one customer caused delays for the following customers in the queue.

Interestingly, in 1989, prior to construction, it was reported that BNFL had asked Siemens for MOX fuel fabrication technology in exchange for lower pricing for THORP reprocessing services for German utilities.[78] By 1992, Siemens and BNFL were planning a £250 million joint venture, with Siemens providing expertise from its planned 120 MTHM/year Hanau 1 MOX plant, which ultimately was aborted.[79] This morphed into an engineering agreement for the fuel rod fabrication technology from the Hanau plant, signed in 1993.[80] During this period, BNFL appeared to be pursuing the Siemens technology in parallel with developing its own.[81] However, by 1995, the technology transfer deal had been drastically scaled back due to incompatibilities between the plants, and ultimately only some instrumentation and control systems were installed at SMP.[82] A subsequently proposed joint venture would have brought Siemens' nuclear subsidiaries and BNFL's fuel fabrication businesses together, excluding reprocessing and MOX.[83] But this collaboration too was eventually scuppered, in favor of BNFL's acquisition of the Westinghouse nuclear business in 1998.[84] Despite failing to acquire access to Siemens' important technology and expertise, BNFL proceeded with SMP on its own.[85]

Production and Economics

Pre-production commissioning of SMP started in 1997, and BNFL expected production to start in 1998.[86] However, an inquiry from the Environment Agency delayed even the uranium-only commissioning into 1999,[87] and then the first MDF data falsification scandal further delayed SMP's full operation. SMP was finally authorized to begin production in October 2001,[88] and the first plutonium was received in December 2001.[89] By this time, the plant had been derated from 120 MTHM/year to 72 MTHM/year.[90] In April 2002, the NII gave its consent and plutonium commissioning began.[91]

The first three SMP contracts were signed in 2001, including with two Swiss customers – NOK's Beznau PWRs,[92] and KKG-D's Gösgen PWR[93] – and the Swedish utility OKG's Oskarshamn three-unit BWR power plant.[94] The Arthur D. Little report indicated that these three contracts covered 11 percent of SMP's "total MOX volume," including three percent for the OKG contract,[95] and that they would be concluded by 2012. Based on the 72 MTHM/year production estimate from 2001,[96] this implies that the three contracts were for a combined 79 MTHM of MOX fuel. An additional 14 percent of the notional MOX production capacity was tentatively committed to German utility E.ON (which had purchased PreussenElektra), and eventually contracts were finalized for its Grohnde and Grafenrheinfeld PWRs.[97] A contract was also signed with Swiss utility BKW FMB Energie for the Mühleberg PWR.[98]

In May 2002, the first MOX pellets were finished,[99] and fuel rod production started in the second half of 2002.[100] Delays in commissioning the plant meant that production was behind schedule. This led to subcontracting the first order for Beznau to BNFL's competitor Cogema,[101] the first of several such subcontracts.

Two major setbacks occurred at the plant in 2003. First, the glovebox filtration system to remove dust during pellet grinding did not work properly.[102] Second, organic contamination (phthalate oil) was found in some gloveboxes used for pellet fabrication. This halted production and led to the Grohnde order being subcontracted to COMMOX,[103] a joint venture of Cogema (60 percent) and Belgonucléaire (40 percent). Despite these challenges, BNFL set up an additional contract with E.ON for the Krümmel BWR.[104] In 2004, a second Grohnde order, and one for the Grafenrheinfeld plant, were also subcontracted to COMMOX.[105] SMP's throughput was so low that the export facility for shipping completed fuel assemblies had yet to open.[106] Due to the plant's poor performance, BNFL sought advice from competitor Cogema on increasing SMP's throughput.[107]

The two Grohnde orders were apparently accomplished via a "flag swap" of plutonium, given that spent fuel from Grohnde already had been reprocessed in THORP, so that its plutonium was in the UK, but the MOX fabrication took place on the continent. Plutonium separated at Cogema's La Hague reprocessing plant was sent to Dessel, Belgium, where it was manufactured into fuel pellets at Belgonucleaire's P0 plant and into assemblies at the adjacent FBFC plant, before being shipped to Germany.[108] Swapping ownership of separated plutonium in the UK and France avoided the costs, risks, and delays of a physical shipment of plutonium via the English Channel, although plutonium still was transported by ground from France to Belgium to complete these orders.[109]

In early-2005, SMP's fuel assembly process finally started and the first four fuel assemblies were shipped. By April, the fuel rods for four more assemblies had been completed, and two of the assemblies were finished.[110] By the following month, all four completed fuel assemblies were shipped to Switzerland's Beznau plant, and another batch was in production.[111] In November 2005, the Swedish Nuclear Power Inspectorate announced that OKG was preparing for eventual shipment of 84 MOX fuel assemblies from Sellafield to Sweden,[112] and OKG's Oskarshamn reactors were licensed for MOX use by January 2007.[113] However, these moves proved premature, as no MOX fuel assemblies were ever completed for Oskarshamn, and eventually OKG transferred ownership of its separated plutonium in the UK to the NDA.[114]

Despite the export in 2005 of completed fuel assemblies, SMP in 2006 was still undergoing commissioning and NII had not issued its "Consent to Operate,"[115] the final safety review of commissioning activities.[116] Nevertheless, in May 2006, a new contract was signed with Germany's EnBW Kernkraft for the Neckarwestheim 2 PWR.[117] The NDA admitted in March 2006 that SMP would never produce more than 40 MTHM/yr in its configuration at the time.[118] In the fiscal year ending March 2007, SMP produced only eight fuel assemblies, just half of its modest production target of 16 assemblies,[119] due to a major unplanned outage.[120] In early 2007, BNFL again reduced its throughput goal to 25 MTHM/yr.[121] In March 2007, the last of the fuel assemblies for the Beznau plant was shipped, and the focus turned to throughput-enhancement projects costing £15.8 million.[122] By the end of 2007, the annual production goal was cut further to only 12 MTHM, or approximately 30 PWR fuel assemblies.[123]

However, even this sharply reduced goal remained out of reach, as no fuel assemblies at all were completed between April 2007 and March 2008.[124] Fuel production at the time was intended for the Grohnde PWR.[125] Then, from April to October 2008, only two fuel assemblies were completed, as rod fabrication remained a major bottleneck.[126] Interestingly, Sellafield Ltd, the new operator of SMP, still had not requested a consent to operate from the NII as of May 2008.[127]

By early 2009, some progress started to be made. In one especially productive week, the plant managed to make 80 fuel rods, including 24 in a single day. By March, the rods for six more assemblies had been completed,[128] and the total batch of eight fuel assemblies for the Grohnde plant was finished by August.[129] For the fiscal year ending March 2010, actual throughput exceeded the extremely modest expectations, as nine fuel assemblies were produced, one more than planned.[130] By May 2010, three of eight assemblies for a second batch of Grohnde fuel had been completed.[131]

In total, by May 2010, SMP had completed 27 fuel assemblies (around 11 MTHM) since the start of commissioning in 2001.[132] The big news of 2010 was that 10 Japanese power companies had agreed to a framework for fabricating all of their separated plutonium in the UK into MOX fuel, and Chubu Electric Power took the lead as the first customer. The NDA directed SMP to quickly wrap up its second Grohnde batch,[133] which was then completed in fiscal year 2011 (likely by summer 2010),[134] but these turned out to be the last fuel assemblies ever produced at SMP. The final shipments of completed assemblies occurred in September and November 2012.[135] In addition, at least one incomplete contract was dealt with via another flag swap: the NDA took ownership of plutonium already separated in the UK from German spent fuel, and an equivalent amount of plutonium in France was used to manufacture MOX fuel assemblies for the German customer.[136]

SMP's lifetime production and economic timeline is detailed in Table 1. Total capital costs were £498 million, with an additional £139.4 million in commissioning costs,[137] and SMP had net revenues of about £98 million.[138] Net capital and operating costs were about £1,471 million, for a total net loss of £1,373 million.[139] The NDA estimated future decommissioning costs would be £800 million (in 2011 pounds).[140]

Retrofit Plans & Closure

After the NDA took ownership of SMP in 2005, it commissioned a study to evaluate the plant's performance. In 2006, the NDA's Near-Term Work Plan estimated that SMP needed improvements costing £13.5 million over two to three years.[141] These improvements were implemented, but as documented above, they did not significantly improve the plant's throughput. A new operating consortium, Nuclear Management Partners Ltd, took over operations at Sellafield in 2008 and was charged by the NDA with making SMP work better. Soon thereafter, Japanese utilities were courted to become the exclusive customers of SMP.[142] This led to the framework agreement with 10 Japanese companies in 2010. Chubu Electric Power was the only one of the 10 to sign a contract – for its Hamaoka plant – before the Great East Japan Earthquake and Fukushima Daiichi nuclear accident in March 2011.[143]

One condition of the 2010 framework agreement was that Sellafield Ltd would contract with Areva to replace SMP's fuel rod production line.[144] By this time, Areva was part of the Nuclear Management Partners Ltd joint venture that operated the Sellafield site for the NDA. After the Grohnde orders were completed in 2010, SMP was shut down, and Areva began work on the New Rod Line Project, using its experience at the MELOX plant in France for the design.[145] The project was expected to last three years, enabling commercial production to restart around 2015.[146]

The economic case for SMP's new rod line was entirely dependent on Japanese demand.[147] In the wake of the Fukushima accident, however, the Japanese government in 2011 announced a

Table 1. SMP Production and Economic Timeline

Fiscal Year[a]	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**Total**
Fuel assy. made[b]	—	—	—	4 (Bez.)	4 (Bez.)	8 (Bez.)	—	2 (Groh.)	9 (Groh.)	8 (Groh.)	—	—	**35**
Fuel assy. shipped[b]	—	—	—	—	8	8	—	—	—	—	—	19	**35**
Goal [MTHM/yr][b]	72				25		12		3		—	—	—
Actual [MTHM/yr][c]	—	—	—	0.3	2.3	2.6	—	1.1	4.8[d]	2.7[e]	—	—	**13.8**[d]
Net cash flow [millions £][c]	n.d.	-78.6	-83.3	-110.1	-79.9	-92.1	-92.1	-89.9	n.d.	n.d.	n.d.	n.d.	**-833.6**[f]
Contracts[g]	Bez. Gös. Gra. Groh. Mühl. Osk.	Krü.				Neck.							
Subcontracts[b]		Bez. Groh.	Groh.	Gra.									

Note: Sources indicated in the row headers with exceptions noted next to some data.

[a] Fiscal years for BNFL and NDA ran April 1 through March 31.

[b] See narrative above.

[c] House of Commons Debates, April 2, 2009, vol. 490, col. 1364W.

[d] Nuclear Decommissioning Authority, "Freedom of Information Act Request for a Copy of Report on 'Lessons Learned from SMP'," July 18, 2012.

[e] Production in FY2011 was taken as the difference between the total production (13.8 MTHM) and the production before FY2011.

[f] Net capital costs, operating costs, and revenue (-£1,471 million) minus capital costs (-£498 million) and commissioning costs (-£139.4 million).

[g] Abbreviations: *Bez.* (Beznau), *Gös* (Gösgen), *Gra.* (Grafenrheinfeld), *Groh.* (Grohnde), *Kru.* (Krümmel), *Mühl.* (Mühleberg), *Neck.* (Neckarwestheim), *Osk.* (Oskarshamn). Note: n.d. means no data were available.

phased shutdown of nuclear power plants to reevaluate plant safety and public opinion.[148] This uncertainty led the NDA to permanently shut down SMP in August 2011.[149] The potential Japanese customers had essentially "pulled the plug."[150] British trade unions opposed the closure, especially in light of ongoing discussions about the disposition of UK-owned plutonium as MOX fuel.[151] SMP is now in a mothballed state, and decommissioning might not begin until 2037.[152]

Security, Safety, and Environment

Security concerns at SMP focused on shipments from Sellafield of MOX fuel and – after the problems with MOX fabrication – of plutonium. Since SMP was connected to the THORP reprocessing plant via a short duct, there was little concern about plutonium dioxide shipments to SMP. However, security concerns about plutonium transport did arise from the subcontracting of some MOX fuel fabrication orders to COMMOX. The plutonium intended to make this fuel had already been separated at Sellafield, so there were two options for fulfilling these orders. First, plutonium dioxide powder from THORP could be shipped to the subcontractor for fuel fabrication, as was considered in 2005.[153] The second option for subcontracted orders, which is what occurred in practice, was to conduct flag swaps between two companies, precluding the need for physical shipments. Some separated plutonium eventually was shipped from Sellafield to Cogema in 2008 to compensate partially for plutonium used to fulfill earlier orders, but the transport was controversial and apparently not repeated.[154] Instead, in 2013, the UK announced that under a commercial arrangement, it was "taking ownership to around 1,850 kg plutonium that was originally allocated to repay plutonium loans (to France) in relation to historic MOX fuel subcontracts."[155] The UK Minister of State for Energy, Baroness Verma, explained that such flag swaps would "benefit the UK, firstly by avoiding the need to transport separated plutonium overseas, which carries with it the associated significant security measures."[156]

A security advantage of SMP's design, which also made production more difficult, was its minimal process hold-up areas. Minimizing buffers between production stages also reduced the residual plutonium buildup and the risk of criticality accidents. Near-real-time materials accountancy software was used to track material between cleanouts.[157] Although the data falsification at MDF came to light after the design of SMP had been finalized, SMP's design did reduce the possibility of a quality-control data falsification because its inspections were extensively automated, digitally recording the dimensions of every pellet.[158]

In response to a Parliamentary question in 2006, the Secretary of State for Trade and Industry stated that about 2.5 percent of SMP's throughput was lost as grinder dust.[159] If the average plutonium concentration in the pellets was around eight percent, then over 25 kg of plutonium would have been left in grinder dust.[160] This dust ultimately was a waste product because it could not be recycled back into production due to contamination.[161]

Worker and public radiation safety risks were judged to be within statutory limits by the Health and Safety Executive. The reference input spent fuel for plant safety analyses had a 45 MWd/kgHM burnup and was stored for five years after removal from a reactor prior to reprocessing.[162] The average annual radiation dose to an SMP worker was calculated to be between 3.2 and 4.4 millisieverts.[163] This was below the Health and Safety Executive's standard limit of 10 millisieverts per year (and far below the U.S. permissible annual dose of 50 millisieverts for a radiation worker). It was even below BNFL's more stringent, self-imposed limit at SMP, which set a group average whole-body dose of five millisieverts per year for plant workers, much tighter than at MDF. This strict safety standard, combined with the need to scale up production by more than a factor of 10, compelled the greater use of automation and remote-handling techniques at SMP.[164] Indeed, the fuel assembly area, where workers otherwise were likely to be exposed to the most radiation, was designed to be entirely remotely operated.[165]

There were two other noteworthy worker safety features of SMP. Gamma and neutron shielding was placed on glove boxes and on rod and assembly handling equipment, borrowing from the design at MDF.[166] Process equipment was also designed to prevent criticality accidents via container shape and size.[167] SMP had one significant accident in January 2007 in which five workers were contaminated. However, their internal doses were within annual limits.[168]

Because SMP used a binderless pellet production process, liquid radionuclide discharges were minimal.[169] Atmospheric discharges were limited to residual airborne radionuclides that escaped HEPA air filters. Solid waste consisted only of intermediate- and low-level radioactive materials.[170] The total plutonium-contaminated solid waste volume was expected to be 120 cubic meters per year.[171] A large portion of this would be empty plutonium dioxide powder canisters from the input stage.[172] Since these estimates were made before SMP started production, it is very likely that the actual waste production rates were much lower given the production delays and low throughput.

Despite SMP being designed to minimize effluents, some outside parties still expressed concerns about radioactive discharges. In particular, the Republic of Ireland and Nordic nations have been concerned historically about radionuclide discharges into the Irish Sea.[173] The Convention for the Protection of the Marine Environment of the North-East Atlantic, commonly known as the OSPAR Convention, laid out the obligations of its 15 members to prevent maritime pollution. Following SMP's approval to operate in October 2001, the Irish government requested an injunction before the International Tribunal for the Law of the Sea (ITLOS), seeking immediately to stop operations at SMP.[174] Although the case is known informally as the "MOX Plant Case," Ireland was at least as concerned about SMP enabling additional production and discharges at its feed-in THORP reprocessing plant. Ultimately, ITLOS denied the provisional injunction to stop SMP from starting up.[175] Ireland continued its case under the United Nations Convention of the Law of the Sea (UNCLOS) via the Permanent Court of Arbitration. In 2006, the European Court of Justice ruled that Ireland had violated various articles of the European Communities Treaty and EURATOM Treaty by circumventing their jurisdiction.[176] Ireland subsequently withdrew its claims with the Permanent Court of Arbitration in 2008.[177]

MOX Use in the UK

The idea of recycling plutonium as MOX fuel in the UK started with fast reactors. MOX fuel was also considered for the UK's thermal reactors but only was used experimentally. Although SMP was built to produce MOX fuel mainly for foreign customers, discussions in the 2000s explored producing domestic MOX to fuel new thermal reactors and to dispose of plutonium as waste in the form of low-spec MOX. By 2009, however, the NDA had concluded that SMP was insufficient to transform the UK's entire separated plutonium stockpile into MOX, based on the plant's expected throughput and lifetime.[178]

UK Reactor Types

The UK has designed and built several different classes of nuclear power reactors since the 1950s. The two fast reactor prototypes – the Dounreay Fast Reactor (DFR) from 1959 to 1977, and the Prototype Fast Reactor (PFR) from 1974 to 1994 – were inherently designed to recycle spent fuel. The DFR used metallic fuel, while the PFR used ceramic oxide fuel.

Calder Hall was the first of the Magnox class of nuclear power plants, so named because of the magnesium-based cladding that surrounded the metallic uranium fuel.[179] It was also one of the world's first nuclear power plants, built at Sellafield in the early 1950s, and was primarily designed to produce plutonium for the UK's nuclear weapons program, although later units were for energy production. These Magnox reactors were thermal-spectrum, moderated by graphite, and cooled with carbon dioxide gas. The design was a compromise due to the UK's initial lack of uranium enrichment and access to heavy water, and the U.S. government's unwillingness to share nuclear technology starting in 1946.[180] Overall, 26 Magnox reactors were built at 11 sites, and the last Magnox reactor, Wylfa 1, shut down in 2015.

The AGR was conceived as a scaled-up refinement to the Magnox design, and similarly used graphite as moderator and carbon dioxide as coolant. Differences included that it was designed to use ceramic oxide rather than metallic fuel, stainless steel instead of magnesium-based cladding, and low-enriched rather than natural uranium. The prototype Windscale AGR started up in 1963. Overall, 14 AGRs were built at seven sites from 1976 to 1989, and the first AGRs are expected to shut down in 2023.

In the early 1970s, the UK AEA built a prototype steam-generating heavy water reactor (SGHWR) at Winfrith. The SGHWR competed for new nuclear capacity with several other designs: the AGR, a high-temperature gas reactor, and a Westinghouse PWR.[181] Although the SGHWR was not commercialized, it did use experimental MOX fuel before shutting down in 1990.[182] Eventually, the Westinghouse PWR was chosen for construction next to an existing Magnox reactor at Sizewell. The single-unit Sizewell B is the only civilian LWR in the UK.

Changing Ownership of Nuclear Reactors: 1979 to 2018

The UK underwent a radical shift in the planning and oversight of its electricity system from the 1980s to the 2000s. This had significant implications for the potential use of MOX fuel in UK reactors. During the three Conservative governments from 1979 to 1990, plans were made for privatization of several state-owned utilities, including gas, water, and electricity. The two main electric utilities – the Central Electricity Generating Board, and the South of Scotland Electricity Board – were broken up into multiple companies around 1990. The government-owned nuclear power plants were originally expected to be sold, but they were found to be uneconomic.[183] So, instead, they were moved into new public companies: Nuclear Electric, and Scottish Nuclear. In 1995, the AGRs and the Sizewell B PWR were combined and sold as a new private company: British Energy. The Magnox reactors were combined into a new public company called Magnox Electric (later Magnox Ltd), which subsequently merged with BNFL.[184] In 2011, British Energy was acquired by Électricité de France (EDF).

From 1990 to 2011, the Magnox power plants changed ownership twice, while the AGRs and Sizewell B PWR changed ownership three times. This meant that potential MOX fuel use had to be reevaluated repeatedly by new owners with different priorities. The biggest shift came during the privatization of Nuclear Electric and Scottish Nuclear to form British Energy. Although the British government maintained a sizeable ownership fraction of British Energy, the nuclear power plants were subjected to shareholder scrutiny for the first time. Thus, starting in 1995, the potential use of MOX fuel in AGRs and the Sizewell B PWRs needed a strong economic case before it could be considered.

Domestic Sources of Plutonium

Because of the UK's long history of nuclear reactor development and use, there are a variety of different sources of domestic plutonium that could be recycled as MOX fuel. The largest source is from the spent fuel of Magnox and AGR power plants. Most of the spent fuel from these plants already has been reprocessed, resulting in separated plutonium oxide powder.[185] Spent fuel from the Sizewell B PWR is also available but is currently stored on site in a pool or in dry casks. Other potential domestic sources of plutonium include operational and retired nuclear weapons, and the spent fuel from naval propulsion reactors and prototype reactors. Excess weapons-grade plutonium has been blended down with reactor-grade plutonium.[186] If the UK's separated plutonium were not used to make fresh fuel, it would have to be further processed to be acceptable for direct underground disposal.[187]

Disposing of plutonium via MOX fabrication and irradiation can be conceived in two different ways. If the resulting spent MOX fuel were considered to be waste destined for a permanent repository – which would provide both a geological barrier and an initial radiation barrier – then from a nonproliferation perspective such irradiation could be conceived as disposing of all the plutonium contained in the MOX. However, if the spent MOX fuel were to be reprocessed, then the appropriate metric would be the net destruction of plutonium achieved by irradiation, which varies by reactor type as discussed below.

Fast Reactors

As noted, the United Kingdom developed two prototype fast-reactor power plants: the DFR and PFR. As fission in both reactors relied on fast neutrons, they required fuel with much higher fissile content than in thermal reactors. The DFR initially used enriched uranium metallic fuel. The PFR used MOX fuel with an average 25-percent plutonium content.[188]

Magnox Reactors

The Magnox alloy, which gives the reactors their name, is used as a cladding around the fuel. It slowly corrodes in water, so the spent fuel cannot be stored for long in fuel ponds. This originally was not a concern since the Magnox spent fuel was intended for reprocessing to obtain plutonium for weapons. After the military's demand for such plutonium subsided, however, spent Magnox fuel still was reprocessed to "manage safety and environmental risks," as there was "no proven alternative," according to the Department of Trade and Industry's 1997 whitepaper on energy.[189] Yet, the two Magnox reactors at Wylfa successfully used dry carbon dioxide stores for their spent fuel for over 40 years.[190]

Since the Magnox reactors used a metallic fuel, they could not operate with MOX. However, a research program for oxide fuel in Magnox reactors, called MAGROX, was started in the late 1990s. MAGROX fuel was very similar to AGR fuel in that ceramic pellets were inserted into stainless steel tubes. The primary driver for MAGROX development was to make a fuel form that could be easily stored, eliminating the need for reprocessing.[191] However, MAGROX theoretically also could have been reprocessed at THORP alongside AGR fuel.[192] In the end, BNFL decided not to pursue MAGROX for the Oldbury and Wylfa reactors because of uncertainty about the return on investment.[193]

The Magnox reactors produced low-burnup spent fuel due to using unenriched, natural uranium fuel. This was desirable for the weapons program since the spent fuel contained plutonium with a high percentage of Pu-239, improving the reliability of its explosive yield.[194] However, the low fuel burnup also meant that a smaller percentage of actinide atoms were fissioned. For this reason, Magnox reactors would be an inefficient way to dispose of plutonium by use in fuel, if the spent fuel were to be reprocessed.

Another measure of plutonium consumption is the conversion ratio of a reactor, which compares the amount of fissile material in the spent and fresh fuel.[195] The OECD Nuclear Energy Agency (NEA) estimated that over a 30-year lifetime, a Magnox reactor would have a conversion ratio of 0.86. This is much higher than the estimated conversion ratio of 0.5 for LWRs and AGRs,[196] indicating that the total fissile content of Magnox fuel is not substantially reduced during irradiation. Although reusing separated plutonium in Magnox reactors was technically feasible, the high conversion ratio meant that it would have taken a long time to reduce plutonium stocks if the spent fuel were reprocessed. However, if the spent fuel were considered as waste destined for a permanent repository, then the short core residence time would have made Magnox reactors a relatively fast way to dispose of separated plutonium.

