Plutonium for Energy?

Explaining the Global Decline of MOX

[EXCERPT]

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MOX in France: Reassessment as Foreign Customers Fade

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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.

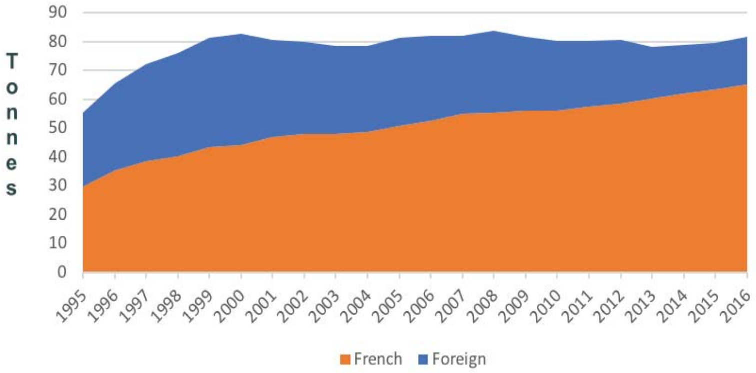
A former EDF executive says the utility avoids reprocessing spent MOX because it wants to maintain the reliable fuel cycle that it has today. He also claims that the utility's strategy is to store spent MOX until fast reactors are "economically needed." He speculates that in 50 to 100 years, a rise in 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]

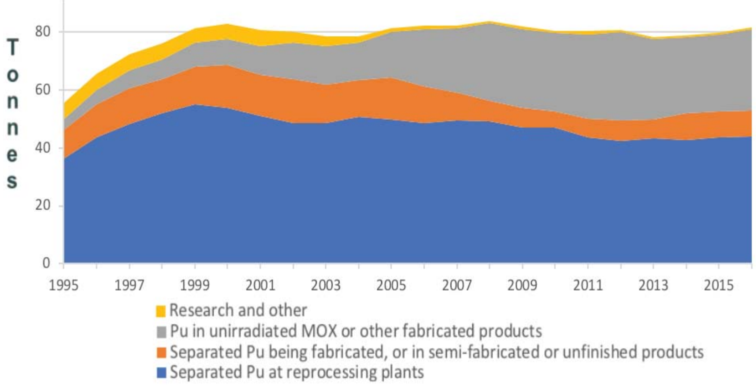
Figure 1. Civil Unirradiated Plutonium in France by Ownership



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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