Plutonium for Energy?

Explaining the Global Decline of MOX

[EXCERPT]

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

NPPP

NUCLEAR PROLIFERATION
PREVENTION PROJECT

The University of Texas at Austin

Edited by Alan J. Kuperman

First Edition: October 2018

Book design by Alan J. Kuperman,
based on concepts by Derek Murphy of Creativindie Design.
Cover design by Alan J. Kuperman.
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Library of Congress Control Number: 2018912516
ISBN-10: 1-7329077-0-6
ISBN-13: 978-1-7329077-0-6

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MOX in Belgium: Engineering Success but Politico-Economic Failure

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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.

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[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.