The age of the Magnox fleet also was a factor in not using MOX fuel. The four Calder Hall units were built in the mid-1950s, and the last Magnox plant at Wylfa came online in 1971. Magnox reactors were designed with 20- to 25-year lifetimes,[197] and several life extensions were granted. By the time Wylfa closed in 2015, the mean lifetime of a Magnox reactor was over 37 years, with the majority closing at 40 years or older. However, since the commercial MOX program in the UK did not start in earnest until the 1990s, the Magnox fleet could have played only a small role in domestic MOX use without further life extensions. As part of its National Stakeholder Dialogue (NSD) in 2003, BNFL suggested that Magnox reactors would be unsuitable for MOX fuel due to "very tight time constraints,"[198] regulatory risk, and political opposition.[199]

Advanced Gas-Cooled Reactors

Although the AGR shared a design heritage with the Magnox reactor, the AGR was not designed to produce weapons plutonium, and its low-enriched oxide fuel is more similar to LWR fuel than Magnox fuel. Fuel burnups (20–30 MWd/kgHM) are also closer to LWRs (45 MWd/kgHM) than to Magnox reactors (seven MWd/kgHM). Despite the successful use of MOX fuel in thermal power reactors in other countries, however, MOX was never used in a British AGR on a large scale. BNFL did produce experimental MOX fuel that was loaded into the prototype Windscale AGR,[200] and the five assemblies produced "excellent results,"[201] demonstrating the technical feasibility of MOX in AGRs. Nevertheless, Peter Hollins, the chief executive of British Energy, told the House of Commons Select Committee on Trade and Industry that AGRs are "physically not capable of using MOX fuel."[202]

The most cited reason for the lack of MOX use in AGRs is unfavorable economics. In 1993, BNFL concluded there was "no economic incentive" to use recycled plutonium in AGRs,[203] and thus did not pursue it.[204] British Energy, owner of the AGRs since 1995, also evaluated them for MOX but in 1998 found that it was "impractical."[205] This had not changed by 2006, when the company advised the CoRWM that the higher fuel cost, combined with the cost for reactor modifications, made MOX commercially unattractive in the AGRs.[206]

The AGRs' age was also an important factor in not using MOX. The NSD Plutonium Working Group estimated in 2003 that it would take 10 years to modify and license the AGRs to use MOX fuel.[207] At the time, British Energy had expected all AGRs to be retired in the 2000s,[208] so it would have made little sense to undertake major plant modifications just prior to shutdown. Since then, AGR plant lives have been extended considerably, with current owner EDF recently extending Heysham B and Torness to 2030,[209] and the other AGRs now scheduled for retirement in the mid-2020s. Although recycling plutonium as MOX is technically feasible in the existing AGRs, the older of these units built in the 1960s may be less suitable for MOX use. The NSD Plutonium Working Group suggested that only the newest AGRs (Heysham B and Torness) should be considered alongside Sizewell B for domestic MOX use.[210]

Two historical operating factors would have made MOX use in AGRs less efficient compared to LWRs. One is the capacity factor, which is the ratio of actual to maximum power generation over a period of time. Historically, AGRs have had much lower capacity factors compared to LWRs. This is due to a combination of reasons including a lack of online refueling at some plants,[211] and major engineering problems.[212] Through 2017, the lifetime capacity factor for the 14 AGRs had averaged 69 percent, with a low of 45 percent at Dungeness B-1 and a high of 79 percent at Heysham B-1.[213] A plant with a 69-percent capacity factor would need about 30 percent longer to use a certain amount of fuel than a plant with a 91-percent capacity factor (the average for Heysham B-1 from 2013–2017). This is undesirable if the goal is to dispose of a plutonium stockpile rapidly.[214]

The second relevant operational factor is the fuel burnup. The higher the burnup, the more energy can be extracted from the fuel, which in MOX means more plutonium fissioned. The average fuel assembly burnup for AGRs varies between 20 to 30 MWd/kgU.[215] In the United States, the average fuel assembly burnup for LWRs has been steadily increasing from a range of 35 to 40 MWd/kgU in the late-1990s to 45 MWd/kgU today.[216] If the burnups for MOX and LEU fuel in AGRs were similar to each other, then a smaller proportion of the plutonium in MOX fuel would be fissioned in AGRs than in LWRs.

Sizewell B PWR

Sizewell B is the only LWR in operation in the UK, the culmination of the country's long struggle over new reactor construction.[217] The final four AGRs were built at Torness and Heysham before the single-unit Sizewell B PWR was brought online in 1995. The original proposal was to build four units at Sizewell. One unit was authorized in 1987, but the other three were cancelled in 1989 after the CEGB's privatization.[218]

Sizewell B has never used MOX fuel. British Energy identified several issues that needed to be addressed before Sizewell B could use MOX. These included fuel assembly handling (due to the higher radioactivity of MOX than LEU, in both fresh and spent fuel), additional security during handling and transport, and regulations for licensing. The original core-control design and reactor pressure-vessel head would have allowed for a 30-percent MOX core, while a 50-percent MOX core would have required minor redesign.[219] A higher percentage of MOX in the core would have been possible with a major redesign and significant cost, but when the pressure-vessel head was replaced in 2006, it was not equipped with the additional control rod drives necessary for high-MOX cores.[220]

In 1998, British Energy also noted that MOX assemblies cost more due to fabrication expenses.[221] The company reiterated this point in 2000, stating that MOX fuel was at least a factor of two more expensive than LEU fuel.[222] In 2001, an independent economic analysis of potential MOX use in Sizewell B, by Sadnicki and Barker, concluded that the long-run, levelized cost of MOX fuel would need to be less than half of its 2001 price to be competitive with LEU fuel.[223] In 2006, a governmental advisory board judged MOX still to be economically unattractive at Sizewell B.[224] In 2013, a parliamentary inquiry dismissed the option of Sizewell B using MOX fuel, judging such fuel to be feasible only in new nuclear power plants.[225]

In Sadnicki and Barker's 2001 study of civil plutonium disposition options,[226] the levelized cost of fabricating fuel for Sizewell B, from 2005 to 2038, was estimated as £650/kg for LEU versus £1,000/kg for MOX.[227] The total cost of using LEU was estimated as £722/kg, including £72/kg for storing plutonium separated from the resulting spent fuel. Additional costs arising from MOX use were estimated as £453/kg, for reactor modifications, relicensing, fuel transportation, operations, and spent MOX disposal. Thus, the estimated long-term cost for LEU fuel, £722/kg, was about half that for MOX fuel, £1,453/kg. However, the study did not quantify uncertainty in these cost assumptions. In addition, it is unclear if the estimated MOX fuel cost included the substantial reprocessing expense to obtain plutonium, or if that input was viewed as free.

Summary of Findings

The UK produced MOX fuel for its domestic fast-reactor development program, for experiments in domestic thermal reactors, and for commercial use in foreign thermal reactors. BNFL, working with the AEA, conceived MDF as a pilot MOX fuel plant for the much larger, follow-on SMP. MDF proved the small-scale commercial viability of the short binderless route pelletizing process but exposed workers to relatively higher doses because it lacked the automation of the subsequent SMP design. MDF's reliance on manual processes also made it vulnerable to falsification of data – which occurred in fuel for at least two of MDF's three customers, leading to MDF's early closure. The third customer, Switzerland's Beznau-1 reactor, suffered cracks in three MOX fuel rods, but no other problems are known with MDF-produced fuel.

BNFL and its successors struggled to get SMP running, and its overall performance fell far short of expectations. This was due to a multitude of factors, but the consensus of many plant workers and managers was that SMP's design flaws led to its production issues.[228] The construction budget was likely too small for the desired throughput, and this led to an undersized building and the use of new equipment and processes without adequate testing at scale.

Many of SMP's processes were partially or wholly automated due to stringent worker radiation dose requirements. On the positive side, the automation of inspections reduced the risk of data falsification as had occurred at MDF. A lack of internal buffer capacity was helpful from a materials accountancy perspective but led to whole-plant shutdowns when problems were encountered. The flawed fuel rod and fuel assembly processes at SMP caused multi-year delays and ultimately were scrapped in favor of Areva's processes from its MELOX plant. However, that change was never implemented, because SMP was shut down in 2011 when its Japanese customers pulled out after the Fukushima accident.

There are several key challenges in manufacturing MOX fuel compared to LEU fuel: powder blending, powder homogeneity, safeguards, criticality, glove-box handling, and sealed manufacturing.[229] BNFL's short binderless route attempted to overcome the powder homogeneity problem with attritor mills to make finer powders. Materials safeguards and accountancy for plutonium were addressed at SMP by minimizing process holdup areas and by implementing near-real-time accountancy techniques. However, removing process buffers contributed to SMP's severe throughput problems. Criticality concerns were successfully managed, and shielded glove boxes protected workers from gamma and neutron doses from plutonium.[230] Sealed manufacturing was necessary to minimize worker dose and accidental discharges of plutonium into the environment. An overall lesson from the UK experience is that the presence of plutonium requires a MOX fabrication plant to have more stringent dose control, security standards, materials accountancy, and safeguards – which sharply increase costs compared to fabricating LEU fuel that is much simpler and has a longer history.[231]

Although the UK was a pioneer in MOX, it never used such fuel commercially. The country has had two fast reactors, two prototype thermal reactors, 26 Magnox reactors, 14 AGRs, and one PWR, but none of these has used MOX fuel for more than experiments. The primary explanation is economics: the cost of MOX fuel has always been at least twice that of uranium fuel. MOX is also not an exact substitute for uranium fuel, so significant upgrades would be required at existing plants, including to fuel-handling facilities, reactor core reactivity controls, and site security. Regulatory approval would also be costly and time-consuming.

Several other factors have also hindered domestic MOX fuel use, including the age of power plants, especially for the Magnox reactors and AGRs. When domestic and global MOX fuel production were ramping up in the 1990s, the Magnox reactors were close to the ends of their lives, so there was little incentive to make modifications, especially a fundamental one such as switching from metallic to oxide fuel. The AGRs probably had enough life left in the 1990s to pursue the necessary modifications for MOX fuel, but the owner at the time, British Energy, expected them to retire much sooner than they have done. In addition, the AGRs' lower historical capacity factor and fuel burnup compared to PWRs would have made them less efficient at destroying plutonium or converting it into a less-accessible form.

Without government subsidies, MOX fuel is clearly unattractive to use in the UK on a commercial basis compared to LEU fuel. However, recycling separated plutonium into MOX could enhance its resistance to terrorism and theft. From an economic perspective, this may be viable only if MOX fuel is produced for burning in reactors, rather than merely producing low-spec MOX for direct disposal as waste.[232]

Conclusion

The UK's MOX fuel production record is mixed. The fast reactor MOX program and MDF demonstrated key fabrication processes at multi-tonne scale. However, these successes did not scale up for the desired production at SMP. Although MDF was the lead-in plant for SMP, the latter design differed substantially from the former. In some ways, SMP itself functioned more like a demonstration plant than a high-performance commercial plant. SMP's performance risk could have been reduced by demonstrating the highly-automated technologies at a much smaller scale first, akin to MDF (on the order of five MTHM/yr). An intermediate-scale plant (approximately 25 MTHM/yr) could have revealed some scaling problems at a lower cost, and if the processes did not work, less money would have been lost on the project.

BNFL did not have enough in-house experience and expertise at Sellafield to overcome SMP's production problems. This led to the Areva contract in 2010 (which was never completed) to replace the fuel-rod production line. BNFL's stringent worker dose requirements drove the automation of processes, which proved to be problematic. Either more relaxed dose standards or a more robust automation design effort might have ameliorated some of these issues.

In addition to production and design risks, there were also regulatory and policy risks that were inadequately addressed. SMP did not receive approval to operate until several years after it was built, which led to a multi-year delay in startup and a loss of revenue. The plant's startup likely would have been expedited if the regulatory approval had already been in place. A similar pathology in the United States has led to the innovation of a combined construction and operating license (COL) for new nuclear power plants.

Since none of the UK's various nuclear power plant owners ever expressed much interest in using MOX fuel, only the export market was viable for MDF and SMP. After MDF's production ended, SMP worked with several different customers in Europe and Japan, but production delays led to subcontracting much of the work to France and Belgium. The 2010 deal with Japan's utilities provided SMP a final lifeline but also made it extremely vulnerable to policy changes by this single country, as occurred after the Fukushima accident.

Currently, the UK government's preferred disposal option for its over 110 tonnes of domestic-owned separated plutonium is to recycle it in MOX fuel. Since SMP is now shuttered, MOX fuel would have to be fabricated in another facility. A new plant could be built in the UK, or the separated plutonium could be sent to a foreign MOX manufacturer. Non-UK fabrication would require shipping separated plutonium via air or sea, thereby raising significant security concerns, as arose when some plutonium was shipped to France in 2008. In 2015, Areva proposed its Convert project to build a MOX fuel fabrication plant at Sellafield.[233] However, the proposal did not include any new reactors to use the MOX fuel in the UK, and no current UK nuclear plant developer has expressed interest in using MOX fuel. Two other foreign companies – GE Hitachi Nuclear Energy and Candu Energy – have each offered to build both a new MOX fuel fabrication plant and new nuclear reactors designed to use MOX fuel, but so far there is little domestic enthusiasm.[234]

For the UK and other countries considering recycling plutonium as MOX fuel in thermal reactors, there should be an open and honest accounting of the lifecycle costs and uncertainties involved in MOX fuel production before that path is pursued. MDF showed that incorporating human factors in plant design is essential to reduce the risk of fraud and subsequent loss of customer confidence. SMP demonstrated the tensions arising from the competing constraints of capital costs, operating costs, worker safety, and materials security. Recycling plutonium in MOX for thermal reactors is clearly more expensive in the short term than a standard once-through fuel cycle based on LEU, which explains the disinterest in and sometimes resistance to using MOX in UK commercial reactors.

Nevertheless, thermal MOX remains interesting for the UK because of the potential revenue from electricity sales to offset plutonium disposal costs. However, it is still unclear whether the lifetime, all-in cost of a thermal MOX program would be less than that of other disposition options for the UK's separated plutonium, such as vitrification with direct disposal. MOX would be an even less compelling option if the reprocessing costs were not already sunk. The UK's MOX production experience, while limited, shows that the costs of providing state-of-the-art worker safety and materials security can be substantial, even though they cannot guarantee success, especially as market and political conditions shift.

Glossary

AEA	UK Atomic Energy Authority
AGR	Advanced gas-cooled reactor
BNFL	British Nuclear Fuels Ltd
BWR	Boiling water reactor
EDF	Électricité de France
ITLOS	International Tribunal for the Law of the Sea
KEPCO	Kansai Electric Power Company, not to be confused with Korea Electric Power Corporation.
LEU	Low-enriched uranium, below 20 weight-percent U-235.
Magnox	British gas-cooled reactor design that used a magnesium–aluminum alloy cladding. Magnox stands for MAGnesium Non-OXidizing.
MDF	MOX Demonstration Facility
MOX	Mixed-oxide fuel consisting of natural, depleted, or recycled uranium oxide and recycled plutonium oxide.
MWd	Megawatt-day, equivalent to 86.4 gigajoules of thermal energy.
NDA	Nuclear Decommissioning Authority
NII	Nuclear Installations Inspectorate
NSD	BNFL National Stakeholder Dialogue
OFC	Springfields Oxide Fuels Complex
ONR	Office for Nuclear Regulation
PWR	Pressurized water reactor
SBR	Short binderless route, a mixed oxide pellet manufacturing process developed by BNFL.
SGHWR	Steam-generating heavy water reactor

SMP	Sellafield MOX Plant
MTHM/yr	Metric tonnes of heavy metal per year. Heavy metal refers to uranium and plutonium.
THORP	Thermal Oxide Reprocessing Plant
UNCLOS	United Nations Convention of the Law of the Sea
WAGR	Windscale advanced gas-cooled reactor

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[176] Court of Justice, "Judgment of the Court (Grand Chamber) of 30 May 2006. Commission of the European Communities v Ireland," May 30, 2006, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:62003CJ0459. Cesare P.R. Romano, "Commission of the European Communities v. Ireland. Case C-459/03. Judgment," *American Journal of International Law* 101, 1 (January 2007): 171–79.

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[178] Nuclear Decommissioning Authority, "Plutonium: Credible Options Technical Analysis," January 30, 2009, https://tools.nda.gov.uk/publication/nda-plutonium-topic-strategy-credible-options-technical-analysis-january-2009/.

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[180] Taylor, *The Fall and Rise of Nuclear Power in Britain*, 7–13.

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[182] C. Brown, et al., "Overview on MOX Fuel for LWRs: Design, Performance and Testing," International symposium on MOX fuel cycle technologies for medium and long term deployment, International Atomic Energy Agency, Vienna, 1999, http://inis.iaea.org/Search/search.aspx?orig_q=RN:31062342. Magnox Ltd, "Steam Generating Heavy Water Reactor – SGHWR: The Final Chapter," April 19, 2015, https://magnoxsites.com/wp-content/uploads/2015/04/J5965-Magnox-SGHWR-Brochure-V3-120315LR.pdf.

[183] Taylor, *The Fall and Rise of Nuclear Power in Britain*, 27–30.

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[185] Magnox and AGR spent fuel has been reprocessed at the Sellafield site. Magnox spent fuel has been reprocessed at either B204 (1951 to 1973) or B205 (1964 to present). AGR spent fuel has been reprocessed at THORP (1997 to present).

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[192] House of Commons Trade and Industry Committee, "Minutes of Evidence, Monday 3 April 2000," in *Ninth Report: Proposed Public Private Partnership for BNFL* (HC 1999–2000), 2000, Appendix 3: "Memorandum submitted by Cumbrians Opposed to a Radioactive Environment," https://publications.parliament.uk/pa/cm199900/cmselect/cmtrdind/307/0040301.htm.

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[195] The conversion ratio of a reactor is the amount of fissile material produced per amount of fissile material consumed. If the conversion ratio is greater than one, the reactor is "breeding" more fissile material than it was initially loaded with. If less than one, it is "burning" more fissile material than it produces.

[196] OECD Nuclear Energy Agency, "Plutonium Fuel: An Assessment. Report by an Expert Group."

[197] S. B. Grover and M. P. Metcalfe, "Graphite Materials Testing in the ATR for Lifetime Management of Magnox Reactors," HTR-2002: Conference on high temperature reactors, Petten, The Netherlands, 2002, http://inis.iaea.org/Search/search.aspx?orig_q=RN:33033025.

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[199] The Environment Council, "BNFL National Stakeholder Dialogue, Plutonium Working Group Final Report," March 2003, 19.

[200] A. J. Bull, "Advanced Fuel Technology – A UK Perspective," Advisory group meeting on advanced fuel technology and performance: Current status and trends, International Atomic Energy Agency, Vienna, 1990, http://inis.iaea.org/Search/search.aspx?orig_q=RN:22026510. Brown, et al., "Overview on MOX Fuel for LWRs."

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[202] House of Commons Trade and Industry Committee, "Minutes of Evidence, Tuesday 21 March 2000," in *Ninth Report: Proposed Public Private Partnership for BNFL* (HC 1999–2000), 2000, Q. 147, https://publications.parliament.uk/pa/cm199900/cmselect/cmtrdind/307/0032101.htm,

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[213] "United Kingdom," IAEA Power Reactor Information System, April 18, 2018,

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5

MOX in Japan: Ambitious Plans Derailed

Hina Acharya

This chapter assesses Japan's ambitious but so far largely derailed plans to use substantial amounts of mixed-oxide (MOX) fuel in light-water nuclear reactors (LWRs). Field interviews were conducted in Japan in 2018 with policymakers, power companies, scholars, and non-governmental organizations. The chapter explores the economics, security, safety, performance, and public acceptance of the MOX program. Japan had planned to commence commercial MOX use in 1997, but numerous scandals delayed the start by a dozen years until 2009. The program paused again in 2011 due to the Fukushima nuclear accident, and then restarted slowly in 2016. To date, only 3.4 tonnes of plutonium in MOX has been irradiated in LWRs, a tiny amount relative to Japan's remaining 47 tonnes of unirradiated, nuclear weapons-usable plutonium that is stockpiled in Europe and Japan, raising significant concerns for East Asian regional security. Japan's MOX fuel has also proved to be significantly more expensive than traditional low-enriched uranium (LEU) fuel. Despite such concerns, the Japanese government still envisions MOX as part of its long-term energy plan. This study recommends that Japan increase interim dry-cask storage of spent nuclear fuel and delay domestic reprocessing, at least until it proves that the MOX program can effectively consume the existing plutonium stockpile.

Japan is today the world's only country without nuclear weapons that nonetheless reprocesses its spent nuclear fuel to separate plutonium, which is a nuclear weapons-usable material. Through domestic and foreign reprocessing, Japan now owns 47 tonnes of unirradiated plutonium in various forms and locations. This large plutonium stockpile, enough to make thousands of nuclear weapons, has caused domestic and international concern and raised regional tension with historic enemies such as China, North Korea, and South Korea. Japan maintains a national policy to use this stockpile in mixed oxide (MOX) plutonium-uranium fuel to generate energy in nuclear reactors, but current trends make it unlikely that the entire stockpile could be consumed in this way any time soon, if ever.

In 2012, Japan essentially finished construction (except for obtaining a final safety license) of a new domestic reprocessing facility, which could separate eight tonnes of plutonium annually once in operation, now slated for 2021 after many postponements. Japan declares that all plutonium separated in the future will also be used in the MOX program, but there are concerns that Japan's plutonium stockpile will continue to grow. Since reduction of Japan's plutonium stockpile and the rationale for domestic reprocessing both hinge on the success of its MOX program, Japan's past experience with such fuel merits close attention.

This study finds that Japan has continuously struggled with its MOX program, characterized by delays and public opposition. Japan had planned to commence commercial MOX use in 1997, but multiple scandals delayed the start by a dozen years until 2009. The program paused again in 2011, due to the Fukushima nuclear accident, and then restarted slowly in 2016. To date, only 3.4 tonnes of plutonium in MOX has been irradiated in light-water reactors (LWRs), a tiny amount relative to Japan's remaining 47 tonnes of unirradiated, nuclear weapons-usable plutonium that is stockpiled in Europe and Japan. Japan's MOX fuel has also proved to be significantly more expensive than traditional low-enriched uranium (LEU) fuel.

The rest of this chapter starts by reviewing the history of Japan's MOX program and its extensive delays. The following section discusses the utilization of MOX, including contracts, economics, security, safety, and performance. Attention then turns to Japanese public perceptions of MOX. The chapter concludes with policy recommendations for Japan and broader lessons for the world.

Japan's Nuclear Program

Japan's nuclear research program began in 1954, and in 1959 a small experimental boiling water reactor (BWR) began operation. In 1965, Japanese nuclear reactors began generating energy commercially. At the peak, Japan had nearly 60 operating commercial LWRs that supplied the country with 34 percent of its energy.[1]

In 1956, the Japanese Atomic Energy Commission (JAEC) released its first long-term plan for reprocessing spent nuclear fuel. The Japanese government stated the intention to separate plutonium for fast breeder reactors (FBRs), and it projected using FBRs for consumer energy by as early as 1985.[2] Japan started development of FBRs in the mid-1960s, and spent $17 billion from 1974 to 2011 on research and development of a commercially viable FBR,[3] but the efforts proved unsuccessful. In 2016, the government announced plans to decommission the prototype Monju FBR.[4] As the result of domestic and foreign reprocessing of Japan's spent fuel, more than 50 tonnes of plutonium have been separated, of which about 47 tonnes remains unirradiated: approximately 22 tonnes in the UK, 16 tonnes in France, and 10 tonnes in Japan.[5] (These figures are rounded and thus do not sum to the total.)

While breeder reactors were under development, MOX fuel use in LWRs was considered a helpful short-term mechanism to reduce Japan's plutonium stockpile.[6] Accordingly, in the 1960s, the Japanese Power Reactor and Nuclear Fuel Development Corporation (PNC) started research and development of MOX fuel for LWRs and advanced thermal reactors (ATRs). In December 1995, a sodium leak and fire at the Monju FBR caused it to go offline until 2010.[7] However, it was not until 2007 that the Japanese Cabinet confirmed an official policy shift, prioritizing use of MOX fuel in LWRs. Despite ending the FBR program, which was the original rationale for reprocessing, Japan plans to start commercial operation of its Rokkasho reprocessing plant in 2021, separating up to an additional eight tonnes of plutonium annually. All of Japan's separated plutonium is now planned to be used for MOX in LWRs.[8]

Japan's Basic Policy for Nuclear Energy states that, "in pursuing the effective use of plutonium, peaceful use is a major precondition. Japan, therefore, should continue to adhere strictly to the principle of not possessing plutonium without a specific purpose."[9] The policy states that the only current practical way of consuming plutonium is in the form of MOX fuel for LWRs. In July 2018, a new government energy plan pledged to "make efforts to cut the stockpile of plutonium."[10]

After the March 2011 Fukushima nuclear accident, all of Japan's nuclear power reactors shut down in an orderly manner during scheduled maintenance by May 2012. Restarting these reactors requires approval under the stricter regulations of a new Nuclear Regulation Authority (NRA), which is tantamount to relicensing and has been partial and gradual. As of July 2018, nine such reactors had restarted, although a court injunction suspended one in December 2017, leaving eight operating. Another five had been cleared for restart by the NRA, 12 were being reviewed by the NRA (including one under construction), 15 had not yet applied for restart (including one under construction), and 18 were being decommissioned (half of them based on decisions prior to the accident). Thus, out of Japan's historical total of 59 reactors (including two under construction), only eight were operating, of which three had some MOX fuel in their cores.[11]

Several government institutions share responsibility for Japan's nuclear power sector. The JAEC's original role was to promote nuclear power and establish basic policies for development and utilization of nuclear energy.[12] After Fukushima, the JAEC transitioned from promotion to management of the nuclear program. The Ministry of Economy, Trade, and Industry (METI) was formed in 2001 and has broad jurisdiction.[13] METI's electricity and gas industry department oversees nuclear energy policy, nuclear facilities development, and the nuclear fuel cycle.[14] The Nuclear Regulation Authority (NRA) was established in 2012, following the Fukushima accident, to rectify a perceived conflict of interest: the country's previous regulatory body was the Nuclear Industrial Safety Agency (NISA) within METI, which gave that ministry responsibility for both promoting and regulating the nuclear industry. NRA now operates under the Ministry of Environment, separating the nuclear regulation body from promotion of the nuclear industry. The Ministry of Education, Culture, Sports, Science, and Technology (MEXT) is responsible for research and development of the nuclear fuel cycle.

Power companies in practice must get approval from a prefecture's governor and the local mayor prior to starting, or restarting, a MOX program, although that is not technically required by law. In 2004, METI introduced a subsidy program to entice local governments to permit use or fabrication of MOX fuel.[15] In 2010, the government subsidy was ¥1 billion ($10 million) per year per facility for five years.[16]

Methods

During January 2018, interviews were conducted in Japan with current and former officials in government, utilities, industry, non-governmental organizations (NGOs), and academia. Utility reports in English were obtained from websites of major Japanese electric companies. The JAEC also has published translations of Japan's annual plutonium management reports. The University of Texas Briscoe Center holds archived publications of the Nuclear Control Institute (NCI), a defunct U.S.-based research center that had actively documented Japan's MOX plans. In addition, until 2014, the Citizen's Nuclear Information Center (CNIC), in Tokyo, published detailed timelines of each LWR using MOX fuel in Japan.

