Plutonium for Energy?

Explaining the Global Decline of MOX

[EXCERPT]

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MOX in Germany: Reprocessing Spurs Opposition to Nuclear Energy

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

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

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

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

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

Germany's Nuclear Program

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

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

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

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

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

Table 1
Commercial Use of MOX in German Power Reactors

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

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

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

Table 2
German Power Reactors Still Operating in 2018

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

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

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

MOX Use in Thermal Reactors

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

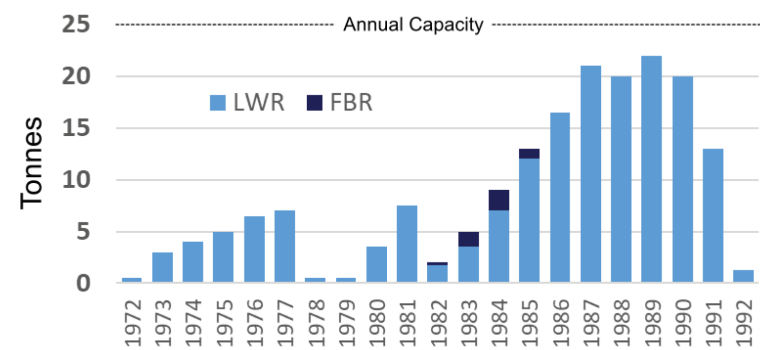
In 2010, German Chancellor Angela Merkel's coalition government extended the operating lifetime of German nuclear power plants by up to 14 years, stretching out the nuclear phase-out that had been adopted by her predecessor, Gerhard Schröder, in 2002.[40] Two months after Merkel's decision, however,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

MOX Fabrication

From 1972 to 1991, a commercial MOX fabrication facility known as Alkem Hanau operated in the state of Hesse. The plant's nominal capacity was 25 tonnes per year,[43] but its average production was only about eight tonnes annually. A former senior official of the facility claims that it fulfilled all contracts until its premature shutdown.[44] The average fissile plutonium content of the MOX produced for thermal reactors apparently increased over time,[45] but on average it was only 2.82 percent, which implies that the total percentage of plutonium in the MOX was about four percent, significantly lower than modern practice.[46] The plant was initially run by Alkem GbmH, which had been established to develop MOX

fabrication technology and which had previously operated a prototype MOX fabrication plant at Karlsruhe for experimental fast reactors.[47] In 1988, Siemens AG took over Alkem, including the existing MOX plant and its planned successor facility, known as Hanau 1.[48] The original plant had been built at the invitation of the government of Hesse, which supported its operation until a "Red-Green" coalition of the Social Democratic and Green parties came to power in the state in January 1991.[49] The plant supplied mainly domestic customers, while 13 percent of its MOX fuel was exported.[50]

Figure 1
Annual MOX Output at Alkem Hanau



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

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

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

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

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

Krellmann cites many reasons why the MOX plant fell so short of its nominal capacity: unforeseen repair work under difficult glove-box conditions; suspension of production during EURATOM

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

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

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

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

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

Summary of Findings

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

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

that phase-out.

Conclusion

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

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[44] Jürgen Krellmann, interview with author, January 5, 2017, Provence, France.

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[51] Krellmann, "MOX Fuel Technology."

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[58] Rupar, et al., "Decommissioning."

[59] Kalinowski, et al., "The German Plutonium Balance," 152, says that production started in 1968, but the graph starts in 1972, implying no substantial output prior to then. See also, Schlosser, "MOX Fuel Utilization in Existing German LWRs."

[60] Kalinowski, et al., "The German Plutonium Balance." This indicates that for the LWR fuel, 4,461 kg of fissile plutonium was contained in 6,585 kg of total plutonium – further evidence that 68 percent of the plutonium was fissile.

[61] Schlosser, "MOX Fuel Utilization."

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