MOX Use in Thermal Reactors

In 1986, Japan first tested a small amount of MOX fuel in its Tsuruga-1 reactor, laying the groundwork for commercialization in LWRs.[17] In 1988 testimony submitted to the U.S. House Committee on Foreign Affairs, Dr. Milton Hoenig of NCI outlined Japan's plans to deploy MOX commercially in LWRs beginning in 1997. At the time, Japan planned to use 96 tonnes of plutonium in 12 LWRs from 1997 to 2017.[18] According to Matsukubo Hajime, a CNIC official who closely followed Japan's MOX program in the 1990s and early 2000s, the specifics of this plan were never made public by Japan's utilities or government. Japan did not meet the desired start date to deploy MOX by 1997. Nevertheless, on February 21, 1997, the Federation of Electric Companies issued a revised proposal including plans to use MOX fuel in 16 to 18 LWRs from 1999 to 2010.[19] In 2005, the deadline for expanding MOX to this many reactors was pushed back five years to 2015.

In the early 1990s, Japan signed contracts for MOX fuel supply from companies in the UK, France, and Belgium. Tokyo Electric Power Company (TEPCO) and Kansai Electric Power Company (KEPCO) were scheduled to be first to utilize MOX fuel.[20]

Due to technical and political issues, however, much of the MOX shipped to Japan has not been used.

Table 1
Initial MOX Contracts

Power Comp.	**Supplier**	**Year of Con-tract**	**Assem-blies con-tracted**	**Reactors**	**Assem-blies received**	**Arrival**	**Pu (kg) in MOX received**
KEPCO	BNFL	1995	16	Takahama -4	8 (returned in 2002)	1999	255 (returned in 2002)
				Takahama -3	0		
TEPCO	COMMOX (BN/ Cogema)	1995	60	Fukushima -3	32	1999	210
				Kashiwa-zaki-Kariwa-3	28	2001	205
TOTAL (net)			**76**		**60**		**415 kg**

Sources: Takagi, et al., *Comprehensive social impact assessment of MOX use in light water reactors*, 252. Masafumi Takubo, "Mixed Oxide (MOX) Fuel Imports/Use/Storage in Japan," April 2015, http://fissilematerials.org/blog/MOXtransportSummary10June2014.pdf.

In France, Cogema's La Hague facility reprocessed TEPCO's spent fuel, and the separated plutonium was used to fabricate MOX fuel in Belgium for TEPCO's Fukushima Daiichi-3 and Kashiwazaki-Kariwa-3 reactors. For the Fukushima reactor, Belgonucleaire's P0 plant in Dessel, Belgium, produced the fuel rods,[21] which were then combined into fuel assemblies by *Franco Belge de Fabrication de Combustible* (FBFC), also in Dessel. The contracted supplier was COMMOX, which was jointly owned by Belgonucleaire and Cogema, which co-owned FBFC. The 32 MOX fuel assemblies for TEPCO's Fukushima Daichii-3, containing 210 kg of plutonium, were trucked to France and then transported by sea to Japan in 1999.[22]

By contrast, KEPCO's spent fuel was reprocessed at the British Nuclear Fuel Ltd (BNFL) Sellafield reprocessing plant. BNFL also was contracted to fabricate the MOX fuel for KEPCO's Takahama-3 and -4 reactors.[23] In 1999, the first shipment for KEPCO from BNFL comprised eight MOX fuel assemblies containing 255 kg of plutonium.[24] The MOX fuel assemblies from BNFL and COMMOX were shipped together from Europe to Japan during July to September 1999.[25]

Delays

In October 1999, Dr. Edwin Lyman of NCI published a report stating that Japanese utilities were on the verge of loading MOX fuel into the Fukushima-3 and Takahama-4 reactors.[26] Soon after, however, reports emerged that BNFL had falsified quality-control data of the MOX fuel for the Takahama reactors. Takahama-4 was planned to be the first reactor to deploy MOX after receiving its shipment of eight assemblies in October 1999. Two months prior, however, BNFL discovered falsification of quality-control data for MOX fuel that it had produced for but not yet shipped to another KEPCO reactor, Takahama-3. BNFL reported this falsification to the UK's Nuclear Installations Inspectorate, to KEPCO, and to Mitsubishi Heavy Industries Ltd., in September 1999. This raised concerns that the data for the Takahama-4 fuel, just arriving in Japan, also had been falsified.

In September 1999, KEPCO, on the basis of its own analysis, reported that the Takahama-4 fuel was safe.[27] However, two anti-nuclear Japanese NGOs, Green Action and Mihama-no-Kai, had already sought to conduct independent analyses of the quality control for the Takahama-4 MOX fuel, asking Japanese officials to obtain the data from BNFL. According to Aileen Mioko Smith, director of Green Action, "the normally conservative Fukui legislature was convinced fairly easily and asked for all raw pellet data from Sellafield."[28] Rather than computer files that would have facilitated analysis, however, BNFL released paper books of the pellet size data. Undeterred, the two NGOs copied and distributed the paper data sets for local citizens to assist in reviewing. The NGOs submitted their analysis to KEPCO, the Fukui Prefectural Assembly, and the Ministry of International Trade and Industry

(MITI, precursor to METI), providing evidence of various types of inspection-data falsification at Sellafield. In November, the UK regulatory authorities confirmed the falsification of Takahama-4 data.[29]

This falsification occurred at the MOX Demonstration Facility (MDF) at BNFL's Sellafield site. In the first step of the inspection process after production, each fuel pellet passed through an automated micrometer to measure pellet diameter. Pellets that failed to meet the predetermined acceptable threshold were automatically rejected. A sample of approximately five percent of the accepted pellets were supposed to undergo an additional check, in which a worker manually measured pellets with a micrometer and entered the data into a spreadsheet. In August 1999, however, a member of MDF's Quality Control Team noticed similarities in pellet diameter data in consecutive spreadsheets and disclosed this to BNFL. After further investigations, BNFL reported in September 1999 that the pellet diameter data had been falsified by workers who simply copied data between spreadsheets.[30] According to Smith, in addition to the copy and paste of Excel sheets, data figures were altered so that pellets of disqualifying size could be included as acceptable.[31]

Following these disclosures, the start dates for MOX in the Takahama-3 and -4 reactors were postponed. Unirradiated MOX assemblies containing 255 kg of plutonium were returned to the UK in 2002. BNFL paid ¥11.2 billion ($100 million) compensation to KEPCO.[32] In March 2004, the Takahama-3 and -4 reactors received renewed approval for MOX. However, due to an accident at the Mihama-3 reactor in August 2004, KEPCO further postponed plans to insert MOX at Takahama.

After the initial delay in MOX fuel at Takahama, Japanese citizens filed a lawsuit to stop the deployment of MOX also at Fukushima Daichii-3. Anti-nuclear activists suspected that the MOX fuel supplied by COMMOX also had poor quality control.[33] They presented evidence to the district court that production standards at Belgonucleaire and FBFC were even lower than those at BNFL, in support of their contention that COMMOX's pellet diameter data was likely also compromised.[34] The activists ultimately lost the case, but the court ruled that Belgonucleaire and FBFC should release their quality-control data.

In an unrelated incident, in 2001, reports surfaced that the Japanese power company TEPCO had falsified inspection data to hide the presence of cracks in certain reactors.[35] This domestic scandal, combined with the BNFL falsification, caused the governor of Fukushima to retract prior consent and refuse to deploy MOX at Fukushima. MOX assemblies that had been shipped to the Fukushima Daichii-3 reactor were not inserted but instead stored at a nuclear power plant.[36]

At Kashiwazaki-Kariwa, according to Smith, there had been years of popular resistance to even building the nuclear reactors, but the receipt of MOX assemblies from France in 2001 magnified public opposition. She recalls that in the small village of Kariwa, adjacent to Kashiwazaki city, "Several local legislators were concerned about general nuclear safety and, with the addition of MOX, could get enough legislators to approve a local referendum" on the introduction of MOX fuel. Anti-nuclear NGOs launched a comprehensive effort to educate the local populace, including by distributing informational leaflets. In the May 2001 referendum, 54 percent of Kariwa voters opposed the deployment of MOX, with a voter turnout of 88 percent.[37] There was some ambiguity, however, as to whether the referendum was legally binding, so in 2002 the mayor of Kariwa village was on the verge of approving MOX, but that year it was also revealed that TEPCO had concealed its periodic inspections data, so he demurred. In September 2002, the prefecture formally withdrew its approval for MOX. At the time of this writing, in July 2018, the fresh MOX assemblies still have not been inserted into the reactor, 17 years after they were delivered.[38] This poses a security risk because the unirradiated MOX contains over 200 kilograms of plutonium, sufficient for at least 20 nuclear weapons.

MOX Supply Contracts in the 2000s

According to a 2007 report by Areva (successor to Cogema), "an important milestone in restarting the Japanese MOX program was reached in 2006."[39] The French company indicated that three MOX fuel supply contracts had been signed for deliveries from 2007 to 2020, and production had started in 2007. Table 2 outlines the contracts signed with Japanese utilities from 2006 to 2010. While 401 assemblies were contracted to be fabricated by Areva, only 133 had been received by Japanese utilities as of 2018.

Table 2
MOX Contracts in the 2000s with Areva

Contract Year	Power Company	Reactor	Assemblies contracted	Assemblies received by 2018	Arrival	Pu (kg) in MOX received
2006	Chubu	Hamaoka-4	108	28	2009	213
2006	Kyushu	Genkai-3	36	16 20	2009 2010	677 801
2006	Shikoku	Ikata-3	21	21	2009	831
2008	KEPCO	Takahama -3 & -4	48	12 20 16	2010 2013 2017	552 901 703
2009	Chugoku	Shimane-2	40			
2010	Hokkaido	Tomari-3	4			
2010	Chubu	Hamaoka-4	144			
		TOTAL	**401**	**133**		**4,678 kg**

Sources:
http://www.cnic.jp/english/topics/cycle/MOX/pluthermplans.html.
http://fissilematerials.org/blog/MOXtransportSummary10June2014.pdf.
http://www.aec.go.jp/jicst/NC/about/kettei/180731_e.pdf.

Japan finally initiated MOX fuel use from 2009 until the 2011 Fukushima accident, and resumed in 2016.[40] Masa Takubo reported in 2015 that Japan had imported MOX fuel including 4,390 kg of plutonium. Of that amount, 1,888 kg had been irradiated in LWRs, while 2,501 kg of plutonium remained in unirradiated MOX stored at reactor sites.[41] Table 3 summarizes Japan's MOX usage as of 2015 – i.e., prior to the 2011 Fukushima accident.

Since the restart of nuclear power after the Fukushima accident, four reactors have irradiated MOX, starting in 2016: Takahama-3 and -4, Genkai-3, and Ikata-3. However, a court injunction in December 2017 suspended operation of Ikata-3, so only three reactors were irradiating MOX at the time of this writing in July 2018. In addition, in 2017, Areva (now known as Orano) signed a new contract for fabrication of 32 MOX fuel assemblies for Takahama-3 and -4.[42] It is unknown if there are other contracts between Orano and Japanese utilities.

Table 3
MOX Fuel Irradiated in Japan Prior to the 2011 Fukushima Accident

Power Comp.	Reactor	MOX First Irradiated	Pu Irradiated (kg)
Kyushu	Genkai-3	November 2009	677
Shikoku	Ikata-3	March 2010	633
TEPCO	Fukushima-3	September 2010	210
KEPCO	Takahama-3	December 2010	368
		TOTAL	**1,888 kg**

Source: http://fissilematerials.org/blog/MOXtransportSummary10June2014.pdf.

Five other power reactors have been licensed for MOX but have not yet irradiated it.[43] Kashiwazaki-Kariwa-3 received its MOX license in 2000, but as noted above, prefectural approval was withdrawn in September 2002.[44] Chugoku Electric's Shimane-2 was licensed for MOX in October 2008, but the plant never received such fuel assemblies. Similarly, Tohoku Onagawa-3 and Hokkaido Tomari-3 were licensed in 2010, but neither has received MOX fuel assemblies. In July 2007, Chubu Electric's Hamaoka-4 was licensed for MOX, and 28 assemblies arrived in May 2009. However, upon inspection it was discovered that metal separators for three of the assemblies had become dislocated during shipment.[45] In December 2010, Chubu's president announced postponement in deploying MOX at Hamaoka-4, citing concerns about the unit's safety in the event of seismic activity. The 2011 Fukushima disaster then shuttered all of Japan's nuclear reactors. Chubu's application to restart is currently pending at the NRA. According to journalist Masakatsu Ota, the local government plans to hold a referendum on whether to start MOX use at the reactor.[46]

Economics

The JAEC estimated in 2011 that, including the cost of reprocessing, commercial MOX fuel production in Japan if it ever started would cost Japan 12 times as much as LEU fuel production.[47] A TEPCO official declined to comment when asked about this estimate. As for imported fuel, no Japanese utility that uses MOX will disclose the price per assembly. In 2017, however, an article in the *Japan Times* used data from the Finance Ministry and other sources to estimate the high and rising cost of MOX fuel from Europe. According to this report, the price of each MOX fuel assembly imported in 1999 by Tokyo Electric (now TEPCO) was $2 million, but by 2013 the average price had climbed to $8.6 million, and in 2016 KEPCO paid over $9.3 million per assembly. This price includes the cost of transport, private security, and insurance.[48] By comparison, the average cost per assembly of LEU fuel in 2013 was less than $1 million, at least nine times less expensive than MOX that year.[49]

In 2011, the JAEC stated that "the proportion of MOX fuel loaded in reactors is small and the effects of MOX fuel cost in the front-end costs are insignificant."[50] However, according to Nagasaki University Professor Tatsujiro Suzuki, who is former Vice-Chairman of the JAEC, Japanese consumers have been charged higher electricity prices due to reprocessing and MOX use since the electricity market was liberalized in 2016.[51] Former TEPCO official Atsufumi Yoshizawa confirmed in an interview that increased costs due to reprocessing and MOX are reflected in the electricity rates.[52] Yet, he emphasized that the price of the fuel itself is a minor fraction of the total cost of producing nuclear energy, which includes reactor construction costs. This is true for uranium fuel, although the operating costs increase substantially if MOX is used. Of the five power companies that have imported MOX fuel, all three that currently have MOX loaded in at least one reactor – KEPCO, Shikoku, and Kyushu – have raised their prices to reflect MOX costs.[53]

Security Issues

The 1988 U.S.-Japan nuclear cooperation agreement requires the United States to approve any transportation plans for shipment of plutonium produced with U.S.-supplied nuclear fuel or technology. In 1987, NCI reported that a European reprocessing company was on the verge of shipping plutonium oxide by air to Japan with a refueling stop in Alaska, despite failure to develop crash-proof shipping casks. In response to this disclosure, the U.S. Congress and President Ronald Reagan enacted a law in December 1987 that sharply increased safety standards on air shipping casks, effectively blocking that mode of transport and compelling Japan's plutonium to be shipped instead by sea.[54] In 1992, the U.S. government required that any sea shipments of Japanese plutonium oxide from Europe to Japan be escorted by a gunboat.[55]

Since 1999, fabricated MOX assemblies have been shipped from Europe to Japan, rather than pure plutonium oxide. Japan insists that the stringent physical protection required for transporting separated plutonium is unnecessary for MOX. While non-proliferation activists objected, the United States ultimately relaxed its stance and approved shipment of MOX fuel without an armed Japanese escort vessel. The first MOX fuel from Europe was shipped on BNFL's commercial freighters in 1999. Two ships, the Pacific Pintail and Pacific Heron, ostensibly protected one another during the shipment. The two ships were also guarded by 26 lightly-armed police officers onboard.[56] Information about which of the two ships held MOX assemblies was not disclosed for security purposes. Dozens of en-route countries condemned the sea shipments, citing environmental and proliferation concerns.[57] After the September 11, 2001 terrorist attacks, the U.S. Nuclear Regulatory Commission (NRC) changed its regulations to limit public disclosure of transport details for U.S.-controlled fissile material due to security concerns. This barred disclosure of the route, timing, and security provisions of future MOX fuel shipments.[58]

In 1997, K. Moriya of TEPCO's Nuclear Power Plan Management Department presented a paper at the International Atomic Energy Agency (IAEA) on Japanese security measures.[59] It acknowledged that increased security measures would be needed after the introduction of MOX, which is Category 1 material due to its plutonium content and potential to be stolen for use in nuclear weapons.[60] Under the UN's Physical Protection Convention, this category includes unirradiated materials with at least two kilograms

(4.4 pounds) of plutonium, such as fresh MOX fuel.

While the 1997 TEPCO document highlighted the security risks of unirradiated MOX fuel, current Japanese government policies downplay such vulnerabilities. The JAEC's 2017 document on plutonium utilization in Japan states that, "MOX itself cannot be used for nuclear weapons purposes, and [is] considered to be nuclear proliferation resistant."[61] Journalist Masakatsu Ota says that this misrepresentation is prevalent in Japan's nuclear industry, which also erroneously claims that reactor-grade plutonium cannot be made into nuclear weapons.[62] Ota said that Ryukichi Imai, Japan's former ambassador to the UN Conference on Disarmament, had an enormous role in shaping Japan's official position. NCI reported that, in 1993, Imai falsely asserted that "reactor grade plutonium . . . is of a nature quite different from what goes into making of weapons . . . it is quite unfit to make a bomb."[63] According to Ota, Imai was warned about ignoring the dangers of reactor-grade plutonium by scientists at the U.S. Los Alamos National Laboratory, but he refused to change his stance.[64]

Japan's domestic unirradiated plutonium is stored at Rokkasho and nine other sites under security that is much lighter than required in other countries including the United States. Japan's government has resisted repeated requests to establish tougher security measures at Rokkasho beyond minimal IAEA guidelines, although it has reportedly adopted a "design basis threat."[65] Even after the 9/11 terrorist attacks, the Rokkasho plant's security still consisted of unarmed guards and a small police unit, and its 2,400 workers were not required to undergo stringent background checks.[66] Naoto Kan, the Prime Minister of Japan at the time of the Fukushima disaster, explained that while the United States faces threats from terrorist attacks, Japan did not consider terrorism a possibility within its own borders.[67] After the establishment of the NRA in the wake of the Fukushima disaster, the agency required more rigorous anti-terrorism measures at nuclear facilities, including credible emergency response exercises.[68]

Safety Concerns

In 1995, MEXT conducted a safety study of irradiating MOX fuel, based on a core design that did not change significantly from that of conventional LEU fuel. The study was based on two MOX fuel assemblies that were irradiated in the JAPC-Tsuruga-1 BWR from 1986 to 1989, and four MOX fuel assemblies that were irradiated at the Mihama-1 pressurized water reactor (PWR) from 1987 to 1991. These irradiation tests were performed as a joint research program with Japanese electric utilities.[69]

The safety study determined that "the thermal hydraulic characteristics between fuel cladding pipe and coolant are the same as uranium fuel."[70] The irradiation behavior also did not vary significantly from that of uranium fuel. The report concluded: "There is no particular safety problem to be found, so from now on, MOX fuel will be used as part of replacement fuel in LWRs."[71] MOX was limited to a maximum one-third of the reactor core, which obviated the need for additional control rods. Officials from both TEPCO and KEPCO confirm that no hardware changes were made before deploying MOX in their LWRs. However, such MOX use required the addition of burnable poisons to fuel assemblies and a higher concentration of boron in the refueling water storage tank and the boron injection tank, according to a 1995 presentation.[72]

The consensus among all interviewees is that MOX fuel has not caused any technical problems with reactor operations so far. However, most interviewees also agree that MOX has not yet been utilized sufficiently in Japan to make definitive statements on its performance and safety. Koshimuta Kazuhiro, a current TEPCO official, confirmed that the power company is unable to accurately evaluate maintenance costs because the utility company has deployed MOX for only a short time.

Selecting Reactors to Use MOX

Each utility was responsible for the plutonium separated from its spent fuel and so picked one or two reactors to recycle the plutonium in MOX fuel. The grounds for choosing which reactors to use MOX varied. The CEO of Kyushu Electric, Matsuo Kyushu, cited three reasons for deployment of MOX at Genkai-3. He explained that Kyushu's plans from the beginning were to operate only one unit with MOX at Genkai. The cores of Genkai-3 and Genkai-4 each comprised 193 assemblies, the largest operated by Kyushu, so either could have loaded 48 MOX fuel assemblies for a

25-percent MOX core. Unit 3 ultimately was chosen because the open space surrounding it was twice that of unit 4, making inspections easier.[73] For Fukushima, according to an interview with Atsufumi Yoshizawa, unit 3 was chosen to deploy MOX because it was the first power reactor constructed with domestic technology.[74] Yoshizawa says TEPCO decided that an indigenous unit would be best for MOX utilization, but other TEPCO officials could not confirm this.[75] Shikoku and KEPCO officials did not respond to inquiries about why Ikata-3, and the Takahama-3 and -4 reactors, respectively, were selected to use MOX.

Plutonium Storage

A majority of Japan's separated plutonium is stored in France and the UK, where Japanese utilities must pay for storage. The 1997 CNIC MOX assessment estimated the cost of plutonium storage at Sellafield and La Hague to be approximately two to four dollars per gram per year.[76] Even without inflation, that would now represent $75 million to $150 million annually. However, Shaun Burnie of Greenpeace says that, for Japanese utilities, storage at foreign sites is a fraction of the price to fabricate the plutonium into MOX fuel assemblies.

Burnie further notes that the UK has offered to take ownership of Japan's plutonium for a price. These plans are actively under discussion and supported by the UK's Nuclear Decommissioning Authority (successor to BNFL), which would receive payment from Japanese utilities. France, by contrast, favors Japanese utilities continuing to pay to have their plutonium fabricated into MOX fuel, because Orano is in dire financial condition and has no prospects of new reprocessing contracts for foreign spent fuel.

Public Perception

Most interviewees suggested that Japan's public does not differentiate between MOX and LEU fuel. However, a clear exception to this was in the village of Kariwa in Niigata prefecture. Mioko Smith, who advocated against MOX at Kashiwazaki-Kariwa, said the proposed introduction of MOX fuel at the plant magnified anti-nuclear sentiment. Before the referendum in 2001, anti-nuclear

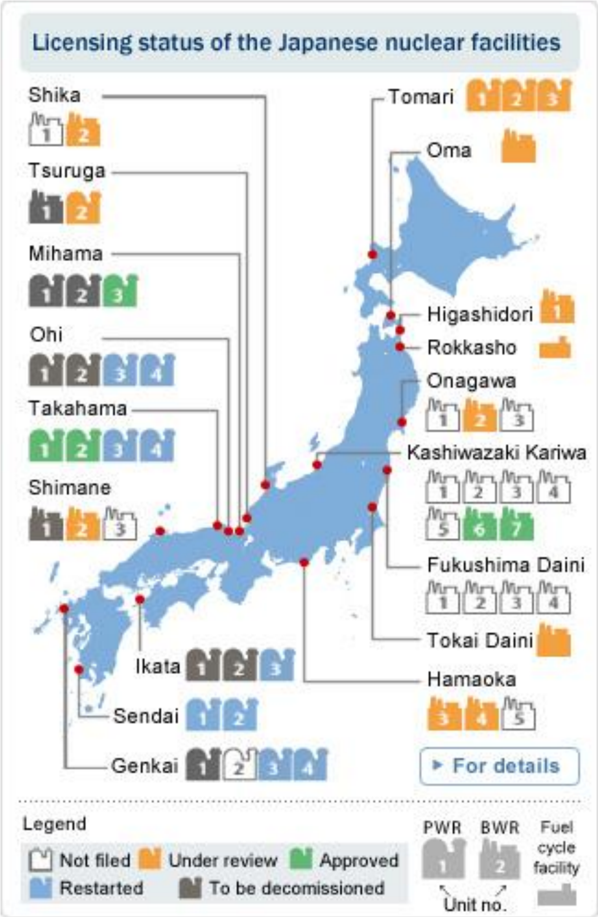
NGOs highlighted the potential dangers of MOX fuel and emphasized that no changes had been made to the evacuation plans in the event of an accident.[77] The 2001 referendum in Kariwa demonstrated that, although most of Japan's public might be unaware of the difference between MOX and LEU, concerted efforts by activists could turn voters against MOX fuel. At the same time, the reactor was permitted to continue operating with LEU fuel, underscoring that MOX can be more controversial than conventional nuclear energy.

According to Mioko Smith, "It's hard to explain to people that MOX can only be used once and that spent MOX has no place to go. We are trying to convince the local governments that spent MOX fuel in some way is a bigger headache for utilities because they have to keep it at their reactor sites since Rokkasho [even if the unfinished plant eventually were started commercially] cannot reprocess it. Storing spent MOX fuel on site also has additional safety concerns compared to LEU fuel."[78] Mioko Smith said that some electricity customers are aware that the extra costs of MOX will be passed down to consumers, but many people are apathetic. Most Japanese anti-nuclear advocates have focused on safety issues, not increased costs, to build public opposition to MOX fuel.

Takuya Hattori, a former TEPCO executive and now senior fellow at the Japan Atomic Industrial Forum, argues that anti-nuclear groups have spread propaganda to build fear. He said that in the 1990s, TEPCO worked hard to explain to local governments and residents that MOX had no extra safety issues. He criticized anti-nuclear energy attitudes and said they were emotional responses to the 1945 nuclear bombings in Hiroshima and Nagasaki. He also said that the media misreads small incidents at nuclear facilities and blows them out of proportion.

Most interviewees cited Japan's bureaucratic culture as a major explanation for the continued use of MOX. Retired bureaucrats often secure lucrative positions in the same companies that they had supervised as public servants, a practice known in Japan as *Amakudari*.[79] The national government is powerful and forges strong connections between the private and public sectors. Senior officials at power companies may acquiesce to national pro-MOX policies due to such personal loyalties.

Figure 1
Post-Fukushima Restart of Japan's Nuclear Power Reactors



Source: http://www.genanshin.jp/english/, July 2018.

Resuming MOX Use

Since the 2011 Fukushima accident, the NRA has cleared 14 LWRs to restart, and nine have done so, including four with some MOX fuel. However, as noted, only eight were online as of July 2018, including three with some MOX fuel. On average, a traditional LWR could use up to about 700 kg of plutonium in fresh fuel per year,[80] so that eventual deployment of MOX in 16 to 18 reactors could utilize more than 10 tonnes of plutonium annually.

Japan's national policy retains this longstanding plan to use MOX in 16 to 18 reactors, but utilities have yet to announce a new deadline for achieving that goal. The JAEC's 2017 proposal includes plans to deploy MOX eventually in only 12 reactors, which highlights the implausibility of the national policy. Moreover, several of these 12 are unlikely ever to use MOX. For example, in a January 2018 interview, former JAEC official Nobuyasu Abe confirmed that Shikoku's Ikata-3 reactor will not load additional MOX fuel.[81] In Shizuoka prefecture, after the governor was elected for the third time in 2017, he announced that he would not consent to the restart of Hamaoka-4.[82] Due to earthquake fault issues at Shimane-2 and Tomari-3, restarting these reactors would be difficult. This reduces to eight the number of reactors envisioned to use MOX. One of these, the under-construction J-Power Ohma reactor, is planned to utilize plutonium at a much higher rate because it would have a full MOX core. However, construction was suspended in 2011, and the license is still being considered by the NRA, so the reactor is not expected to deploy MOX until 2024 at the earliest.[83]

In a January 2018 study, Frank Von Hippel and Masafumi Takubo estimated that by later that year, four reactors – Takahama-3 and -4, Ikata-3, and Genkai-3 – would be loading MOX containing 2.2 tonnes of plutonium per year. If Shimane-2 and Tomari-3 eventually receive NRA approval in 2019, they together could irradiate another 0.6 tonnes of plutonium per year, resulting in a total of 2.8 tonnes of plutonium in MOX fuel loaded per year. However, since Ikata-3 no longer plans to use additional MOX, the amount of plutonium loaded and irradiated will be less. Several other reactors have been proposed to use plutonium fuel but they lack MOX licenses and in most cases also face additional hurdles.[84]

Moreover, less than two tonnes of plutonium in unirradiated MOX fuel is currently in Japan for potential use. While KEPCO has signed a contract with Orano for MOX fuel containing 1.45 tonnes of plutonium, it is not estimated to arrive for two to three years. Thus, during the next few years, it is estimated that Japan annually will load MOX fuel containing only about one tonne of plutonium, barely reducing its stockpile of 47 tonnes of unirradiated plutonium at home and abroad.[85]

Table 4
Annual Plutonium Loading (Tonnes) in Reactors Licensed for MOX

Reactor	**Re-start?**	**Oper-ating?**	**Pu in MOX per Year** *Now*	*Likely*	*Potential*	**Notes**
Takahama-3	Yes	Yes	0.5	0.5	0.5	
Takahama-4	Yes	Yes	0.5	0.5	0.5	
Genkai-3	Yes	Yes	0.6	0.6	0.6	
Ikata-3	Yes				0.6	December 2017 injunction halted operation. Ex-JAEC official: will not use more MOX.
Tomari-3					0.3	Earthquake concerns hinder restart.
Shimane-2					0.3	Earthquake concerns hinder restart.
Hamaoka-4					0.6	Governor opposes restart.
Onagawa-3					0.3	Has not applied for restart.
Kashiwazaki-Kariwa-3					0	Has not applied for restart. Prefecture withdrew MOX approval in 2002.
Maximum			**1.5**	**1.5**	**3.6**	

Note: Amounts are total plutonium, estimated from fissile plutonium, and are rounded to nearest tenth, so may not sum to maximum.
Sources: "Plans for the Utilization of Plutonium to be Recovered at the Rokkasho Reprocessing Plant (RRP), FY2010," March 15, 2010, http://www.fepc.or.jp/english/news/plans/__icsFiles/afieldfile/2010/03/16/attachment_1_0315.pdf. Masafumi Takubo and Frank Von Hippel, "An alternative to the continued accumulation of the bomb materials that destroyed Nagasaki," January 2018.

Domestic Fuel-Cycle Facilities

Japan has never produced MOX fuel for use in commercial LWRs, but the domestic Tokai Works has had two dedicated facilities for MOX fuel fabrication. The first was PNC's Plutonium Fuel Fabrication Facility (PFFF), which started production of MOX fuel for the fast reactor Joyo in 1972 and for the Fugen advanced thermal reactor (ATR) in 1975.[86] Based on this experience, a second plant, the Plutonium Fuel Production Facility (PFPF), came online in 1987. This plant started producing MOX for the JOYO fast reactor in 1988 and for the MONJU FBR in 1989. [87] The plant initially had performance problems, but eventually they were resolved. According to PNC's successor organization, "In the beginning of operation, the PFPF encountered difficulties in fuel fabrication caused by unaccustomed operation of fully automated equipment. However, those difficulties have been overcome by the improvement of process equipment and operational conditions in the PFPF."[88]

The first production line, PFFF, produced five tonnes of MOX for JOYO using one tonne of plutonium, and 139 tonnes of MOX for Fugen using 1.8 tonnes of plutonium. (Fugen had a 100-percent MOX core, but the fuel had a very low plutonium content because the reactor was moderated by heavy water.) After Fugen's operation ended in 2003, the PFFF was terminated and fuel fabrication for JOYO switched to the PFPF.[89] From 1988 to 2017, the PFPF produced 301 MOX fuel assemblies for JOYO, using an estimated 0.8 to 1.2 tonnes of plutonium, and 366 MOX fuel assemblies for Monju, using an estimated 2.6 to 3.9 tonnes of plutonium.[90]

The PFPF suffered substantial material accountancy failures. As early as 1988, operators noticed plutonium stuck to gloveboxes. While further changes were made to measure the residual holdup, *in situ*, the system still has a measurement uncertainty of about 15 percent. By 1994, the PFPF's Material Unaccounted For (MUF) was about 69 kg of plutonium.[91] PNC did not comply with the IAEA's repeated requests to cut open the gloveboxes and directly remove the buildup. Eventually, after a pressure campaign by NCI, the operator of the PFPF spent $100 million to clean the gloveboxes. In November 1996, PNC announced that the MUF was less than 10 kg. While the IAEA requires that such issues be resolved within one month of discovery, PNC in this case took two years.

The PFPF is a prototype for a larger MOX fabrication plant at Rokkasho-Mura, Japan.[92] In 2006, Tadahiro Katsuta and Tatsujiro Suzuki wrote about plans for this facility, which they reported required an investment of approximately $1.2 billion for construction.[93] The J-MOX plant is intended to fabricate MOX fuel for both PWRs and BWRs, with a capacity of 130 tonnes of heavy metal per year. Currently, J-MOX is only 12-percent constructed, and the expected completion date has been delayed from 2010 to 2022.[94]

Although the Rokkasho plant to reprocess spent LEU fuel still has not started commercial operation, in 2011 the JAEC announced plans to build a second reprocessing facility to reprocess spent MOX fuel. In a 2018 interview, Koichiro Maruta, Deputy Director of the Nuclear Industry Division at METI, confirmed that the national policy remains unchanged and requires all spent fuel, including MOX, to be reprocessed.[95] However, Maruta stated that there is currently no way to reuse plutonium separated from spent MOX fuel and no ongoing research and development of recycling spent MOX fuel.

Japan's Tokai pilot reprocessing plant operated from 1981 to 2006. Plans for the facility were met with criticism from President Jimmy Carter's National Security Council on nonproliferation grounds, but the U.S. administration eventually acquiesced.[96] The plant reprocessed spent LEU fuel from LWRs and spent MOX fuel from the experimental Fugen ATR.[97] The Tokai plant had a nominal capacity to reprocess 210 tonnes of spent fuel per year but never reached this capacity and on average reprocessed only 40 tonnes per year.[98] Japan has announced that the plant will soon be decommissioned because the cost of upgrades to meet new, post-Fukushima safety regulations would be too high.[99]

Spent Fuel

With cooling ponds close to capacity, spent nuclear fuel storage is a pressing issue in Japan. The Japanese government shies away from discussing permanent direct disposal of spent fuel due to the political climate in Japan. As a condition of constructing the Rokkasho reprocessing plant in Aomori, the local populace understood that the prefecture would serve only as a temporary storage site for spent fuel, and that radioactive waste would be sent back to power companies after reprocessing. In 2010, as spent fuel pools at reactors and Rokkasho filled up, TEPCO and Japan Atomic Power Co (JAPC) started construction of an interim dry-cask storage facility in Mutsu in Aomori prefecture. The facility, still pending NRA approval, was designed to hold excess spent fuel that ostensibly would eventually be treated at a proposed second reprocessing plant, 40 kilometers away in Rokkasho. However, delays in starting commercial operations at the first Rokkasho reprocessing plant have spurred fears that the prefecture could serve as a final disposal site for spent fuel.[100] Accordingly, any discussion of abandoning reprocessing in favor of direct disposal of spent fuel would trigger calls from Aomori prefecture for the return to utilities of the approximately 3,000 tonnes of spent fuel stored there.[101]

This dynamic is illustrated by the case of KEPCO. Prior to restarting its reactors in 2016, that utility assured Fukui prefecture that past and future spent nuclear fuel would eventually be transferred to a site outside the prefecture. In 2018, reports surfaced that KEPCO had made a deal with Aomori Prefecture to send its spent fuel to Mutsu. However, this proposed arrangement was met with fierce resistance from the people of Mutsu and forced KEPCO to deny the report. Due to such opposition from Aomori, Japan's government is offering financial grants to other local governments to encourage dry cask-storage at nuclear power plants, according to a 2017 report.[102] However, after the Fukushima accident, no prefecture is likely to accept an interim storage facility within its borders, even though dry-cask storage is quite safe.

According to Shaun Burnie, Japanese utilities have little confidence that Rokkasho ever will commence commercial reprocessing. As early as 1996, TEPCO pushed for a change in the Japanese policy requiring reprocessing, and construction paused at Rokkasho while utilities attended a series of meetings on whether to proceed with the reprocessing plant. TEPCO was the lead utility pushing for a change in direction but was successfully opposed by Chubu and KEPCO, whom Burnie refers to as the "plutonium priesthood."[103] In an interview, Takuya Hattori, the former TEPCO official, argued that TEPCO was not against reprocessing but sought a more practical approach.[104] Hattori said that TEPCO could not fully depend on reprocessing, so the company wanted to develop a back-up plan. This would be consistent with TEPCO's significant investments in dry-cask storage of spent fuel.

Summary of Findings

Since the 1990s, Japan has attempted to implement its strategy of recycling separated plutonium in MOX for LWRs. However, due to data falsification scandals and increased anti-nuclear sentiment after the 2011 Fukushima accident, the initiative has been severely delayed and under-achieving. The MOX program finally started in 2009, more than a decade late, but soon was forced to pause after Fukushima. During this brief implementation, only four LWRs deployed MOX, and Japan's stockpile of approximately 50 tonnes of unirradiated plutonium decreased by less than two tons, or four percent.

While Japan seems to have increased security measures after the Fukushima disaster, it continues to assert falsely that MOX fuel is not a proliferation concern. In terms of safety, Japan continues to treat MOX fuel as equivalent to LEU fuel, although anti-nuclear activists have claimed for years that MOX increases accident risks. Economically, while the cost of MOX fuel is not officially disclosed, estimates suggest that imported MOX fuel costs nearly ten times as much as LEU fuel, and future domestically produced MOX would cost even more.

Following the post-Fukushima restart of Japan's nuclear program, only three Japanese reactors were using any MOX in summer 2018, and the plutonium stockpile had decreased by less than another two tonnes. Japan's current stocks and known orders of MOX fuel indicate that over the next several years, the country can irradiate only about one tonne annually of plutonium. It is implausible that Japan will come anywhere close to its national policy of deploying MOX in 16 to 18 reactors in the foreseeable future. Thus, if Japan proceeds with its plan to start commercial operation of the Rokkasho reprocessing plant, the country's already enormous plutonium stockpile could grow rapidly.

Recommendations

1. *Increase Transparency.* Japan's MOX fuel program has been characterized by its opaqueness. Japan has increased security measures after the 9/11 attacks and the Fukushima accident, indicating that the government is aware of the security dangers of fresh MOX and separated plutonium. However, official government

documents continue to underplay the security risks of commercial plutonium and falsely assert that MOX fuel is proliferation resistant. Japan's government should publicly acknowledge and address the security risks of MOX fuel. Japan's government and industry also obscure the economics of MOX fuel. Since the increased costs of MOX are passed on to consumers, utilities should publicly disclose the cost of MOX.

2. Announce Realistic Goals for Plutonium Consumption. Japan continues to affirm its policy of reducing its plutonium stockpile. However, utilities are legally allowed to continue reprocessing their spent fuel by claiming an intended use for the separated plutonium up to 50 years in the future. This makes the policy vague, ineffective, and illusory. The international community should pressure the Japanese government to prohibit further plutonium stockpiling and to limit the permissible time between future plutonium separation and use.

3. Delay Operation of the Rokkasho Reprocessing Plant. It is illogical for Japan to separate more plutonium before LWRs are licensed, and approved by local authorities, to consume it in MOX. Priority should be given to reducing Japan's in-country plutonium stockpile and its stocks in the UK and France.

4. Expand Dry-cask Storage of Spent Fuel. With most spent fuel pools close to capacity in Japan, and no need for the plutonium that would be separated by reprocessing additional spent fuel, plans should be developed to expand storage of spent fuel. Dry-cask storage is much safer than spent fuel ponds and would save money in the long run, compared to reprocessing.

5. Pay the UK to Take Title to Japanese Plutonium. In 2012, the British government announced that, "subject to compliance with inter-governmental agreements and acceptable commercial arrangements, the UK is prepared to take ownership of overseas plutonium stored in the UK."[105] Japan and the UK are reportedly in discussions to transfer ownership to the UK of Japanese plutonium stored there. Such a deal would be win-win. The UK's NDA would gain revenue from Japanese utilities, which in turn would save money by avoiding the costs of paying for fabrication of MOX fuel.

6. Adopt Once-Through Fuel Cycle. A once-through cycle is safer, more secure, and cheaper than reprocessing spent fuel and recycling plutonium in MOX. While such a switch would have domestic political ramifications in Japan in the short-term, it would lead to a safer, more secure, and wealthier society over the long-term.

Conclusion

Most countries that once used MOX fuel have decided to phase out their programs due to economic and public acceptance concerns. Lessons from Japan similarly demonstrate that MOX fuel is expensive, increases security risks, and may prove unable to decrease large plutonium stocks. If Japan continues with its current plan to expand reprocessing and MOX recycling, it could set a precedent for other countries, especially in the region, to pursue similar programs, which could be destabilizing. South Korea, with spent fuel sites close to capacity, is seriously considering recycling spent fuel. China's plans are even more advanced, as the government already has announced plans to develop a closed nuclear fuel cycle.[106] This poses the danger of a latent nuclear arms race that could undermine efforts to persuade North Korea to dismantle its nuclear weapons program. The Japanese government could take steps towards resolving this problem by first admitting what it has known for years: MOX is not a viable long-term solution. Next, the government should transparently discuss options to revise its current policies, including by considering alternatives to the MOX program. Otherwise, Japan's refusal to change course could have detrimental security consequences for Japan, East Asia, and beyond.

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6

MOX in Germany: Reprocessing Spurs Opposition to Nuclear Energy

Kelli Kennedy

This chapter presents a historical overview of mixed oxide (MOX) plutonium-uranium fuel in Germany, focusing on its fabrication for, and use in, light-water nuclear power reactors. Interviews were conducted in Germany and France in 2018 with current and former officials from government, industry, utilities, think-tanks, and non-governmental organizations. The chapter explores the economic, security, performance, safety/environmental, and public acceptance aspects of the German MOX experience. MOX fuel eventually performed well in German nuclear power plants, but it cost three to five times as much as LEU fuel. Commercial attempts to reprocess spent nuclear fuel domestically failed due to public opposition. Germany did produce MOX fuel commercially from 1972 to 1991, but ceased because of local opposition following a radiation accident. German utilities also exported spent fuel to – and imported MOX fuel from – France, the United Kingdom, and Belgium. This proved especially controversial, as anti-nuclear groups successfully stigmatized the international nuclear shipments on environmental and nonproliferation grounds. Ironically, the insistence of the German government on closing the nuclear fuel cycle, ostensibly to promote nuclear power, inadvertently contributed to the demise of nuclear energy in Germany.

When "Atoms for Peace" began in the 1950s, the German Federal Republic (FRG) – West Germany – sought a complete national fuel cycle. This included a mixed oxide (MOX) fuel fabrication program, originally intended for the country's future fast breeder reactor (FBR) fleet. When commercial breeder reactors proved unfeasible, however, Germany instead recycled plutonium in 13 commercial light-water reactors (LWRs), more than any country to date except France. Later, however, a reunified Germany reversed itself, by first halting reprocessing and then phasing out nuclear power entirely.

West Germany initially was interested in both the military and energy potential of nuclear technology. This led to intense domestic debate over the closed fuel cycle, which potentially enabled a nuclear-weapons option. The overt argument for MOX and the closed fuel cycle was that it would allow Germany to become energy independent. By contrast, opponents cited the weapons utility of a closed cycle and the health concerns of plutonium. Germany's anti-nuclear movement emerged from this debate and remains entrenched in society. Ultimately, the German nuclear power sector failed to overcome the anti-nuclear messaging of Greenpeace and like-minded organizations.

This study finds that the cost of MOX fuel in Germany was about three to five times that of traditional low-enriched uranium (LEU) fuel. Accordingly, utilities had to be pressured into reprocessing spent fuel and recycling the recovered plutonium in MOX fuel. While MOX itself was not especially controversial among the German public, the required international transports of radioactive material proved extremely so. Plutonium's association with nuclear weapons, combined with widespread public opposition to such weapons, helped drive Germany's original decision in 2002 to phase out nuclear power. The government later reconsidered that decision, but Japan's 2011 Fukushima nuclear accident ended such reconsideration.

This study employed a combination of primary and secondary research, including field interviews in Germany and France in January 2018. Interviewees included current and former officials from German government, industry, utilities, think-tanks, and non-governmental organizations. The remainder of this chapter assesses the economic, security, performance, safety/environmental, and public acceptance aspects of MOX fuel fabrication and use in Germany. It also gleans lessons for other countries that might consider initiating or expanding the recycling of plutonium for energy.

Germany's Nuclear Program

U.S. President Dwight D. Eisenhower's 1953 "Atoms for Peace" speech bred excitement in West Germany at the possibilities of nuclear energy.[1] The FRG saw nuclear as a path to energy security, and so immediately sought a complete national fuel cycle. The anticipated global demand for, and perceived insufficient supply of, uranium led Germany to believe that future nuclear energy would be derived from breeder reactors. As a result, Germany founded the Fast Breeder Project in Karlsruhe in 1960, and worked diligently to see the technology realized. In March 1991, however, the project and the completed SNR-300 breeder reactor succumbed to political opposition.[2]

Reprocessing, a necessary part of the closed fuel cycle, was initially driven by the German chemical industry.[3] Later, in the 1970s, the West German government put its utilities in charge, when the chemical industry lost interest.[4] After it became clear that commercial breeder reactors would not materialize, reprocessing was still viewed as necessary for waste management. In fact, amendments to the Atomic Energy Act, in 1976, effectively made reprocessing a legal requirement. These changes mandated, as a precondition of operating a nuclear power reactor, that utilities provide proof of a disposition plan for the spent nuclear fuel (SNF) six years in advance of its creation.[5] This left reprocessing as the only feasible option, since there was not yet a permanent repository for SNF in Germany.

Germany successfully operated a pilot reprocessing plant at Karlsruhe from 1971 to 1990. In 1985, construction began on a commercial reprocessing plant in Wackersdorf, Bavaria, but the facility was never completed, succumbing to public opposition in 1989. Protests ranged from peaceful demonstrations to violent confrontations between the West German police and protestors.[6]

Direct disposal of SNF was made a legal option in Germany on July 31, 1994. Less than a decade later, in 2002, an amendment outlawed exports of SNF for reprocessing after 2005.[7] Commercial reprocessing never reached fruition in Germany. Instead, for decades, spent fuel was exported to facilities in France, the United Kingdom, and Belgium to be reprocessed. The resulting separated plutonium was fabricated in these countries into MOX fuel that was returned to Germany, along with the resulting high-level and long-lived intermediate-level radioactive waste.

Since 2005, however, all German spent fuel has gone into interim storage pending a final disposal decision. Nuclear power plants, after shutdown, become interim storage sites overseen by the new Agency for Interim Disposal, *Bundesgesellschaft für Zwischenlagerung (BGZ)*. Under the 2013 Site Selection Act, a final disposal location must be chosen by 2031, and ready to receive spent fuel and other high-level waste by 2050.[8] A 700-page report by a special commission in 2016 specified the required characteristics of such a site and reiterated the deadlines of 2031 and 2050.[9] Despite the proclaimed confidence of politicians, no one interviewed for this study believes the site will be ready to receive high-level waste until much later. For low-level radioactive waste, a licensing process began in 1982 for the Konrad disposal site, but it took a quarter-century, until 2007, for the site to receive final approval from the regulator and courts.[10]

Table 1
Commercial Use of MOX in German Power Reactors

Reactor	**Type**	**Start Year**	**Licensed MOX %**
Obrigheim KWO	Pressurized	1972	29
Gundremmingen KRB A	Boiling	1974	n/a
Neckarwestheim GKN I	Pressurized	1982	9
Unterweser KKU	Pressurized	1984	33
Grafenrheinfeld KKG	Pressurized	1985	33
Grohnde KWG	Pressurized	1988	33
Philippsburg KKP 2	Pressurized	1988	37
Brokdorf KBR	Pressurized	1989	33
Gundremmingen KRB B	Boiling	1995	38
Gundremmingen KRB C	Boiling	1996	38
Isar KKI 2	Pressurized	1998	50
Neckarwestheim GKN II	Pressurized	1998	37
Emsland KKE	Pressurized	2004	25

Notes: Gundremmingen KRB A was shut down in 1977. Excludes experimental use at the Kahl VAK experimental BWR, Lingen KWL prototype BWR, and MZFR heavy-water reactor.
Sources: Ahlswede and Kalinowski, "Germany's Current and Future Plutonium Inventory," 303. D. Broking and W. Mester, "Fuel Cycle options for light water reactors and heavy water reactors," 39.

MOX fuel was introduced experimentally in West German LWRs at the Kahl VAK boiling water reactor (BWR) in 1966, at the Lingen KWL BWR in 1968, at the Obrigheim KWO pressurized water reactor (PWR) in 1972, and at Gundremmingen KRB-A BWR in 1974.[11] The future commercial use of MOX in German LWRs was based on analysis of the experiences at these plants. Eventually, 13 German commercial power reactors (ten PWRs and three BWRs) were licensed to use partial cores of MOX fuel, out of 24 commercial LWRs (16 PWRs and eight BWRs) that had traditionally used LEU fuel.[12] Thus, just over half of Germany's LWRs were "MOX-ified," and there was a clear preference for MOX-ifying PWRs over BWRs. Krummel (a BWR) was slated to be the fourteenth power reactor to receive a MOX license, but in the aftermath of Fukushima, it and seven other reactors were immediately shut down. As of 2018, seven German power reactors remain open, of which six are licensed for MOX, but all are scheduled to close by the end of 2022 (see Table 2).[13]

Table 2
German Power Reactors Still Operating in 2018

Reactor	MOX Licensed?	Closure Year
Philippsburg KKP 2	Yes	2019
Brokdorf KBR	Yes	2021
Grohnde KWG	Yes	2021
Gundremmingen KRB C	No	2021
Emsland KKE	Yes	2022
Isar KKI 2	Yes	2022
Neckarwestheim GKN II	Yes	2022

From 1972 to 1991, Germany operated a commercial MOX fabrication plant in the state of Hesse. In the summer of 1991, however, a glovebox accident leading to plutonium contamination forced the facility to halt operations. Due to political opposition, it never reopened. A second, state-of-the-art MOX fabrication plant, also at Hanau, was constructed but never permitted to operate. Consequently, after 1991, all MOX fuel for German reactors had to be imported.

Germany has a complicated history regarding nuclear weapons. Although the United States was the first country to build an atomic bomb, Germany was the first country to start down that path. Scientists in Nazi Germany formed the German Uranium Club, *Uranverein*, after discovering nuclear fission.[14] During the Cold War, West German academic and political circles worried whether U.S. extended deterrence, the "nuclear umbrella," could be trusted. Ideas were floated domestically and by western allies on how best to integrate West Germany within the NATO military framework. However, the West German public was averse to militarization in the wake of two world wars. A domestic anti-nuclear movement grew from these sentiments, and it continues to be a force within Germany despite the country lacking nuclear weapons and currently phasing out nuclear power. While the West German government considered the possibility of acquiring nuclear weapons, the public remained steadfastly opposed.[15]

MOX Use in Thermal Reactors

As noted, the German MOX fuel program was initiated in anticipation of commercial FBRs. When those failed to materialize, West Germany pursued the use of MOX in "thermal" reactors, which employ a moderator – in LWRs, it is water – to transform neutrons from fast to thermal in order to facilitate energy-producing fission. West German officials viewed such MOX recycle in thermal reactors as the most economical and least wasteful way to use uranium resources that at the time were perceived as scarce (but which later turned out to be relatively plentiful). Experimental reprocessing of German spent fuel started at Karlsruhe, involving about 205 metric tons of heavy metal (MTHM) from 1971 to 1990. German utilities also exported about 6,300 tonnes of spent fuel for commercial reprocessing. Of this exported SNF, 86 percent went to France's Cogema/Areva, 14 percent to the UK's British Nuclear Fuel Ltd (BNFL), and less than half a percent to Belgium.[16] Germany's final SNF export occurred in 2005, and the last return of high-level waste, from reprocessing in France, occurred in November 2011.[17]

After the UK stopped producing MOX fuel in 2011, Germany carried out "flag swaps" of its plutonium in the UK for an equivalent amount in France to be fabricated there into MOX fuel for German utilities.[18] By the end of 2014, German reactors had recycled in MOX fuel about 97 percent of the plutonium that had been separated from German SNF,[19] and by the end of 2016, less than one percent of such plutonium remained to be irradiated.[20] In January 2017, the final MOX fuel assembly was inserted into the Emsland reactor, and it should be removed around early 2021, ending Germany's use of MOX fuel. However, the country is still left with a legacy of spent MOX that must be disposed domestically as waste.

The 1976 amendment to the German Atomic Energy Act required utilities to have a back-end solution in order to receive a license for a nuclear power reactor. According to a former utility official, he and his colleagues were hesitant to reprocess SNF because they believed it was an economically unsound business move, but they felt obligated legally. Each utility thus was compelled to have at least one reactor in its fleet licensed to use MOX.

After the feasibility of commercial use of MOX fuel was demonstrated in one PWR and one BWR in the early-1970s, Germany's utilities and its MOX fuel fabricator jointly decided on efficiency grounds to focus on producing a largely standardized fuel for a single type of reactor, and the PWR was chosen because it was more plentiful in Germany, had higher power, and used simpler fuel.[21] Thus, from 1982 to 1989, all six German reactors that initiated use of MOX fuel were PWRs (Table 1). Subsequently, imported MOX fuel was used in two additional German BWRs, starting in 1995 and 1996, respectively. Another deciding factor for utilities in picking which reactors to license for MOX was whether the facility could easily accommodate the fuel. For example, KKP determined that its BWR could not handle the additional heat from MOX use, so the utility instead introduced the fuel into its PWR.[22]

Licenses for nuclear plants were granted not at the national level but by the *Lander* (i.e., state). The licensing process for MOX included a safety analysis of the effects of MOX fuel on irradiation behavior and other physical parameters.[23] Lander governments were required to make public their findings, including the safety analysis, before approving a license for MOX fuel.[24]

The licensed maximum amount of MOX in each core varied, but in 12 of the 13 MOX-ified LWRs, it was no more than 38 percent.

One reactor, Isar KKI 2, was licensed up to 50-percent MOX in the core.[25] According to a paper by German safety officials, "As a conclusion it can be stated that MOX fuel influences some safety related parameters which has to be accounted for in the safety analyses. Up to an amount of about 50-percent MOX assemblies in a normal LWR core, though, no effects were identified during the numerous licensing procedures concerning MOX insertion in German LWRs, which would indicate that an operation with MOX fuel were less safe or would demand an alteration in safety systems or even different rules and regulations than operation with UO2 [LEU] fuel only."[26]

As detailed below, the percentage of plutonium in the MOX for Germany's reactors appears to have been quite low by current international standards, at least in the German MOX produced domestically through the early 1990s. On average, MOX fuel produced at Hanau for thermal reactors contained only about four-percent plutonium (2.8-percent fissile plutonium), which is less than half the percentage in the MOX fuel that France currently uses in its LWRs. This may partly explain why Germany did not need to increase the number of control rods in its MOX-ified reactors, in contrast to France, despite similarly licensing its reactors for about one-third core of MOX.

When MOX was first introduced in German LWRs, safety concerns included the higher thermal-neutron absorption cross-section of plutonium compared to uranium, which reduced the effectiveness of control rods and boron in the moderator, especially in high-MOX cores, and the positive temperature reactivity coefficient of plutonium.[27] As a German nuclear safety official noted in 1995, "The boron worth decreases with increasing number of MOX fuel assemblies . . . The boron control systems need higher boron stocks." However, it was determined that additional control rods were not required if MOX were limited to one-third to one-half of the core. Another challenge, especially in BWRs, was that the plutonium content in the MOX fuel rods needed to vary within the core to reduce the neutron flux gradient between MOX and LEU assemblies.[28]

MOX fuel use in German reactors caused no major reported safety incidents. The environmental impact of MOX use was also roughly equivalent to LEU fuel, according to multiple interviewees. However, BNFL's 1999 falsification of quality-assurance records for some of its MOX fuel (see Chapter 4) led PreussenElektra to temporarily shut down the Unterweser plant, which contained four BNFL MOX assemblies inserted in 1997.[29] Although the fuel had been irradiated in the reactor for three years without incident, it was removed as a precaution, and the German government suspended MOX imports from BNFL.[30]

The transport and storage of MOX fuel, both fresh and spent, also raised safety issues due to the fuel's substantially higher thermal heat and radioactivity compared to LEU. Several new casks had to be designed for such transport and storage. In addition, when spent MOX was shipped, it was combined in a cask with about twice as much spent LEU, to avoid the excessive heat and radiation of a cask filled entirely with spent MOX.[31]

The cost to produce MOX fuel was three to five times that of LEU fuel, according to German experts interviewed from government, industry, and civil society.[32] Virtually all of them also said this substantial extra cost was not justified by any societal benefit of using MOX. Only one interviewee argued that the cost difference was irrelevant because people still needed energy, but he did not explain why plutonium recycling was necessary for energy. When asked about this higher cost, Jürgen Krellmann, the former executive director of the Hanau Fuel Fabrication Facility, who subsequently directed the world's largest MOX fabrication facility, France's MELOX plant, replied simply that, "no one ever asked me to make MOX cheaper."[33]

Notably, the level of security at power reactors supplied with MOX fuel was no higher than at other reactors, according to a German official interviewed, despite such fresh fuel containing nuclear weapons-usable plutonium. By contrast, during transport of fresh fuel, security was higher for MOX than for LEU, according to German officials. Environmental activists also say that Germany employed higher security on transport than did neighboring Belgium and France.[34] Nevertheless, Greenpeace successfully provided journalists advance notification of the location and time of nuclear transports, including of fresh MOX, underscoring the vulnerability of such fuel during transit and upon arrival at reactor sites.[35]

It is unclear why Germany required extra security for fresh MOX fuel during transport but not during storage at reactors prior to irradiation, since similar risks arise. Under German law, transport support services are provided by the Lander-level authorities, but the private sector is responsible for ensuring that nuclear materials arrive safely at their destination. Shipments of fresh MOX fuel from the United Kingdom involved sea shipment, so container trucks were driven onto a ship ("roll-on, roll-off") in the UK and driven off upon arrival in Germany, to minimize safety and security risks.[36]

Reprocessing and the international shipments entailed by Germany's closed fuel cycle proved more controversial than the use of MOX fuel, *per se*, which the German public initially did not differentiate from LEU fuel. Reprocessing was controversial because of its environmental and proliferation implications, especially in light of the German public's longstanding opposition to the spread of nuclear weapons.[37] The German anti-nuclear movement emerged in the 1970s with People's Initiative Groups and quickly gained momentum, leading to formation of the country's Green Party, one of the strongest environmental parties in the world.[38] Transports of spent fuel and fresh MOX fuel became increasingly controversial among the German public, so that in later years they occurred less frequently and under more secrecy, to avoid interference from protestors.

Former industry officials concede that the German nuclear sector failed effectively to counter the messaging of its opponents, such as Greenpeace. In one vivid example, according to Shaun Burnie of Greenpeace-Germany, the environmental organization encapsulated radioactive water from the sea outside France's La Hague reprocessing plant and shipped it to German utility and government officials, in a campaign known as "return to sender." Greenpeace also routinely blocked transports by rail, highway, and sea. Interestingly, Greenpeace's most effective anti-nuclear campaigns focused on the closed fuel cycle – reprocessing, MOX fuel, and high-level waste shipments – rather than nuclear power itself. Thus, Germany's decision to close the nuclear fuel cycle unintentionally provided Greenpeace with ammunition to turn the German public against nuclear energy entirely.

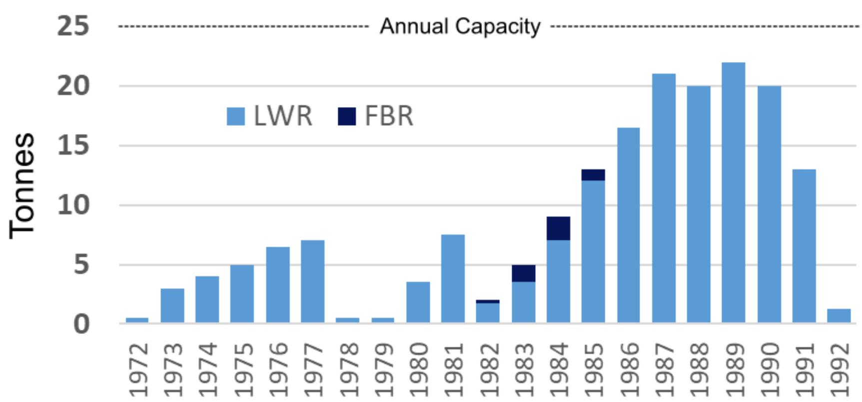
Anti-nuclear demonstrations routinely drew thousands of people from across the country and the political spectrum. Protests often occurred at existing and proposed nuclear facilities, or outside government buildings. The protests were mostly peaceful, but there were also instances of violent clashes between the police and protestors. In one case, a protester was killed by a train after chaining himself to the tracks. The repatriation of nuclear waste from foreign reprocessing plants to Gorleben, a town of fewer than 700 people, sparked especially fierce protests.[39]

In 2010, German Chancellor Angela Merkel's coalition government extended the operating lifetime of German nuclear power plants by up to 14 years, stretching out the nuclear phase-out that had been adopted by her predecessor, Gerhard Schröder, in 2002.[40] Two months after Merkel's decision, however, tens of thousands of protesters gathered along the route of another transport of nuclear waste to Gorleben, requiring 30,000 police. Then, in March 2011, public outrage at Japan's Fukushima accident compelled Merkel to reverse course. On March 14, 2011, the German chancellor ordered the immediate shutdown of eight of the country's 17 remaining power reactors.[41] Three months later, the Bundestag overwhelmingly approved an 11-year nuclear phase-out plan proposed by Merkel's coalition. The only opposing votes were from the Left Party, which wanted an even faster phase-out.[42]

MOX Fabrication

From 1972 to 1991, a commercial MOX fabrication facility known as Alkem Hanau operated in the state of Hesse. The plant's nominal capacity was 25 tonnes per year,[43] but its average production was only about eight tonnes annually. A former senior official of the facility claims that it fulfilled all contracts until its premature shutdown.[44] The average fissile plutonium content of the MOX produced for thermal reactors apparently increased over time,[45] but on average it was only 2.82 percent, which implies that the total percentage of plutonium in the MOX was about four percent, significantly lower than modern practice.[46] The plant was initially run by Alkem GbmH, which had been established to develop MOX fabrication technology and which had previously operated a prototype MOX fabrication plant at Karlsruhe for experimental fast reactors.[47] In 1988, Siemens AG took over Alkem, including the existing MOX plant and its planned successor facility, known as Hanau 1.[48] The original plant had been built at the invitation of the government of Hesse, which supported its operation until a "Red-Green" coalition of the Social Democratic and Green parties came to power in the state in January 1991.[49] The plant supplied mainly domestic customers, while 13 percent of its MOX fuel was exported.[50]

Figure 1
Annual MOX Output at Alkem Hanau



Note: Annual timeframe is probably fiscal year, because output is indicated for 1992 even though production halted in 1991.
Source: Kalinowski, et al., "The German plutonium balance, 1968–1999," *The Nonproliferation Review* 9, 1 (2002): 152.

In 1982, construction started on the proposed follow-on facility, Hanau 1, designed with two fabrication lines and a nominal annual production capacity of 120 MTHM/year.[51] A joint effort between Siemens and the German utilities, the plant received its first license in 1975, and was authorized to possess 2.5 tonnes of plutonium.[52] Both the original Alkem Hanau plant and the successor Hanau 1 were designed to make fuel for both LWRs and FBRs.[53] In the early 1990s, Siemens and the federal government, especially Environment Minister Klaus Töpfer, fought to enable operation of Hanau 1, which was nearly completed and had met all safety and security requirements.[54] However, the Red-Green Hesse government and its Minister for the Environment, Joschka Fischer, repeatedly prolonged the licensing process, until Siemens eventually abandoned the project in 1995.[55]

The first Alkem Hanau plant shut down on June 17, 1991, after a glovebox contamination incident, which resulted in a worker receiving a small dose of plutonium after sustaining a cut through both his protective gloves and skin.[56] At the time, the facility still had five contracts with German utilities. The Red-Green government of Hesse cited the incident as grounds to close the facility and rejected petitions from Siemens and the federal government to restart operations, leading to permanent closure in 1994. Residual materials from previous production campaigns were processed either for shipment or long-term storage.[57] Of the remaining material found suitable for shipment, 550 kg of plutonium in oxide and mixed-oxide forms was sent to the UK and France for further processing.[58]

From 1972 to 1991, the Alkem Hanau MOX fabrication facility processed 8,553 kg of plutonium.[59] Seventy-seven percent of this plutonium wound up in fuel for commercial thermal nuclear power plants. A much smaller portion resulted in fuel for prototype reactors such as the SNR 300 FBR. The remainder ended up in scrap or incompletely processed material.[60] The MOX fuel from Alkem reportedly performed without incident.

In the early years of German MOX fabrication, only plutonium from MAGNOX reactors with a high percentage of Pu-239 (up to 76 percent) was used. Starting in 1977, Alkem Hanau also used plutonium from the reprocessing of LWR fuel, which had a lower percentage of Pu-239.[61] Overall, from 1972 to 1991, Alkem Hanau produced 164 tonnes of MOX fuel – mainly for LWRs but also for FBRs and including scrap – or about 8 tonnes annually, a fraction of its nominal 25 MTHM/year capacity (see Figure 1). In only four of those 22 years did the plant approach its nominal capacity, producing at least 20 MTHM.[62]

Krellmann cites many reasons why the MOX plant fell so short of its nominal capacity: unforeseen repair work under difficult glove-box conditions; suspension of production during EURATOM safeguards inspections; introduction of complicated new equipment, including to produce MOX that could be reprocessed; delays in LWR fuel production while fabricating FBR fuel; intervention of government authorities concerning plutonium transportation; political opposition from the Hesse government; complications in hiring new personnel; occasional plutonium contamination in fabrication areas, requiring time-consuming cleanup; and planned maintenance work.[63] It should be noted, however, that under-performance is common at MOX fabrication facilities, having also occurred in the UK and Belgium (see Chapters 2 and 4), and is another reason why MOX fuel costs much more than LEU fuel to produce.

The most challenging technical aspect, according to Krellmann, was producing MOX fuel that was close to fully soluble (at least 99 percent) in nitric acid, in anticipation of eventual reprocessing of spent MOX, which in practice turned out to be extremely rare. This challenge was not particular to Hanau or Germany, but generic to MOX fabrication, because plutonium is more difficult than uranium to dissolve in nitric acid. Eventually, Alkem pioneered the OCOM and AU/PuC processes, enabling spent MOX fuel to achieve the desired solubility.

Security was a concern at German nuclear fuel installations, in part due to Cold War tensions. Alkem Hanau had armed guards, and Hanau 1 was designed with additional safety and security measures, including protections against fire, airplane crashes, and helicopter infiltration.[64] Hanau 1 was designed as a cubic building, reducing the footprint of the production facility to make it easier to defend.[65] The walls were at least two meters thick, and the facility was designed to withstand not only civilian planes such as the Boeing-747, but also high-speed military jets.[66] As noted, the plant never opened, so these concepts never were tested in practice.

Hanau 1 was also designed with a highly automated operating system to minimize the chance of human exposure to plutonium.[67] In addition, Siemens had created a new computerized safeguards system for supranational authorities, in cooperation with Euratom, the International Atomic Energy Agency (IAEA), and the U.S. Los Alamos National Laboratory.[68] Inspectors could have followed the flow of materials on their computers in real time or afterward.[69] Siemens would have had no access to the results of this safeguards system, but would have had its own independent measurement system.[70] This bifurcated arrangement would have allowed Siemens and the supranational authorities to compare results to help resolve discrepancies.[71]

Neither of the MOX fabrication plants directly affected German public opinion of nuclear power. However, the plants suffered from mounting opposition to nuclear power, aroused by transports for the closed fuel cycle. The first MOX fabrication facility had been invited by the Lander government, but by the time the second facility neared completion, the new local government opposed its operation. In the interim, the 1986 Chernobyl nuclear accident in nearby Ukraine had traumatized Germany, intensifying public opposition to nuclear fuel-cycle facilities that entailed processing of toxic and highly radioactive plutonium.

Summary of Findings

From the beginning of its nuclear program, West Germany's government was interested in both the military and energy applications of nuclear technology. Public concern about the military option led to intense debate over the closed fuel cycle.[72] The government's main rhetorical argument for MOX and the closed cycle was that it would allow Germany to become energy independent. When it became clear that commercial fast breeder reactors would not materialize soon, Germany stuck with reprocessing but switched to recycling MOX in thermal reactors, believing it was the most efficient way to use uranium resources perceived as scarce.

MOX fuel cost three to five times as much to produce in Germany as LEU fuel. Accordingly, utilities had to be pressured by German law into reprocessing spent fuel and recycling plutonium in MOX fuel. The closed fuel cycle led to routine international transports of SNF, MOX, and high-level waste, which provoked public protests on environmental and nonproliferation grounds.[73] Closing the fuel cycle thus became highly controversial in Germany and fostered popular opposition to nuclear power more generally, culminating in the 2002 decision to phase out nuclear energy.[74] In 2011, Japan's Fukushima nuclear accident ended reconsideration of that phase-out.

Conclusion

Ironically, the German government's insistence on closing the fuel cycle, a decision that was supposed to promote the growth of domestic nuclear energy, helped mobilize opposition that ended nuclear power in Germany. Based on the German experience with MOX, this study cannot recommend that other countries close the fuel cycle, for several reasons including that it is much more expensive than the once-through cycle without compensating benefits. These concerns and risks may apply not only to traditional reprocessing and MOX, but also to alternative technologies that have been proposed to close the nuclear fuel cycle, such as pyroprocessing and the use of plutonium in metallic fuel for fast reactors.

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7

MOX in Switzerland: Explaining an Uneconomic Fuel Choice

Mu Kwan (Harry) Kim
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This chapter assesses Switzerland's use of mixed-oxide (MOX) fuel in light-water nuclear reactors (LWRs). Interviews were conducted in Switzerland, France, and Germany, in 2018, with parliamentary officials, regulators, nuclear power-plant operators, and experts at non-governmental organizations and think-tanks. The chapter explores multiple aspects of MOX use in Switzerland, including its motivations, economics, operational performance, safety, security, public acceptance, and waste management. The research finds that Switzerland's use of MOX fuel arose from the absence of a national nuclear waste-management policy, concern about global uranium supplies, and the desire to preserve a nuclear-weapons option. Performance of MOX fuel in Switzerland was acceptable but not without controversy. MOX fuel rods suffered cladding failures and leakage in the core, in 1990 and 1997, raising safety concerns and public unease about nuclear energy. The cost of fresh MOX fuel to Swiss utilities was several times that of traditional low-enriched uranium (LEU) fuel. Spent MOX fuel will require more casks and volume in Switzerland's eventual geological repository than an equivalent amount of spent LEU. The Swiss experience demonstrates that the closed fuel cycle is more expensive than the once-through fuel cycle even if a country does not construct and operate plants for reprocessing spent fuel or fabricating MOX fuel. It also underscores that closing the fuel cycle does not necessarily simplify a country's nuclear waste disposal challenge.

Switzerland has rarely been a major focus for the study of nuclear energy use in Europe. In contrast to countries such as France, Germany, and the United Kingdom, Switzerland has neither a large number of nuclear power plants (NPPs) nor fuel-cycle facilities for reprocessing spent nuclear fuel (SNF) and fabricating MOX fuel. However, Switzerland's use of MOX fuel merits attention for three main reasons. First, despite the absence of domestic fuel-cycle facilities, Swiss utilities were among the earliest to recycle their spent fuel, relying on reprocessing and MOX fabrication plants elsewhere in Europe. Second, Switzerland has 40 years of experience using MOX fuel in light-water reactors (LWRs). Finally, Swiss utilities no longer use or plan to use MOX fuel. Switzerland, therefore, is an interesting case where researchers can evaluate the start to finish of the experience of using MOX fuel without domestic fuel-cycle facilities. This chapter aims to inform ongoing decision-making in other countries, for example in East Asia, about whether to recycle SNF to use plutonium for energy.

The next section of this chapter summarizes the history of Switzerland's nuclear industry, including its NPPs, reprocessing of SNF in foreign countries, MOX fuel use, and relevant laws and regulatory bodies. Then the chapter elaborates its research methods. The following section explains Switzerland's decision to use MOX and the resulting outcome, in terms of economics, operational performance, safety, security, waste management, and public opinion. The study concludes with policy recommendations.

This chapter finds that the major downside of MOX fuel in Switzerland was economics. MOX fuel proved to be much more expensive than LEU fuel due in part to depressed uranium prices, which resulted from lower than expected global demand and higher than expected global supply. MOX fuel rods suffered in-core cladding failures and leakages in 1990 and 1997 at the Beznau power plant. Otherwise, MOX fuel performed similarly to traditional low-enriched uranium (LEU) fuel, although with some safety and security complications. Though MOX fuel itself was never a major political issue in Switzerland, opposition to nuclear energy and the closed fuel cycle mounted in the late 1990s, leading to a 2003 referendum that imposed a moratorium on reprocessing and MOX use.

Swiss Nuclear Power

Nuclear energy started in Switzerland due to economic and environmental concerns. Previously, the country had relied mainly on hydropower,[1] but by the 1960s it became evident that energy demand would exceed hydropower capacity.[2] Swiss utilities proposed coal- and oil-fueled power plants as a solution, but that provoked strong opposition from domestic environmental groups concerned that fossil fuels would violate the country's commitment to clean power generation. In addition, fossil fuels were not domestically available, which raised concerns about energy security.

An alternative solution was nuclear power. In 1946, the Swiss Parliament approved the Federal Council's resolution concerning the promotion of nuclear energy, and the private sector pursued that option.[3] To ensure safety and promote commercial use, Swiss voters in 1957 approved a referendum that became the Atomic Energy Act of 1959.[4] To facilitate international nuclear commerce, in 1965, the Swiss government signed a revised nuclear cooperation agreement with the United States.[5]

Table 1
Swiss Nuclear Power Plants

Reactor	**Operator**	**First Power**	**MWe (Net)**	**Type**
Beznau-1	Axpo Power AG	1969	380	Pressurized
Beznau-2	Axpo Power AG	1971	380	Pressurized
Mühleberg	BKW Energie AG	1972	390	Boiling
Gösgen	Kernkraftwerk Gösgen-Däniken AG	1979	985	Pressurized
Leibstadt	Kernkraftwerk Leibstadt AG	1984	1275	Boiling

Source: World Nuclear Association.

Four Swiss utilities then purchased four nuclear power reactors from the United States and one from Germany (Table 1, Figure 1), which began operation in the following order:

- Nordostschweizerische Kraftwerke AG (NOK) opened two Westinghouse pressurized water reactors (PWRs): Beznau-1 in 1969, and Beznau-2 in 1971.
- Bernische Kraftwerke AG (BKW) opened a General Electric boiling water reactor (BWR), known as Mühleberg, in 1972.
- Kernkraftwerk Gösgen (KKG) opened a Siemens PWR in 1979.
- Kernkraftwerk Leibstadt (KKL) opened a General Electric BWR in 1984.

Figure 1
Map of Switzerland's Five Nuclear Power Reactors

Source: Wikimedia Commons.

However, Swiss public opinion started to shift against nuclear power after the Soviet Union's Chernobyl nuclear accident in 1986. In 1990, Swiss voters supported a 10-year moratorium on new plant construction, signaling a growing disenchantment with nuclear energy.[6] Safety concerns were also raised in 1990, and again in 1997, by the discovery that several MOX fuel rods had suffered cladding failures and leakage of irradiated fuel into the water moderator at the Beznau power plant. In 2003, voters approved a moratorium on exports of SNF for reprocessing, codified in the Nuclear Energy Act of 2005.[7]

Despite such opposition to recycling plutonium for energy, three new NPPs were planned in 2007 – in Niederamt, Beznau, and Mühleberg. However, Japan's 2011 Fukushima accident undermined remaining Swiss public support for nuclear energy,[8] compelling the Federal Council to suspend review of the three pending applications.[9] In May 2011, the Federal Council and Parliament laid the foundations for a new policy, Energy Strategy 2050, which included a phase-out of nuclear power by around mid-century.[10] In May 2017, the strategy was approved by voters in a national referendum.

Reprocessing and MOX Fuel

When Swiss nuclear power generation began in the 1970s, there was no national policy on the back-end of the fuel cycle. Utilities were free to choose between reprocessing or direct disposal of the SNF,[11] but for economic and political reasons all four nuclear utilities initially opted for reprocessing. Only the three PWRs ended up using MOX fuel, while the two BWRs did not – due to economic, political, and safety considerations (Table 2). Plutonium separated from the BWRs' spent fuel was instead recycled in MOX for the PWRs, under contractual arrangements.

Table 2
Historical Reprocessing and MOX Use for Swiss Power Plants

Reactor	SNF Reprocessed?	MOX Licensed?	MOX Used?	Type
Beznau-1	✓	✓	✓	Pressurized
Beznau-2	✓	✓	✓	Pressurized
Mühleberg	✓			Boiling
Gösgen	✓	✓	✓	Pressurized
Leibstadt	✓	✓		Boiling

Prior to the 10-year moratorium on the export of spent fuel for reprocessing, which became effective in July 2006, Swiss utilities exported about 1,139 tonnes of SNF – to Cogema in France, and British Nuclear Fuel Ltd (BNFL) in the UK.[12] The resulting separated plutonium was fabricated into MOX fuel by companies in Belgium, France, Germany, the United Kingdom, and the United States. All of that exported Swiss SNF already has been reprocessed, and the radioactive waste (high- and intermediate-level) arising from the reprocessing and subsequent MOX fabrication has been returned to Switzerland.[13]

Nuclear Regulation

When Switzerland bought its first research reactor, the 10-MWt SAPHIR, and started its operation in 1957, there was no national regulatory authority, so the local canton was responsible for reactor safety. The Atomic Energy Act of 1959 established the country's first nuclear safety regulator, the Swiss Federal Nuclear Safety Commission (NSC), which started operation in 1960.[14] The NSC has functioned as an advisor on the safety of nuclear facilities to multiple agencies: the Federal Council; the Federal Department of the Environment, Transport, Energy, and Communication (DETEC); and nuclear regulatory bodies.[15]

In 1964, the Federal Council created a nuclear regulatory authority known as the Department for the Safety of Nuclear Facilities, which in 1982 transformed into the Principal Nuclear Safety Division (HSK) within the Swiss Federal Office for Energy (SFOE).[16] HSK was responsible for nuclear safety and security at all nuclear facilities. However, the fact that HSK reported directly to the SFOE appeared to compromise its independence, as required by both the 2005 Nuclear Energy Act and the International Atomic Energy Agency (IAEA) Convention on Nuclear Safety, which Switzerland ratified in 1996.[17] To rectify this, the Swiss Parliament in 2007 approved a law that in 2009 established the Swiss Federal Nuclear Safety Inspectorate (ENSI), independent of the SFOE and supervised by a board appointed by the Federal Council.[18] ENSI is responsible for the following:[19]

- Safety and security of all nuclear facilities throughout their lifetimes;
- Safety and security of nuclear facilities' staff and the nearby public from radiation, sabotage, and terrorism;
- Transportation of radioactive materials to and from nuclear facilities; and
- Geoscientific investigations to identify a suitable location for a permanent repository for radioactive waste.

Currently, the Federal Council grants general licenses for nuclear facilities, while DETEC grants construction and operating licenses, and ENSI supervises nuclear safety and security.

Methods

Field research for this chapter was conducted in January 2018 in France, Germany, and Switzerland, and included the following interviewees: Felix Altorfer and Ralph Schulz of the Swiss Federal Nuclear Safety Inspectorate; Stefan Muller-Attermatt of the Swiss Parliament; Fabian Jatuff of the Gösgen Nuclear Power Plant Fuel Division; Christopher Pistner of the Oeko-Institut; Jürg Joss of Fokus Anti-Atom; Mycle Schneider of World Nuclear Industry Status Report; and Stefan Füglister of Campaign Forum GmbH. Primary source material was also obtained from the Swiss government, international organizations, the nuclear industry, non-governmental organizations (NGOs), and think-tanks.

Findings

In the 1970s, Swiss utilities decided to reprocess their spent fuel and to recycle the separated plutonium in MOX fuel for several reasons. A major factor was the perceived absence of an alternative, direct disposal pathway for spent fuel. Switzerland lacked a national policy concerning SNF until the late 1970s, so NPP operators were ostensibly free to choose between direct disposal and reprocessing. However, in the absence of a national plan for domestic storage of waste, the nuclear utilities viewed exporting their SNF as the only feasible option because it effectively postponed having to deal with nuclear waste domestically. It also avoided the political controversy and potential expense of a domestic reprocessing plant, which could have inhibited nuclear power. As a result, according to a NOK official, all four Swiss nuclear utilities became "locked into long-term reprocessing contracts, which were at the time, in the mid-70's, the only viable fuel-cycle option for the back end."[20]

By contrast, the publicly stated Swiss rationale for reprocessing and MOX use was the ostensibly limited global stock of uranium. That perceived shortage, it was argued, would jeopardize the stable supply – and increase the price – of LEU fuel to a growing number of nuclear power plants around the world.[21] MOX fuel was said to diversify the fuel supply and lay the groundwork for fast breeder reactors.[22]

A less overt national motivation for reprocessing and MOX use was to facilitate a potential Swiss nuclear-weapons program. Starting in 1945, and continuing during much of the Cold War, the Swiss government seriously considered pursuing such weapons to deter perceived threats, especially after the Soviet Union invaded Hungary in 1956.[23] In a referendum in the 1960s, Swiss voters chose not to prohibit nuclear weapons but to leave that decision in government hands. Although the government's preferred potential pathway to nuclear weapons relied on highly enriched uranium, military officials considered poaching specialists from Switzerland's civil nuclear power program and exploiting their reprocessing contracts to potentially acquire separated plutonium.[24] In 1977, Switzerland ratified the Nuclear Non-Proliferation Treaty (NPT), but the government continued to contemplate the nuclear-weapons option until 1988. As one former official explained, "some people thought that the NPT would not work."[25]

Switzerland eventually adopted a nuclear waste policy in 1978, under which operating licenses for new NPPs would require a guarantee of permanent and safe storage of the resulting radioactive waste.[26] This led to the "Project Gewahr [Guarantee] of 1985," a promise by the NPP operators to commission temporary and permanent nuclear waste disposal. Central interim storage was implemented by the utility-owned company Zwilag. A deep-geological repository is being sited by the National Cooperative for Disposal of Radioactive Waste (NAGRA).[27]

Recycling Plutonium in MOX Fuel

Starting in the 1970s, the utility NOK exported the spent fuel from its two Beznau reactors for reprocessing abroad at Cogema in France, and BNFL in the UK. The plutonium separated from this SNF, and from the Leibstadt reactor's SNF, was fabricated into MOX abroad and imported for use in the two Beznau NPPs.[28] To enable a steadier supply of MOX fuel and to ensure the irradiation of all separated plutonium, two mechanisms were employed to borrow and lend plutonium temporarily with other domestic and foreign utilities. Cogema's policy was to supply MOX fuel based on the amount of SNF that a customer had shipped to France for reprocessing, regardless of whether that specific SNF had yet been reprocessed,[29] so the company effectively loaned and borrowed plutonium between its customers. The Swiss utilities also sought additional loans of plutonium for several reasons: to enable an earlier start of MOX use, to compensate for interruptions in MOX fuel production, and to avoid leftover plutonium when their reactors shut down. As NOK officials explained, "An early decision was taken to operate a smoothed program of MOX recycle, borrowing plutonium from other holders of material for return in later years."[30]

To demonstrate the feasibility of this new fuel, in 1978, NOK inserted into Beznau-1 its first four MOX assemblies. These consisted of borrowed plutonium fabricated into pellets and rods in the United States – prior to the 1977 U.S. policy decision against plutonium fuel – and manufactured into assemblies by FBFC in Belgium.[31] Once NOK started commercial utilization of MOX in 1984, in Beznau-2, it imported such fuel from multiple suppliers in Germany, Belgium, France, and the UK. Initial supply contracts were with the Alkem plant (later Siemens) in Hanau, Germany (1984 to 1995), the COMMOX consortium of Belgonucleaire and Cogema (1988 to 1992), BNFL's MDF and SMP in the UK (1994 to 2005), and then COMMOX again (1999 to 2005).[32] A total of 232 MOX fuel assemblies were irradiated in Beznau-1 and -2, and the last assemblies were unloaded from the reactors in 2013 and 2012, respectively.[33]

The utility conducted a safety evaluation with HSK, obtaining a license for a maximum of 40-percent MOX in the core

(48 of 121 assemblies) of each Beznau reactor.[34] However, the highest percentage of MOX actually loaded in the core of either reactor was 34 percent (41 assemblies) in Beznau-1, in 1992.[35] The percentage of MOX in each core fluctuated substantially over time due to the availability of plutonium and MOX fabrication services (see Appendix 1).[36]

Table 3
MOX Use in Swiss Power Plants

	Beznau-1 and -2	**Gösgen**
Assemblies (LEU & MOX) per core	121	177
Year of 1st MOX insertion	1978 (-1), 1984 (-2)	1997
Total MOX assemblies irradiated	232	148
Max % of MOX licensed in core	40	36
Max % of MOX inserted in core	34	36.2
Average % Pu-fissile per MOX assembly	3.5 – 4.1	4.8
Max % Pu-fissile in MOX rod	4.7	5.5

Source: Swiss Federal Nuclear Safety Inspectorate (HSK).

The Gösgen NPP's first eight MOX fuel assemblies, fabricated by Belgonucleaire, were inserted in 1997. Eventually, Gösgen received 136 MOX assemblies from Belgonucleaire and BNFL, incorporating the amount of plutonium separated from about 1,000 spent LEU assemblies that Gösgen exported for reprocessing to Cogema and BNFL.[37] In addition, Gösgen received 12 MOX assemblies fabricated with the amount of plutonium that had been separated from the Mühleberg reactor's SNF by Cogema.[38] All 148 MOX fuel assemblies were irradiated, and the last was unloaded in 2012.[39] The Gösgen NPP operator, in consultation with HSK, obtained a license for a maximum of 36-percent MOX (64 assemblies) in the core.[40] Contrary to the Beznau reactors, the Gösgen NPP did achieve its licensed maximum, in 2000 and 2001.[41]

Economics

Citing contractual privacy, Swiss utilities declined to reveal the exact cost of foreign reprocessing and MOX fuel fabrication.

However, available information suggests that MOX fuel was several times more expensive than LEU fuel for the Swiss utilities. Belgonucleaire stated in 1996 that the estimated manufacturing cost of MOX fuel for PWRs was $1,300 per kilogram of heavy metal (uranium and plutonium),[42] which is about $2,100 in 2018 dollars. The actual price to foreign customers was presumably higher than this cost, to enable some profit. By contrast, NOK, the operator of the Beznau NPPs, is reported to acquire LEU fuel at $370 per kilogram of uranium.[43] Thus, the historical price of MOX fuel to Swiss utilities (adjusted for inflation) may have been around six times the recent price of LEU fuel.

The high cost of MOX fabrication directly affected the Swiss utilities' choices about fuel design. Plutonium in MOX fuel can be mixed with depleted uranium, natural uranium, or reprocessed LEU that is still slightly enriched. The lower the U-235 percentage of the uranium, the more fissile plutonium is required, all else being equal. Thus, a given amount of plutonium can entail a larger or smaller amount of MOX to be fabricated, depending on the type of uranium used. In light of the high price of MOX fabrication, Swiss utilities intentionally chose the option that minimized the amount of such fuel that they would need to purchase. As NOK officials explained in 1998, "Economics require that the plutonium content of the MOX fuel assemblies be as high as possible. For this reason depleted or tails uranium is normally used as the fuel matrix."[44]

Operational Performance

According to ENSI and the utilities, the operating experience with MOX fuel generally was satisfactory.[45] No significant differences between the performance of LEU and MOX fuel were observed.[46] The average assembly burnup limits for MOX fuel were identical to those for LEU fuel.[47] At Gösgen, no MOX fuel failures were observed.[48]

At the Beznau NPPs, however, four leaking MOX fuel assemblies, including a total of five defective fuel rods, were identified. The first two breaks in the cladding in 1990 were determined to be caused by debris fretting, resulting from wearing and corrosion by foreign matter. This caused a leakage of radioactive irradiated fuel into the core's surrounding water, which serves as its coolant and moderator. The primary cause of the three remaining cladding defects, in 1997, could not be determined from visual inspections.[49]

Such problems are not unique to MOX fuel and have occurred also with LEU fuel in Switzerland, including in the 1990 incident.[50] However, given that the Beznau reactors used many times more LEU than MOX assemblies, the latter appear to have had a higher failure rate.

Security

In accordance with the Swiss Nuclear Energy Act, operators of nuclear facilities are responsible for their secure operation.[51] For the design, construction, and operation of NPPs, operators are required to implement security measures that comply with international standards. Such measures aim to prevent the theft of nuclear materials, the intentional dispersal of radioactive materials into the environment, and the compromise of nuclear safety through unauthorized actions.

The Swiss government does not release information about additional security measures required or taken for MOX fuel. However, interviews with NPP operators and NGO experts suggest that at the nuclear reactors, physical security measures – such as the number of security guards, and the height of perimeter fences – were not increased when MOX fuel was introduced. However, the transport of MOX fuel from foreign suppliers over a route of 1,000 to 2,000 km (600 to 1250 miles) – involving ground, sea, and air modes – did entail more security than for LEU fuel. For example, trucks of fresh MOX fuel were escorted by four to five federal police vehicles upon entering Switzerland, and delivery schedules were varied.[52] Air transport was sometimes used for MOX assemblies, which lowered the security risk – by reducing transport time, border crossings, and accessibility – but increased the environmental risk of an accident and fire releasing aerosolized plutonium.[53]

At reactors, fresh MOX fuel was stored in the same dry storage channels as fresh LEU fuel. However, the IAEA imposed more stringent safeguards on the fresh MOX, including locking the cover plates and applying IAEA seals. For fresh MOX, the IAEA also applied constant camera surveillance and conducted inspections monthly, in contrast to every three months for spent LEU fuel, and an IAEA inspector was present when the fresh MOX was removed from the channel and loaded in the reactor.[54] In addition, delivery of fresh MOX typically was timed so that the fuel could be loaded almost immediately, unlike LEU fuel that sometimes was kept in reserve.[55]

Safety

Under Swiss law, the NPP operator must renew its operating license or permit – entailing public intervention – if a significant change in the core physics is expected.[56] However, when the operators proposed partial MOX cores, HSK deemed this an insignificant change, thereby not requiring a new license but only regulatory approval.[57] For safety analysis, HSK established "reference cores" of 36-percent and 40-percent MOX for the Gösgen and Beznau NPPs, respectively.[58] Loading beyond those limits would have required additional safety analysis. HSK summarized the differences between MOX fuel and LEU fuel in a safety evaluation matrix (Table 4).

Table 4
Safety Evaluation Matrix for MOX Fuel

Evaluation Domain	**Issues of Special Concern**
Fuel Rod Design	Fission Gas Pressure Corrosion Properties
Nuclear Reactor Design	Power Peaking Boron Worth Control Rod Worth
Transient Analysis	Boron Worth Control Rod Worth
Accident Analysis	Control Rod Ejection Accident (REA) Loss of Coolant Accident (LOCA)
Storage	Subcriticality Decay Heat
Radiological Analysis	Activity Inventory and Release Rates

Source: HSK, "Licensing of MOX Fuel in Switzerland."

HSK and the operators took steps to address several issues caused by the introduction of MOX fuel. The first challenge was the reduction in control rod "worth" due to the large thermal-neutron capture cross-section of plutonium isotopes. The solutions were to limit the percentage of MOX in the core and to adjust the core design so that MOX assemblies were in only 16 of 48 control rod positions, and mainly those at the periphery.[59] This apparently obviated the need for additional control rods, as a NOK official reported that no "equipment modifications" were needed.[60]

A second issue was the need to substantially increase boron concentrations in the water of both the emergency core cooling system and the chemical and volume control system. The required increase, however, exceeded the solubility of boron in water at normal temperatures. Accordingly, NOK opted for enriched boron (increasing the isotope B-10 to 28 percent, above its natural concentration of 20 percent), which meant that the total boron concentration in the water only had to be increased slightly.[61]

A third concern was power peaking between adjacent MOX and LEU fuel assemblies. The solution was to reduce the plutonium content in MOX fuel rods adjacent to LEU assemblies. In addition, in each MOX fuel assembly, the center fuel rod was replaced with a rod of moderator, to increase the moderator-to-fuel ratio.[62] Interestingly, the computer codes used at the time proved far less accurate for MOX fuel than for LEU fuel, so that the actual and predicted MOX performances were quite different, but this does not appear to have caused safety problems.[63]

Fresh MOX fuel increased potential worker hazards due its higher radioactivity than LEU. According to a 1995 study co-authored by a NOK official, "Operator proximity to the assemblies and handling times are adjusted accordingly."[64] If the plutonium in the MOX had been separated from spent fuel many years prior, and thus had higher radioactivity from buildup of americium-241, water canisters were placed on top of the fresh fuel storage channels at the reactor to serve as shielding.[65] The utilities also monitored the age of plutonium in their fresh MOX, and the resulting americium accumulation, to properly define the fuel's reactivity when loaded into the reactor.[66]

Waste Management

Under the 1985 Gewahr project, NPP operators constructed and are operating the Zwilag central interim storage site.[67] They also commissioned NAGRA in 1985 to construct a deep geological repository for various types of radioactive wastes arising from the country's nuclear operations. NAGRA hopes to submit the required general license for a high-level waste site by 2022, and to begin operating the repository by 2060.[68] NAGRA estimates that by the end of the Swiss NPPs' operations, they will have discharged around 12,000 spent fuel assemblies, only 380 of which will be MOX.[69]

Table 5
Estimated Lifetime Fuel Assemblies to be Discharged

Reactor	**Type**	**LEU**	**MOX**
Beznau-1 & -2	Pressurized	>1,500	~230
Gösgen	Pressurized	>1,500	~150
Leibstadt	Boiling	>7,000	0
Mühleberg	Boiling	>1,000	0
Totals		**>3,000 PWR LEU** **>8,000 BWR LEU**	**~380 PWR MOX**

Note: BWR assemblies typically are considerably less massive than PWR assemblies.
Source: Stefano Caruso and Manuel Pantelias Garces, "Spent Nuclear Fuel Management in Switzerland: Perspective for Final Disposal," 2015.

A major impact of spent MOX on waste management is that its additional long-run decay heat reduces the capacity of SNF casks for geological disposal. For PWR SNF, NAGRA is planning to insert four LEU assemblies per cask.[70] However, when a MOX assembly is included, less than three other LEU assemblies can be inserted, to avoid exceeding the heat limit of 1.5 kw/cask.[71]

Politics and Public Opinion

MOX fuel was not a particularly contentious topic in Switzerland. The public knew little about MOX fuel and rarely was consulted in the utilities' decision-making about it. However, the closed fuel cycle clearly was less popular than nuclear power, *per se*. Swiss voters repeatedly rejected proposals to shut down nuclear power quickly, as recently as 2016.[72] By contrast, in a 2003 referendum, they voted to impose a moratorium within three years on SNF reprocessing and MOX recycle – while at the same time authorizing potential new power reactors.

This last episode traces back to 1999, when Switzerland's Green Party and the environmental Coalition Against Nuclear Energy (CAN) collected more than 100,000 signatures from voters within 18 months to launch a "popular initiative" – the procedure to request an amendment to the federal constitution.[73] The initiative comprised two sections: (1) permanent prohibition of the export of SNF for reprocessing, which would compel progress on a permanent repository; and (2) no additional NPPs.[74] The Swiss parliament struck down these proposals and instead offered a referendum that would impose a temporary moratorium on the reprocessing of SNF in exchange for the possibility of constructing new nuclear power plants. In 2003, voters approved the referendum, thereby imposing the 10-year moratorium on SNF exports that started in 2006.

In so doing, the Swiss electorate effectively ended the country's closed fuel cycle, as later codified in a 2017 referendum on Energy Strategy 2050 that permanently banned reprocessing of SNF. Because the moratorium started after the expiration of the original long-term, foreign fuel-cycle contracts, Switzerland's nuclear utilities did not have to break any agreements or pay any penalties. The last export of SNF appears to have occurred in 2004 to France.[75] The final MOX assemblies were imported from Cogema in 2006,[76] and from BNFL's Sellafield MOX Plant in 2007 (see chapter 4).

Summary of Findings

In the 1970s, Switzerland opted to pursue reprocessing of SNF and recycling of plutonium in MOX fuel for a variety of reasons: economics, energy security, convenience, and a secret nuclear-weapons option. In the absence of a national nuclear waste management policy, exporting SNF for reprocessing was a way to postpone hard decisions. Operators of NPPs also sought to diversify a supply of fuel perceived as limited. In addition, Switzerland's government and military during the Cold War supported the closed fuel cycle as a way to facilitate a potential nuclear-weapons capability.

Overall, Switzerland's experience with MOX fuel was mixed. The major downside was economics, as Swiss utilities appear to have paid many times more for MOX fuel than LEU fuel. Ironically, Swiss utilities originally had opted for MOX partly to guard against LEU price increases, but this backfired.

MOX fuel did not cause significant operational, safety, or security problems from the perspective of NPP operators or nuclear safety regulatory bodies. However, two incidents of MOX fuel rods leaking, in 1990 and 1997, may have contributed to anti-nuclear sentiment. For permanent disposal in a geological repository, spent MOX will require more casks than an equal amount of spent LEU, due to its higher heat output.

In Switzerland, the public, NGOs, and political parties played little to no role in the decision to initiate MOX. However, the Chernobyl accident ignited public fear and skepticism about nuclear energy, and the two failures of MOX fuel exacerbated such public concern. Switzerland's Green Party and anti-nuclear NGOs capitalized on this shifting public sentiment to spur a referendum that ended both reprocessing of SNF and use of MOX fuel by 2007, although nuclear power continued.

Conclusion

Based on Switzerland's experience with MOX fuel, other countries contemplating the processing of SNF to recycle plutonium for fresh fuel should take away at least two lessons:

The closed fuel cycle is more expensive than the once-through fuel cycle even if a country does not build and operate domestic reprocessing and plutonium fuel fabrication facilities.

Swiss utilities never operated domestic reprocessing or MOX fuel fabrication facilities. Instead, they made contracts with foreign companies to close their fuel cycle. The result was that MOX fuel cost several times more than LEU fuel, even excluding the additional costs to address domestic safety and security issues associated with plutonium in fresh fuel.

The closed fuel cycle does not significantly reduce the nuclear-waste challenge and may even complicate it.

Advocates of the closed fuel cycle claim that it reduces the nuclear-waste problem. Swiss utilities opted in the 1970s to export SNF for reprocessing in part to postpone implementing a sustainable waste management solution. Despite this, they soon had to contract for central interim storage and a geological repository, including to store spent MOX fuel and the radioactive wastes arising from foreign reprocessing of spent LEU fuel and fabrication of MOX fuel. The repatriated high- and intermediate-level waste might require marginally less volume in a repository than the exported spent LEU fuel, but the spent MOX fuel will require greater volume than spent LEU fuel. In addition, due to its temporary decision to close the fuel cycle, Switzerland now must deal with multiple waste forms.

Switzerland's experience with MOX fuel failed to fulfill the original hopes of utilities. MOX fuel cost much more than LEU fuel, harmed the image of nuclear energy, and failed to provide a sustainable waste management solution. These negative outcomes contributed to the Swiss votes in two referenda: in 2003, to impose a 10-year moratorium on reprocessing and MOX recycling; and in 2017, to ban those activities permanently while gradually phasing out nuclear energy. Though every country is different, Switzerland illustrates that closing the nuclear fuel cycle may create more problems than it solves.

Appendix 1

MOX Loading History in Three Swiss Power Plants

Table 6
MOX Loading in Beznau-1 (core comprises 121 assemblies)

Fuel Cycle #	Year	MOX Assemblies in Core	MOX % in Core
9	1978	4	3.3
10	1979	4	3.3
11	1980	4	3.3
12-18	1981-87	0	0
19	1988	12	9.9
20	1989	24	19.8
21	1990	32	26.4
22	1991	36	29.8
23	1992	41	33.9
24	1993	40	33.1
25	1994	40	33.1
26	1995	37	30.6
27	1996	32	26.4
28	1997	8	6.6
29	1998	0	0
30	1999	16	13.2
31	2000	20	16.5
32	2001	29	24
33	2002	24	19.8
34	2003	32	26.4
35	2004	32	26.4
36	2005	28	23.1
37	2006	24	19.8
38	2007	24	19.8
39	2008	16	13.2
40	2009	16	13.2
41	2010	12	9.9
42	2011	8	6.6
43	2012	8	6.6
44	2013	0	0

Source: MOX Study by Coalition Anti Nucleaire (Courtesy Fokus Anti-Atom).

Table 7
MOX Loading in Beznau-2 (core comprises 121 assemblies)

Fuel Cycle #	Year	MOX Assemblies in Core	MOX % in Core
13	1984	4	3.3
14	1985	12	9.9
15	1986	16	13.2
16	1987	24	19.8
17	1988	28	23.1
18	1989	24	19.8
19	1990	36	29.8
20	1991	28	23.1
21	1992	20	16.5
22	1993	8	6.6
23	1994	8	6.6
24	1995	0	0
25	1996	0	0
26	1997	0	0
27	1998	4	3.3
28	1999	12	9.9
29	2000	16	13.2
30	2001	16	13.2
31	2002	32	26.4
32	2003	28	23.1
33	2004	20	16.5
34	2005	28	23.1
35	2006	36	29.8
36	2007	36	29.8
37	2008	24	19.8
38	2009	28	23.1
39	2010	32	26.4
40	2011	24	19.8
41	2012	0	0

Source: MOX Study by Coalition Anti Nucleaire (Courtesy Fokus Anti-Atom).

Table 8
MOX Loading in Gösgen (core comprises 177 assemblies)

Fuel Cycle #	Year	MOX Assemblies in Core	MOX % in Core
19	1997	8	4.5
20	1998	28	15.8
21	1999	48	27.1
22	2000	64	36.2
23	2001	64	36.2
24	2002	56	31.6
25	2003	64	36.2
26	2004	56	31.6
27	2005	36	20.3
28	2006	52	29.4
29	2007	36	20.3
30	2008	32	18.1
31	2009	48	27.1
32	2010	32	18.1
33	2011	16	9.0
34	2012	0	0

Source: Interview with Dr. Schulz Ralph.

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8

MOX in the Netherlands: Plutonium as a Liability

Alan J. Kuperman

This chapter assesses the Netherlands' belated introduction of plutonium for energy – initiating commercial use of thermal mixed-oxide (MOX) fuel in 2014 – when most other global users were phasing it out due to economic and other concerns. Interviews were conducted in the Netherlands in 2018 with officials from the regulatory agency, the utility, the waste facility operator, and non-governmental organizations. The chapter finds that for the first 45 years of Dutch nuclear energy, based on traditional low-enriched uranium (LEU), the spent fuel was exported for reprocessing but Dutch utilities then paid other countries to take the separated plutonium off their hands. In 2006, France changed its environmental law to require that reprocessing contracts specify in advance the disposition of the plutonium to be separated, but foreign utilities were no longer interested in being paid to take Dutch plutonium because they were phasing out MOX fuel or already had large surpluses of plutonium. The Dutch utility EPZ, operator of the country's sole remaining power reactor, considered halting the foreign reprocessing and instead directly disposing of its spent fuel as waste. Ultimately, however, it opted to continue the reprocessing and to begin recycling the separated plutonium in MOX fuel. Licensing documents claim that this decision was made on economic grounds, but the utility did not actually engage in price negotiations over the alternative of direct disposal of its spent fuel. By signing long-term contracts for foreign reprocessing and MOX fabrication, and for domestic disposal of the repatriated waste from those activities – all of which carry severe financial penalties for cancellation – the utility effectively discouraged the government from closing the reactor prior to its scheduled shutdown in 2033, despite the power plant being uneconomical. Contrary to the utility's hopes, MOX fuel has proved to be substantially more expensive than LEU fuel, especially as uranium prices have plummeted by 80 percent. The Netherlands was the first country in a quarter-century to decide to initiate commercial use of MOX fuel in thermal reactors, and it may well prove to be the last.

The belated introduction of mixed-oxide (MOX) fuel in the Netherlands is puzzling, because the country only started using such plutonium-based fuel in 2014, after several other countries already had abandoned it on multiple grounds including economics. Of the five countries that historically had used MOX fuel commercially in thermal reactors, three of them – Belgium, Germany, and Switzerland – already had chosen not to renew contracts for reprocessing their spent nuclear fuel (SNF) and so were implementing schedules to irradiate their final MOX fuel assemblies. In addition, the United Kingdom, which historically had fabricated MOX fuel in two commercial facilities for export, closed both of them and chose not to initiate domestic commercial use of MOX fuel. Despite this, the Dutch utility EPZ, operator of the Netherlands' sole active nuclear power plant, at Borssele, chose in 2012 to sign a contract with the French company Areva (now Orano) to reprocess its SNF and recycle the separated plutonium in MOX fuel until the reactor's scheduled shutdown in 2033.

The Netherlands' recent embrace of MOX fuel might appear to call into question the lessons from the other case studies in this book, which illustrate the costs and dangers of recycling plutonium for energy. In fact, however, the Dutch case underscores these lessons. EPZ had never seriously considered using MOX fuel until foreign utilities ceased being willing to be paid to take its plutonium because they were abandoning the use of MOX fuel. EPZ was left with two options if it wanted to continue operating the reactor: start using MOX fuel, or halt reprocessing and instead dispose of SNF directly as waste. The Dutch utility considered both options but for a variety of reasons chose the former. In retrospect, in light of the subsequent decline of uranium prices, and persistently high MOX fabrication costs, that choice appears to have been a bad bet, underscoring the economic downside of using plutonium for energy.

This chapter's next section explains its research methods. Following that comes a brief overview of the Netherlands' nuclear energy program. The chapter then details the Dutch decision to initiate MOX use. After that, it analyzes the relatively brief Dutch experience so far with MOX fuel – including economics, security, safety/environment, performance, and public opinion. The chapter concludes with lessons from the Dutch case for other countries considering processing SNF to recycle plutonium for energy.

Methods

Primary and secondary documentation was supplemented by field research in the Netherlands in March 2018. Interviewees included officials from the regulatory agency, the utility, the waste facility operator, and non-governmental organizations (NGOs). Several Dutch politicians declined to be interviewed for this study.

Small Nuclear Program

Although the Netherlands is home to a major nuclear research reactor at Petten that helps produce a significant share of the world's medical isotopes, its historical nuclear energy program has been relatively tiny, comprising just two small nuclear power reactors.[1] The first, in the center of the country, was the demonstration Dodewaard boiling water reactor (BWR), rated at only 55 MWe, which is about five percent of the output of modern nuclear plants. It produced power for three decades from 1968 to 1997,[2] when for economic reasons it closed seven years earlier than planned, leaving a lifetime total of only about 64 tonnes of SNF, an amount that modern reactors produce in less than three years. All of its SNF was exported for reprocessing, and the resulting high-level waste was returned to the Netherlands, but the separated plutonium was not.

A fraction of Dodewaard's SNF, about 8.5 tonnes, was reprocessed at the Eurochemic plant in Belgium between 1974 and 1981, and the resulting separated plutonium apparently was used to make MOX fuel for non-Dutch reactors. But the bulk of Dodewaard's SNF, about 55.5 tons, was reprocessed at BNFL's Sellafield facility in the United Kingdom.[3] In modern light-water reactors, the SNF contains about 0.9-percent plutonium, but the Dodewaard SNF had low burn-up resulting in only 0.7-percent, totaling 351 kg, of separated plutonium.[4] BNFL originally intended to fabricate this plutonium into MOX fuel for non-Dutch customers, but its Sellafield MOX Plant never functioned properly and then shut down prematurely in 2011 (see Chapter 4). As a result, in 2013, the UK government announced that under commercial arrangements it was "taking ownership of around 350 kg of material previously owned by Dutch utilities."[5]

The Netherlands' second nuclear power plant, at Borssele in the country's southwest, is a relatively small pressurized water reactor (PWR) rated at 485 MWe (net) – about half the output of modern PWRs. The Borssele reactor began operation in 1973, is now expected to continue until 2033, and currently produces three percent of the country's electricity.[6] The operator had no plan for the back-end of the fuel cycle when the reactor started, but in 1978 it signed a contract with France's Cogema (later Areva) to reprocess the reactor's first 30 years of spent fuel. This covered SNF exports to France through 2004, allowing two years for low-enriched uranium (LEU) SNF to cool in the reactor's pool. EPZ thus joined Cogema's founding foreign partners of the La Hague UP2 facility's oxide reprocessing capability, which started in 1976 (see Chapter 3).

Under French law, the plutonium and major radioactive waste separated from the SNF had to be removed from France.[7] In practice, the SNF from multiple customers was comingled at La Hague, so that each utility was assigned a *pro rata* share of the plutonium and waste. EPZ's contract specified that the disposition of its share of the plutonium would be determined in concert with the other foreign partners of the facility, meaning that EPZ could make financial arrangements for another country's utility to take the plutonium back in fresh fuel. From the reprocessing of Borssele's SNF arising until 1989, the separated plutonium was used to make fuel for demonstration fast reactors in France and Germany.[8]

For the plutonium separated from Borselle's next batch of SNF, the Dutch utility eventually paid Cogema to arrange for Swiss and German utilities to accept it in the form of fabricated thermal MOX fuel.[9] The price that EPZ paid was estimated by the leading Dutch nuclear institute, in 1997, to be about $15,000 per kg.[10] However, according to EPZ's chief financial officer, in a March 2018 interview, the price to get rid of plutonium is higher now than it used to be.[11]

In 2004, EPZ renewed with Areva for another 10 years, meaning the Dutch utility could continue to export SNF to France until about 2016 without specifying in advance the disposition of the plutonium to be separated by reprocessing. An EPZ spokesperson declared in 2004 that the separated plutonium would *not* be recycled as MOX in the Borssele reactor, "because our plant is too small."[12] Thus, the operators of both Dutch nuclear power plants chose for over 45 years to have their spent fuel reprocessed abroad, but they did not take back the three tons of separated plutonium as MOX fuel or otherwise, and they instead paid others to take it.[13]

The repatriated radioactive waste from foreign reprocessing is stored on an interim basis for up to 100 years at a facility in the southwest of the Netherlands adjacent to Borssele. The site is run by a state-owned company called the *Centrale Organisatie Voor Radioactief Afval* (COVRA), or the Central Organization For Radioactive Waste, which EPZ pays to take ownership of the waste. At COVRA, high-level waste is held in a building known as *Hoogradioactief Afval Behandelings- en OpslagGebouw* (HABOG) in vaults, which are a series of above-ground cavities that enable monitored and retrievable storage. The building is designed to provide safety and security from intentional or accidental disruption. HABOG also stores unreprocessed research-reactor SNF, which is much smaller physically than power reactor SNF and is under IAEA safeguards. In a neighboring building, the returned long-lasting intermediate level waste from reprocessing is stored in a less robust fashion.

Vault storage is also possible for power-reactor SNF, and Spain is reportedly constructing such a facility based on the COVRA design. HABOG required €125 million and four years to construct, took five years to license, opened in 2003, and accepted its first waste in 2004. The building is modular, and an extension (adding two vaults to the existing three) is projected to be completed in 2020.[14] In light of this long-term interim storage capacity, the Netherlands has deferred decisions about permanent geological disposal of nuclear waste.

Why Switch to MOX?

The Dutch utility's decision to change past practice in 2012, by signing a combined reprocessing and MOX fabrication contract with Areva to initiate use of plutonium for energy at Borssele, is especially puzzling because the contract required EPZ to pay for a large amount of MOX fuel fabrication, which is notoriously expensive. Borssele typically had produced around 10 tonnes of spent LEU fuel annually, containing about 93 kg of plutonium. The renewed Areva contract covers 20 years of fuel discharges from 2015 to 2034, which using LEU fuel would include about 1,860 kg of plutonium. Each MOX assembly for Borssele contains about 27.5 kg plutonium, so one might assume that EPZ was required to pay to fabricate 68 MOX fuel assemblies – i.e., 1,860 divided by 27.5.

However, that is not how the Areva contract works. When EPZ sends its plutonium-laden spent MOX back to France, the Dutch utility is required to take back an equivalent amount of plutonium in still more fresh MOX. Given that MOX SNF contains several times as much plutonium as LEU SNF, this provision more than doubles – to 144 assemblies – the amount of MOX that EPZ must pay to fabricate under the contract.[15] If EPZ had not initiated MOX but continued to have its LEU SNF reprocessed, it would have had to pay for disposition of only 1,860 kg of plutonium. By contrast, under the Areva contract, it must pay for disposition of 3,960 kg of plutonium, more than twice as much, by having it fabricated into about 50 tonnes of MOX fuel.

A number of competing explanations have been offered for EPZ's belated adoption of MOX fuel, but some are more credible than others. First, the utility itself, in licensing documents, claims the switch was motivated by a desire to diversify fuel sources to hedge against potential increases in the price of uranium. Second, government documents and a licensing official say the move was actually motivated by two different factors: a change in French law that required reprocessing contracts to include up-front arrangements for plutonium disposition, and the absence of any foreign utility willing to be paid to take Borssele's plutonium. Third, a non-governmental watchdog hypothesizes that EPZ may have signed the long-term MOX contract, which imposes stiff financial penalties for cancellation, to deter the Dutch government from potentially shutting the reactor prematurely.[16]

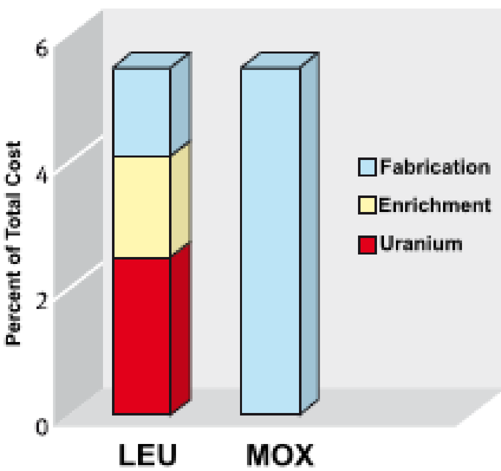
The Dutch utility's chief financial officer, Bram-Paul Jobse, offers a fourth, more nuanced explanation. He says the change in French policy, combined with the absence of foreign utilities willing to be paid to take separated plutonium, left EPZ with two choices if it wanted to continue operating the reactor. The Dutch utility either could initiate the use of MOX fuel in Borssele, or it could halt reprocessing and instead pay COVRA to store the SNF on an interim basis in preparation for its geological disposal as waste. In the 1990s, EPZ had rejected MOX recycle on economic grounds, in part due to uncertainty about whether the reactor's life would be extended, but in 2006 the government granted an extension until 2033. Jobse claims that EPZ then conducted a new study, which found that the expected price for each option – MOX recycle or interim storage of SNF – was approximately the same, but the Dutch utility chose the recycling option as less risky.[17] A fifth explanation, inferred from a government report, is that interim storage was not feasible because COVRA could not have constructed a new facility quickly enough. Each of these hypotheses is interrogated below.

Is MOX Cheaper?

Perhaps least persuasive is the explanation offered by EPZ in licensing documents, that the utility opted for MOX to diversify its fuel supply and reduce financial risk from potential uranium price increases. By all other accounts, this was not the original impetus. Although the utility may have viewed cost control as a potential benefit after other factors compelled it to explore MOX, in reality the recycling of plutonium significantly increased its fuel costs, especially after uranium prices plummeted, which was a foreseeable risk.

In its July 2010 environmental submission under the licensing process, the utility stated that, "EPZ sees a limited use of MOX elements as a cost control option."[18] The company conceded that fabrication costs were much higher for MOX than LEU. However, it argued that all the potential costs for MOX fuel were fixed – "free" plutonium, virtually free depleted uranium, and fabrication under long-term contracts – whereas the cost of LEU fuel was susceptible to the volatile price of uranium and the steadily rising price of enrichment.[19] Moreover, EPZ reportedly had a long-term contract for a modest amount of uranium at a low price, so that by initiating partial MOX use it could stretch out its existing uranium supply and thereby reduce its exposure to uranium price increases.[20] In a notional chart (see Figure 1), EPZ argued that the high price of uranium already had made the costs of LEU fuel and MOX fuel equivalent, so that if the price of uranium increased further, MOX fuel would actually be cheaper. According to the utility, this would compensate for the limited extra costs that MOX fuel would impose on its equipment for handling, measurement, and reactor control. The licensing submission concluded, "From the point of view of cost control, it is therefore attractive for EPZ to bet on MOX fuel."[21]

Figure 1
Cost Comparison in EPZ's 2010 Environmental Impact Assessment

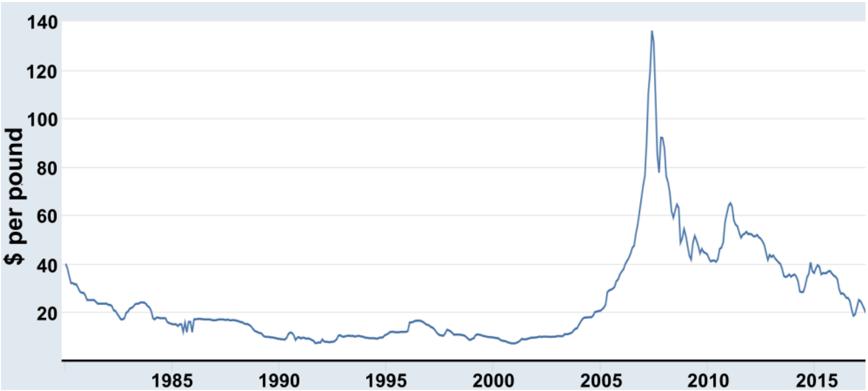


Source: Adapted from EPZ, "Milieueffectrapportage Brandstofdiversificatie," July 2010, Figure 2.9.1.
Note: "Total Cost" – to produce electricity – includes the amortization of reactor construction.

However, this argument is misleading in at least four respects. First, EPZ's chart suggests that in 2010, the price of MOX fuel was the same as LEU fuel, but that has never been true. Estimates from all five of the other countries that have used MOX commercially in thermal reactors indicate that MOX fuel has cost three to nine times as much as LEU fuel, and the highest estimates come from the countries that had to import MOX fuel, as EPZ proposed to do. Second, EPZ's submission suggests that the price risk of uranium was entirely on the up side. In reality, in 2010, the price of uranium was about four times its historical norm, but less than one-third of its recent high (Figure 2). Thus, there was risk of the price either increasing or decreasing, and history suggested that it was more likely to fall, as in fact soon did occur.

Third, EPZ claimed that MOX unlike LEU could avoid price risk, but this was misleading in two more ways. In reality, uranium can be purchased on the futures market, which also eliminates price risk. Moreover, it is irrational to eliminate price risk by overpaying for a substitute. For example, if the price of red apples fluctuates from $0.10 to $1 per pound, it would be irrational to eliminate such price risk by purchasing green apples for a fixed price of $2 per pound. But that is essentially what EPZ advocated in its submission, and what it has done in practice by purchasing MOX fuel to replace LEU fuel. Overall, the economic argument in EPZ's submission is contradicted by the facts and makes little economic sense, so it is unlikely the main reason that the utility opted for MOX fuel.

Figure 2
Historical Price of Uranium



Source: Federal Reserve Bank of St. Louis, based on International Monetary Fund, https://fred.stlouisfed.org/series/PURANUSDM.
Note: Price is in current dollars, not adjusted for inflation.

In a 2018 interview, the utility's CFO Jobse offered a slightly different economic argument. He conceded that MOX fuel was more expensive than LEU fuel, but claimed that the price difference was less than the amount that EPZ would have had to pay to get rid of its separated plutonium, especially because Areva was the only potential taker and thus could have dictated the price.[22] Moreover, Areva had an economic incentive to inflate its requested price for taking ownership of EPZ's plutonium, to persuade the utility instead to purchase MOX fabrication services.

If this is really why EPZ opted for MOX, it would indicate that the negative market value of plutonium must be substantially higher than the $15,000 per kilogram reported in the late-1990s. Assuming, conservatively, that MOX fuel costs $1,500 more per kilogram than LEU fuel (see Chapter 7), then EPZ's purchase of about 50 tonnes of MOX fuel incurred a price penalty of at least $75 million. If that was cheaper than the price that EPZ would have had to pay to get rid of 1,860 kg of plutonium, then the negative market price of plutonium must have been over $40,000 per kilogram. Such a high negative market price for energy-rich plutonium would reflect both the low worldwide demand for, and the high fabrication cost of, MOX fuel.

New French Law?

A major impetus for Dutch MOX was France's 2006 change in environmental law. Cogema had always required that when it reprocessed foreign SNF, the customer was responsible for the resulting plutonium and major radioactive waste, but the specifics did not need to be worked out in advance. However, according to a 2017 Dutch government report, "In July 2006, new French legislation entered into force, which prescribes that a return-scheme for the radioactive waste has to be formalized at the moment the spent fuel is sent to France."[23] This posed a problem for EPZ if it wanted to renew its reprocessing contract with Areva for SNF arising after 2016, since foreign utilities no longer were willing to take plutonium even for a price, because the few countries that previously had used MOX were now phasing it out or, in the cases of Japan and France, already had enormous plutonium surpluses.

According to CFO Jobse, EPZ in 2006 engaged in talks with colleagues in Germany, Switzerland, France, and the UK, [24] presumably about paying them to take plutonium in the future, but apparently without success. As EPZ explained in a July 2010 press release, by initiating MOX at Borssele, the utility avoided the challenge of trying to find a foreign MOX-licensed reactor whose operator was willing to be paid to take the plutonium.[25] A Dutch nuclear regulatory official, Gert Jan Auwerda, suggested in an interview that, "If France had not changed the law, EPZ would not have started using MOX."[26]

Jobse contends that even without the new French environmental law, EPZ would have conducted a cost assessment of the MOX option after the Borssele reactor received its life extension to 2033.[27] EPZ's fuel cycle manager, Jan Wieman, concurs that the extension was "a real game changer: it meant that EPZ could optimize its fuel strategy for Borssele's final 20 years of operation."[28] However, if not for the French legal change, Jobse concedes that considerations of risk minimization probably would have led EPZ to avoid the uncertain licensing of MOX fuel by continuing to pay Areva to arrange alternative end-users for the separated plutonium.[29]

Better than Direct Disposal?

The new French law and the lack of global demand for separated plutonium did not by themselves necessitate that EPZ initiate MOX use. The utility had the alternative of not renewing its reprocessing contracts and instead disposing of its SNF directly as waste. Three explanations have been offered as to why EPZ did not embrace this option – timing, economics, and risk – but none is fully supported by the facts.

In a 2011 report, the Dutch government claimed that constructing a building for interim storage of SNF would take too long, citing the history of the HABOG facility for high-level waste. In that earlier instance, according to the report, "a period of more than ten years prior to submitting the preliminary memorandum was required to find a suitable location. From that moment on, the total turnaround time to arrive at a definitive license was about seven years. The HABOG was then built and commissioned in five years." The report estimated that 10 years would be required to finish a new interim storage facility for SNF, given that the waste site already existed, but it characterized that as too long. Published in 2011, the report concluded that, "If a scenario is chosen for the direct storage of the fuel elements, a facility for this must be available by 2016 at the latest. This is not feasible, given the expected 10-year turnaround time for the realization of such a building."[30]

However, this asserted deadline of 2016 for an interim storage facility was artificial. If EPZ had opted not to renew its reprocessing contract, the temporary domestic buildup of SNF could have been accommodated by either increasing the capacity of the reactor's pool or resorting to dry-cask storage. Such steps might have required additional authorization but are commonplace around the world and would have provided additional time if necessary to complete an interim SNF storage facility. By ignoring these options, the Dutch government report appears intended to justify renewal of the reprocessing contract, rather than to assess rigorously the alternative of direct disposal.

Regarding the cost of interim storage of SNF, Jobse claims that the utility compared this to plutonium recycling in a 2006 study, including by discussing with COVRA the potential price of such a facility. Jobse and Wieman say the study found that the cost of interim storage was roughly the same as that for reprocessing plus MOX fabrication,[31] and Dutch regulator Auwerda confirms that EPZ conducted such a study.[32] Jobse also claims that "confidential" pricing information showed that the back-end was cheaper with reprocessing and MOX recycling, compared to direct disposal, thereby compensating for the extra cost of MOX fuel. Accordingly, he insists it is "incorrect to conclude that long term contracts for reprocessing and fabrication of MOX significantly increased the costs of EPZ."[33]

However, COVRA's Deputy Director, Ewoud Verhoef, says the waste company never conducted a detailed cost study for interim storage of SNF.[34] When Jobse was confronted with this fact, he replied that EPZ's assessment of direct disposal was conducted "using other European utilities (not COVRA) as a reference."[35] However, these foreign entities use entirely different waste storage concepts than COVRA. Evidently, EPZ concluded that direct disposal had the same cost as the MOX recycling option without ever negotiating the domestic price of direct disposal. This suggests that cost was not the determining factor in the utility's embrace of MOX over direct disposal.

Indeed, Jobse says that the decisive factor for EPZ was that MOX had less "risk," in that it required less change than the direct-disposal option. He acknowledges that introducing MOX fuel did entail some risk, mainly from licensing the new fuel and developing new casks for fresh and spent MOX. Yet other parts of the fuel cycle would be unaffected, including exporting spent fuel to France and receiving back radioactive waste in the same form already stored at HABOG, whose capacity could be expanded by two modules to accommodate the additional volume of waste arising from future reprocessing and MOX fabrication. By contrast, he says, direct disposal would have required new laws, new regulations, a newly designed vault facility for interim storage of SNF, and perhaps a new cask for dry storage while that facility was being constructed.[36] A 2012 EPZ presentation highlighted these concerns, claiming that "the development of an alternative back-end process could risk the continued plant operation of Borssele."[37]

Deterring Premature Closure?

It is unquestionable that by signing a long-term contract in 2012 with Areva for reprocessing of SNF and fabrication of MOX fuel, EPZ effectively inhibited the Dutch government from prematurely shutting down the Borssele reactor prior to the 2033 expiration of its safety report, given the financial penalties that would result. The only question is whether this was one of the motives, or even the primary motive, for EPZ opting for MOX.

A 2016 study commissioned by the government (the "Holtkamp report") says that EPZ estimated the costs of closing the reactor and terminating the Areva contract as up to "€1 to €1.3 billion."[38] Although some of this cost would stem from lost payments to the decommissioning fund, a significant portion would represent the consequences of canceling the Areva contract. As the report states, "The costs related to the buyout of contracts and the entering into new contracts for fuel supply and disposal are estimated to be high in this scenario, in the hundreds of millions [of Euros]." Such costs would include the following: disposing of plutonium already separated under the contract, either domestically as waste or more likely by paying someone else to take it; paying

COVRA for lost income and the unnecessary expansion of HABOG; and returning to France some MOX assemblies that were unirradiated yet slightly contaminated by having been stored in Borssele's spent fuel pool, potentially requiring the licensing of a new transport cask.[39]

According to Dutch regulator Auwerda, if a premature government shutdown of the reactor imposed such costs on EPZ, the utility could sue the government,[40] making it potentially liable for hundreds of millions of euros. Thus, EPZ's 2012 contract for reprocessing and MOX fabrication had the effect of strongly discouraging the Dutch government from contemplating the premature shutdown of the Borssele reactor, which otherwise might have been a serious prospect, given that the Green Party was in the governing coalition and that the reactor was cost inefficient (see below). It is possible that EPZ considered this as it weighed the two options of direct disposal versus MOX recycling, especially in light of the utility's strong emphasis on risk minimization. However, the company's CFO Jobse insists that, "The contractual penalties of all EPZ contracts are limited," and "EPZ formally denies that this was the strategy behind the choice for the continued closed fuel cycle."[41]

Implementing MOX

In 2008, EPZ applied for authorization to load up to a 40-percent core of MOX fuel in Borssele. Licensing of nuclear activities in the Netherlands has historically been divided between two ministries: economics and infrastructure. (The names of these ministries have changed over time.) When EPZ submitted its MOX application, overall responsibility fell to the Department of Nuclear Safety, Security, and Safeguards (KFD), within the Inspectorate of the Ministry of Housing, Spatial Planning, and the Environment (VROM Inspectorate). In 2015, the nuclear regulatory functions were separated from promotional activities and combined into a single institution, the Authority for Nuclear Safety and Radiation Protection (ANVS), which is responsible for assessing Borssele's nuclear safety and radiation protection. Due to the limited size of the Dutch regulatory apparatus, a German organization, *Gesellschaft fur Anlagen und Reacktorsicherheit* (GRS), has assisted both KFD and ANVS on safety assessments, including of potential

MOX fuel use at Borssele.[42]

Pre-Cycling

In light of the unusual circumstances of Borssele's proposed use of MOX fuel – EPZ having only a single reactor, not already having a surplus of separated plutonium, and being required to use a large amount of plutonium in MOX over a short time before the reactor's scheduled shutdown in 2033 – Areva devised a special arrangement called "pre-cycling." At the start, EPZ would borrow plutonium from Areva so that the French company could fabricate MOX fuel for Borssele, and then EPZ would pay back the plutonium in SNF. Ultimately EPZ would receive fresh MOX fuel containing the same amount of plutonium that EPZ would send to Areva in SNF (LEU and MOX) under the contract.

Considering that spent MOX requires two extra years of cooling before it can be removed from the reactor's spent fuel pool and exported for reprocessing, the last MOX fuel would be removed from the reactor's core two years prior to its shutdown, meaning it would be loaded six years prior to shutdown.[43] Under this arrangement, the reactor would "consume a sufficient quantity of plutonium early in its operational life to fully compensate for the plutonium arising later, including treatment of the final core."[44] According to EPZ, this led to "an ambitious scheme of MOX loading," comprising 144 MOX assemblies over 13 years from 2014 to 2026.[45] In most years, 12 MOX assemblies would be loaded, for a steady state loading of 48 MOX assemblies out of 121 total assemblies, or just under 40 percent, although the first loading in 2014 would be limited to eight MOX assemblies. On average, the MOX would contain about 7.8-percent plutonium,[46] including 5.41-percent fissile plutonium, providing equivalent burnup to the reactor's 4.4-percent enriched LEU fuel.[47] According to EPZ's Wieman in 2015, "This means that the reactor will have about 20 percent more plutonium in the core than any other commercial light water reactor," which may refer to the plutonium as a percentage of the core's heavy metal.[48]

Safety and Licensing

The introduction of MOX fuel raised several safety issues identified in EPZ's licensing submissions.[49] Perhaps most significant was that MOX fuel reduced the effectiveness of boron as a neutron poison in emergency cooling and control systems, due to the increased thermal-neutron capture cross-section of plutonium. Accordingly, EPZ switched from natural boron to enriched boron, raising the atomic percentage of Boron-10 from 20 to 32 percent, which required a license change.[50] MOX fuel also caused a harder neutron spectrum, which required a new safety analysis report on worst-case accident scenarios and embrittlement of the reactor pressure vessel. Using plutonium-based fuel also reduced the percentage of delayed neutrons, so EPZ needed to modify its reactor-control system.[51]

Due to the higher radioactivity of MOX than LEU in both fresh and spent fuel, EPZ also had to procure two new types of shipping casks for importing and exporting MOX fuel. According to EPZ's environmental submission, the more robust casks not only provided greater shielding from radiation but also extra protection against transportation accidents and security threats.[52] Nevertheless, the environmental report warned of an expected "higher [radiation] dose load for the EPZ employees who are deployed to receive the" MOX fuel.[53] The report also noted that MOX fuel rods could be more prone to radioactive release in an accident scenario, due to increased pressure from fission gases and decreased thermal conductivity of plutonium oxide particles.[54]

The regulatory process required both safety and environmental reviews.[55] KFD approved the safety review,[56] and the ministry for environment, after a public consultation on EPZ's submission, approved the environmental review. Based on both findings, on June 27, 2011, KFD granted "final" approval for EPZ to use MOX.[57] However, environmental groups then launched a two-year judicial challenge, which ultimately proved unsuccessful. In 2013, EPZ received "irrevocable" approval, and in 2014 the first MOX assemblies were loaded at Borssele.[58] The regulators required a gradual ramp-up of MOX fuel, which is why only eight assemblies initially were loaded. ANVS also required a post-hoc evaluation to assess if MOX fuel was behaving as predicted. That study, prepared by Arcadis and delivered in 2017, reported that MOX fuel was performing within safety margins and that the worker dose actually was reduced due to the new casks and procedures for handling MOX fuel.[59]

Economics

It is difficult to evaluate the precise economic impact of introducing MOX fuel at Borssele because the prices in contracts are withheld as proprietary. However, it is known that after 2008, the price of uranium dropped precipitously from $140 to $20 per pound (Figure 1), a reduction of about 85 percent. If EPZ's assumption in its environmental submission that MOX and LEU fuel had the same total cost (Figure 2) was based on uranium at $140 per pound, then today's uranium price would result in MOX fuel costing twice as much as LEU fuel. Accordingly, a 40-percent MOX core would increase total fuel costs by about 40 percent. However, the actual increase in fuel costs would depend on many factors, including EPZ's contracted prices for uranium, enrichment, and fabrication of LEU and MOX fuel. Moreover, most experts would dispute the assumption in EPZ's environmental submission that MOX fuel ever cost as little as LEU fuel. If that assumption was overoptimistic, then for EPZ today the price of MOX fuel could be several times that of LEU fuel, as has been the case for every other country that has commercially utilized thermal MOX fuel. If so, EPZ's initiation of MOX fuel has increased its overall fuel costs by much more than 40 percent.

The good news for EPZ is that, under a long-term contract, it is paid above market price for the electricity it produces. EPZ sells its electricity for a fixed price of €43 per MWh to PZEM, which is owned by local governments and resells to customers at the market price, which in 2016 was only €31.50 per MWh. As a result, the local governments lose money whenever the Borssele reactor delivers electricity.[60] Not surprisingly, this has raised public calls to shut the plant. One result was the Holtkamp report, which highlighted that shutting the reactor prematurely would incur financial penalties from terminating EPZ's contracts for reprocessing, MOX recycle, and disposal of resulting waste. Whether intentional or not, EPZ's long-term contracts for MOX now function as a poison pill, deterring premature shutdown of a reactor that is producing electricity uneconomically.

Security

Although the introduction of nuclear weapons-usable plutonium in unirradiated MOX fuel in the Netherlands created unprecedented security challenges, it is unclear how the government evaluated them. The safety assessment for MOX states merely that, "The KFD also assessed the changes in security and safeguards due to the transport and storage of fresh MOX fuel assemblies. No further announcements can be made about this."[61] Only after the MOX license was issued did the Dutch government assess and accept EPZ's security plan and grant a separate transport license for MOX fuel.[62] The government declines to discuss the details of any upgraded security measures for MOX, but a few steps have been reported. First, the schedule for delivery of fresh MOX is less predictable than when only LEU fuel was delivered.[63] Second, fresh MOX fuel is transported by a "security vehicle," utilizing an MX6-type cask that provides some physical protection.

Beyond that, however, Jobse says that EPZ protects fresh MOX as it does LEU SNF, which if true would be inadequate.[64] Although both fresh MOX and LEU SNF contain plutonium, spent LEU is highly radioactive and thus deemed "self-protecting" against terrorist theft and processing to separate plutonium for nuclear weapons. By contrast, fresh MOX lacks sufficiently high radiation to prevent terrorists from stealing it to obtain plutonium.

Each of Borssele's MOX assemblies contains 27.5 kg of plutonium, sufficient for multiple nuclear weapons. The ground route for fresh MOX fuel from France's MELOX fabrication facility to Borssele is over 1,000 km (620 miles). Greenpeace noted in a 2011 report that it had provided evidence to the French military that "plutonium and MOX fuel transports could be identified, tracked, and in one case blocked and seized by Greenpeace activists." Accordingly, the report concluded, "A decision by EPZ and the Dutch state to use fresh MOX fuel increases the targets for nuclear terrorism."[65]

Public Opinion

Dutch environmental organizations – including the Laka Foundation, Greenpeace-Netherlands, and the Zeeland Environmental Federation – have opposed both continued operation of the Borssele reactor and its introduction of MOX fuel. The reactor is relatively old, having operated for 45 years, and is located within 120 miles of the Dutch cities of Amsterdam, Utrecht, and Rotterdam, and even closer to the Belgian cities of Antwerp, Brussels, and Ghent.[66] Domestic environmental groups demand further research on the safety risks arising from MOX fuel in accident scenarios and the potential need to modify emergency plans and evacuation zones.[67] A few demonstrations were organized against shipments of SNF from Borssele to France, but they failed to arouse the intense opposition to nuclear recycling that had emerged in other countries such as Germany in the 1990s.

Dutch environmentalists offer several explanations for this lack of popular resistance to MOX fuel in the Netherlands.[68] The country now has only a single power reactor, so the number of shipments of SNF, MOX fuel, and high-level waste is relatively small. Moreover, Borssele and COVRA are adjacent to Belgium, which is the route to and from France, so that ground transport through the Netherlands is quite brief – only about 35 km (20 miles) – and in sparsely populated territory that circumbscribes the directly affected population. The domestic political process is also less participatory than that of countries such as Germany, which reduces the opportunity for grassroots engagement. Finally, EPZ 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. Possibly for these reasons, the introduction of MOX fuel in the Netherlands has failed to arouse substantial public opposition, parliamentary debate, or judicial intervention.

Summary of Findings

For 45 years, the operators of both of the Netherlands' nuclear power plants exported their spent LEU fuel for reprocessing, and while the radioactive waste was repatriated, the separated plutonium remained abroad. Dutch operators paid for other countries to take title to the plutonium, which was then kept in storage or used as fuel in fast or thermal reactors. In 2006, however, France changed its environmental law, requiring that reprocessing contracts specify in advance the disposition of the plutonium to be separated. Foreign utilities were no longer interested in being paid to take Dutch plutonium because they were phasing out MOX fuel or had large surpluses of plutonium. This left EPZ, operator of the sole remaining Dutch nuclear plant, with three choices: shut the reactor, stop reprocessing and instead dispose of SNF directly, or recycle future separated plutonium in MOX fuel.

In 2006, after the government agreed to extend the lifetime of the reactor by 20 years to 2033,[69] the Dutch utility EPZ conducted a comparative assessment of the latter two options, and chose to initiate use of MOX fuel. This decision does not appear to have been driven primarily by economics, because EPZ did not engage in negotiations over the price of interim storage of SNF with the Dutch government-owned company responsible for radioactive waste disposal. EPZ says its choice was driven mainly by the perception that MOX recycling was the less risky option, in that the only significant hurdle was obtaining a license to irradiate MOX, whereas direct disposal would have required several major changes on the back-end of the fuel cycle.

EPZ's licensing submission claims that the initiation of MOX fuel was driven by an economic desire to diversify fuel sources, but there is little evidence of that. MOX fuel was always likely to increase EPZ's fuel costs, especially given that the Areva contract required EPZ to pay for an unusually large amount of MOX fabrication, which even EPZ's submission acknowledges costs about five times as much as fabricating traditional LEU fuel. During most of the 13 years from 2014 to 2026, EPZ plans to use nearly 40-percent MOX fuel in the reactor's core. The sharp decline of uranium prices since 2008, by more than 80 percent, has likely increased substantially the financial penalty that EPZ will pay for substituting MOX for LEU.

EPZ is able to absorb this cost in part because the local-government owners of the reactor pay EPZ a fixed price, well above market rate, for the electricity produced. Thus, local governments lose money whenever the Borssele reactor delivers energy, but EPZ has a financial interest in ensuring that the reactor is not shut prematurely. Notably, EPZ's contract for recycling of plutonium in MOX fuel, if terminated prematurely, would result in hundreds of millions of Euros in penalty fees, which the utility likely would seek to recover from the government. Thus, EPZ's decision to initiate MOX fuel has had the effect of deterring the Dutch government from shutting the reactor prematurely, although it is unclear if EPZ was motivated by such calculus.

In light of EPZ's unique circumstances – only one reactor, no surplus plutonium to start, and the need to recycle by 2033 all of the plutonium it would produce by then – Areva devised a "pre-cycling" scheme. The French company initially loaned plutonium to EPZ in fresh MOX fuel and subsequently accepted repayment in SNF. The major reactor modification was switching from natural to enriched boron in emergency cooling and control systems, which raised the percentage of Boron-10 from 20 to 32 percent. Two new cask designs were also developed for fresh and spent MOX fuel. In 2017, although the reactor's core had yet to reach full MOX capacity, a safety assessment reported that the new fuel was performing safely.

Security procedures for fresh MOX fuel, compared to LEU fuel, are only marginally more rigorous and reportedly equivalent to those for SNF. This appears inadequate for fresh MOX, which contains nuclear weapons-usable plutonium and is insufficiently radioactive to deter terrorist theft. Domestic environmental groups opposed the introduction of MOX fuel on safety and security grounds, but they had little impact on Dutch residents, legislators, or courts. This may be because few Dutch citizens are directly affected by shipments for the reactor and waste site, both of which lie near the border with Belgium, which is the transit route.

Conclusion

The Netherlands initiated commercial use of MOX fuel in thermal reactors in 2014, after most other countries using such fuel already had decided to phase it out. This might appear to signal a revival of global use of plutonium for energy. However, the details of the case reveal exactly the opposite. The Dutch utility's preference was not to recycle plutonium in its reactor but to pay someone else to take it. Only when it could not find a taker, because MOX is so unpopular globally, did the utility seriously explore using such fuel itself. The Dutch experience also underscores two financial insights about the closed fuel cycle: MOX is much more expensive than LEU, and direct disposal of SNF offers an economically competitive alternative to reprocessing. This was true even before the 2008 collapse of uranium prices, which has made it only more so. Nevertheless, due to unique domestic political considerations, EPZ chose to sign long-term contracts for SNF reprocessing and MOX fuel fabrication, which appear to have significantly increased its costs. The Netherlands was the first country in a quarter-century to decide to initiate commercial use of MOX fuel in thermal reactors, and it may well prove to be the last.

Endnotes

[1] The author gratefully acknowledges research assistance by Ms. Yeo-Ri Kim.

[2] World Nuclear Association, "Nuclear Power in the Netherlands," April 2018, http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/netherlands.aspx.

[3] Ann MacLachlan, "UK returns reprocessing waste from shutdown Dutch reactor," *NuclearFuel*, March 22, 2010. Ministry of Economic Affairs and the Environment, "Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management," National Report of the Kingdom of the Netherlands for the Sixth Review Meeting, October 2017, 81, https://zoek.officielebekendmakingen.nl/blg-820682.pdf. Martin Forwood, Cumbrians Opposed to a Radioactive Environment (CORE), email to author, February 27, 2018.

[4] Martin Forwood, Cumbrians Opposed to a Radioactive Environment (CORE), email to author, March 1, 2018. Ministry of Economic Affairs and the Environment, "Joint Convention," 16. Xavier Coeytaux and Yves Marignac, "Extension of Dutch Reprocessing: Upholding the Plutonium Industry at Dutch Society's Expenses?" WISE-Paris, June 2004, 2, https://www.laka.org/docu/catalogue/publication/1.01.4.40/10_extension-of-dutch-reprocessing-upholding-the-plu. The fuel burnup was 24,823 megawatt-days per tonne of uranium.

[5] UK Department of Energy & Climate Change, "Plutonium deal brings security benefits," press release, April 23, 2013, https://www.gov.uk/government/news/plutonium-deal-brings-security-benefits. See also, Ministry of Economic Affairs and the Environment, "Joint Convention," 27-28.

[6] World Nuclear Association, "Nuclear Power in the Netherlands."

[7] R.J.M. Konings and D.H. Dodd, "Nader onderzoek naar de verwerking van gebruikte splijtstof uit Nederlandse kerncentrales [Further research into the processing of spent nuclear fuel from Dutch nuclear power plants]," Nuclear Research & Consultancy Group (NRG), Report No. 21483/99.24187/p, commissioned by the Ministry of Economic Affairs, Petten, Netherlands, March 24, 1999, Section 4.2, says the amount of "fissile" plutonium in the SNF must be returned under the reprocessing contract. https://www.laka.org/docu/catalogue/publication/1.01.4.40/08_nader-onderzoek-naar-de-verwerking-van-gebruikte-s.

[8] Peter Breitenstein and Jan Wieman, "Pre-cycling within plant lifetime," paper presented at the Top Fuel 2012 conference, Manchester, United

Kingdom, September 2-6, 2012, 318. The two fast reactors were Germany's Kalkar and France's SuperPhenix.

[9] Drs. A.P. (Bram-Paul) Jobse RA, Chief Financial Officer, N.V. Elektriciteits-Produktiemaatschappij Zuid-Nederland (EPZ), interview with author, March 8, 2018. Breitenstein and Wieman, "Pre-cycling within plant lifetime," 318, 321. Ministry of Economic Affairs and the Environment, "Joint Convention," 27-28.

[10] D.H. Dodd, R.J.S. Harry, J.L. Kloosterman, R.J.M. Konings, A.M. Versteegh, "Opwerking van Nederlandse Splijtstof," Energy Research Centre of the Netherlands (ECN), Report No. ECN-C--97-031, 1997, https://www.ecn.nl/publicaties/ECN-C--97-031, 34, states that, "The increasing global surplus of plutonium and the high costs associated with the manufacture of MOX fuel mean that separated plutonium currently has a negative market value. It is assumed here that EPZ will have to pay 30 NLG/gPu for someone to take it (ECN estimate)" [author's translation]. See also, Konings and Dodd, "Nader onderzoek naar de verwerking," Section 3.5.

[11] Jobse, interview, March 8, 2018.

[12] Ann MacLachlan, "Dutch utility announces renewal of reprocessing with Cogema," *NuclearFuel*, March 15, 2004.

[13] Breitenstein and Wieman, "Pre-cycling," 321.

[14] Dr. Ir. Ewoud V. Verhoef, Deputy Director, COVRA NV, interview with author, March 8, 2018.

[15] EPZ, "Milieueffectrapportage Brandstofdiversificatie," July 2010. https://www.laka.org/docu/catalogue/publication/1.01.8.23/33_milieueffectrapportage-brandstofdiversificatie. Jobse, interview, March 8, 2018.

[16] Dirk Bannink, Laka Foundation, interview with author, March 7, 2018.

[17] Jobse, interview, March 8, 2018.

[18] EPZ, "Milieueffectrapportage Brandstofdiversificatie."

[19] The cost of enrichment was highlighted in another submission. See, EPZ, "Aanvraag tot wijziging van de kernenergiewetvergunning Brandstofdiversificatie," July 2010, 12.

[20] Jobse, interview, March 8, 2018.

[21] EPZ, "Milieueffectrapportage Brandstofdiversificatie," 14, states that, "Vanuit het oogpunt van kostenbeheersing is het daarom voor EPZ aantrekkelijk om MOXsplijtstof te kunnen inzetten."

[22] Jobse, interview, March 8, 2018.

[23] Ministry of Economic Affairs and the Environment, "Joint Convention," 27-28.

[24] Jobse, interview, March 8, 2018.

[25] EPZ, "EPZ applies for a permit for re-use of fuels at the nuclear power plant," Press release, July 8, 2010. The statement also says that the "price

of natural uranium has risen sharply in recent years," although in fact the price had plummeted in the preceding two years.

[26] Gert Jan Auwerda, ANVS, interview with author, March 7, 2018.

[27] Jobse, interview, March 8, 2018.

[28] Jan Wieman, "Borssele Moves to MOX," *Nuclear Engineering International*, March 11, 2015, http://www.neimagazine.com/features/featureborssele-moves-to-mox-4530062/.

[29] Jobse, interview, March 8, 2018.

[30] Minister for Economic Affairs, Agriculture and Innovation, "Reprocessing of radioactive material," letter to the President of the House of Representatives of the States General, Parliamentary paper 25422, no. 87, The Hague, January 17, 2011, author's translation, https://zoek.officielebekendmakingen.nl/kst-25422-87.html. COVRA's Deputy Director, Ewoud Verhoef, email to author, August 13, 2018, says that HABOG actually took four years to construct (1999-2003), following a five-year licensing phase (1994-1999), which implies that the entire process for a new facility might have required nine years.

[31] Jobse, interview, March 8, 2018. Wieman, "Borssele Moves to MOX," reports similarly that, "EPZ assessments found that the cost of continuing fuel recycling would not be much different from the expected cost of direct fuel disposal."

[32] Auwerda, interview, March 7, 2018.

[33] Drs. A.P. (Bram-Paul) Jobse, email to author, August 23, 2018.

[34] Verhoef, interview, March 8, 2018. He estimates that such a facility would have cost at least as much as the original HABOG, which was €125 million.

[35] Jobse, email to author, August 23, 2018.

[36] Jobse, interview, March 8, 2018. See also, Wieman, "Borssele Moves to MOX."

[37] Breitenstein and Wieman, "Pre-cycling," 321.

[38] Mr. A.B. Holtkamp, Drs. W.J. Laman RA, and Dr. H.A. Selling, "Rapport betreffende de validatie van de onderliggende aannames m.b.t. de operationele kosten en kosten van mogelijke sluitingsscenarios van de kerncentrale Borssele" [Report on the validation of the underlying assumptions regarding the operational costs and costs of possible closure scenarios of the Borssele nuclear power plant], September 15, 2016, 11-13, https://www.rijksoverheid.nl/documenten/rapporten/2016/09/15/rapport-betreffende-de-validatie-van-de-onderliggende-aannames-m-b-t-de-operationele-kosten-en-kosten-van-mogelijke-sluitingsscenarios-van-de-kerncentrale-borssele.

[39] Holtkamp, et al., "Rapport betreffende de validatie," 11-13.

[40] Auwerda, interview, March 7, 2018.

[41] Jobse, email to author, August 23, 2018.

[42] GRS, "GRS assists Dutch regulatory authority KFD," July 26, 2010, https://www.grs.de/en/content/kfd.

[43] EPZ, "Milieueffectrapportage Brandstofdiversificatie," states that LEU SNF requires one to two years of cooling in the pool, but that MOX SNF requires an extra one to two years.

[44] Breitenstein and Wieman, "Pre-cycling," 320.

[45] Wieman, "Borssele Moves to MOX." Breitenstein and Wieman, "Pre-cycling," 316.

[46] Shaun Burnie and Frank Barnaby, "Safety Implications of MOX Fuel Use in The Borssele Nuclear Power Plant – Lessons from Fukushima," Greenpeace, August 3, 2011, 2, http://www.greenpeace.nl/Global/nederland/image/2011/PDF/moxfueluse_borssele.pdf.

[47] Breitenstein and Wieman, "Pre-cycling," 322.

[48] Wieman, "Borssele Moves to MOX."

[49] This includes the environmental impact assessment, dated July 2010, and submitted in autumn 2010. EPZ, "Milieueffectrapportage Brandstofdiversificatie." Wieman, "Borssele Moves to MOX."

[50] EPZ, "Milieueffectrapportage Brandstofdiversificatie," 28.

[51] Auwerda, interview, March 7, 2018. EPZ, "Milieueffectrapportage Brandstofdiversificatie."

[52] EPZ, "Milieueffectrapportage Brandstofdiversificatie," 29, 70-72.

[53] EPZ, "Milieueffectrapportage Brandstofdiversificatie."

[54] EPZ, "Milieueffectrapportage Brandstofdiversificatie," 58.

[55] Jan Haverkamp, Greenpeace-Netherlands, interview with author, March 5, 2018.

[56] Ministry of Infrastructure and the Environment, "Brandstofdiversificatie KCB – beoordelingsrapport veiligheidstechnische onderbouwing," VROM Inspectorate, April 29, 2011.

[57] *Government Gazette 2011*, No. 11565, June 29, 2011.

[58] Wieman, "Borssele Moves to MOX."

[59] Auwerda, interview, March 7, 2018. ARCADIS, "Evaluatie Mer Brandstofdiversificatie EPZ: Gebruik van Mixed-Oxide splijtstof in de Kerncentrale Borssele," May 2017.

[60] WISE-Nederland, "Borssele maakt winst... hoe zit dat?" July 11, 2017, https://wisenederland.nl/borssele-maakt-winst-hoe-zit-dat. PZEM is 100-percent owned by the Zeeland municipalities and the Province of Zeeland.

[61] Ministry of Infrastructure and the Environment, "Brandstofdiversificatie KCB," 13.

[62] Auwerda, interview, March 7, 2018. Jobse, interview, March 8, 2018.

[63] Haverkamp, interview, March 5, 2018.

[64] Jobse, interview, March 8, 2018.

[65] Burnie and Barnaby, "Safety Implications of MOX," 17-20.

[66] Burnie and Barnaby, "Safety Implications of MOX," 13.

[67] "EPZ mag plutonium gaan gebruiken," *Omroep Zeeland*, February 13, 2013, https://www.omroepzeeland.nl/nieuws/63064/EPZ-mag-plutonium-gaan-gebruiken.

[68] Bannink, interview, March 7, 2018. Shaun Burnie, phone interview with author, February 23, 2018. Haverkamp, interview, March 5, 2018.

[69] "Borssele Nuclear Power Plant Convenant," June 2006, https://laka.org/docu/boeken/pdf/1-01-8-20-45.pdf#page=2. The actual license change was granted later. See, Minister of Economic Affairs, "Amendment of the Nuclear Energy Act Licence Granted To NV EPZ for the Extension of the Design Lifetime of the Borssele Nuclear Power Plant," March 20, 2013, https://www.unece.org/fileadmin/DAM/env/pp/compliance/C2014-104/Correspondence_with_Party_concerned/frPartyC104_03.02.2015/Appendix_6_-_Borssele_NPP_LTO_license_final.pdf.

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Plutonium is a controversial fuel for three reasons: it can be used to make nuclear weapons, causes cancer, and is extremely costly to produce. Yet, relatively little information has been publicly available regarding the main use of this fuel around the world, in traditional ("light water") nuclear power reactors. This book offers the first comprehensive global study of plutonium "mixed oxide" (MOX) fuel in those reactors. Field research was conducted in all seven countries that have commercially manufactured or used such MOX: Belgium, France, Germany, Japan, the Netherlands, Switzerland, and the United Kingdom. The chapters explain why five of the countries have decided to phase out MOX, due to concerns about security, economics, safety, the environment, and public acceptance. This volume should inform ongoing decision-making – in China, Japan, South Korea, the United States, and beyond – about whether to recycle plutonium for energy.

About the Editor

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