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

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 Switzerland: Explaining an Uneconomic Fuel Choice

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

Switzerland has rarely been a major focus for the study of nuclear energy use in Europe. In contrast to countries such as France, Germany, and the United Kingdom, Switzerland has neither a large number of nuclear power plants (NPPs) nor fuel-cycle facilities for

reprocessing spent nuclear fuel (SNF) and fabricating MOX fuel. However, Switzerland's use of MOX fuel merits attention for three main reasons. First, despite the absence of domestic fuel-cycle facilities, Swiss utilities were among the earliest to recycle their spent fuel, relying on reprocessing and MOX fabrication plants elsewhere in Europe. Second, Switzerland has 40 years of experience using MOX fuel in light-water reactors (LWRs). Finally, Swiss utilities no longer use or plan to use MOX fuel. Switzerland, therefore, is an interesting case where researchers can evaluate the start to finish of the experience of using MOX fuel without domestic fuel-cycle facilities. This chapter aims to inform ongoing decision-making in other countries, for example in East Asia, about whether to recycle SNF to use plutonium for energy.

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

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

Swiss Nuclear Power

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

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

Table 1
Swiss Nuclear Power Plants

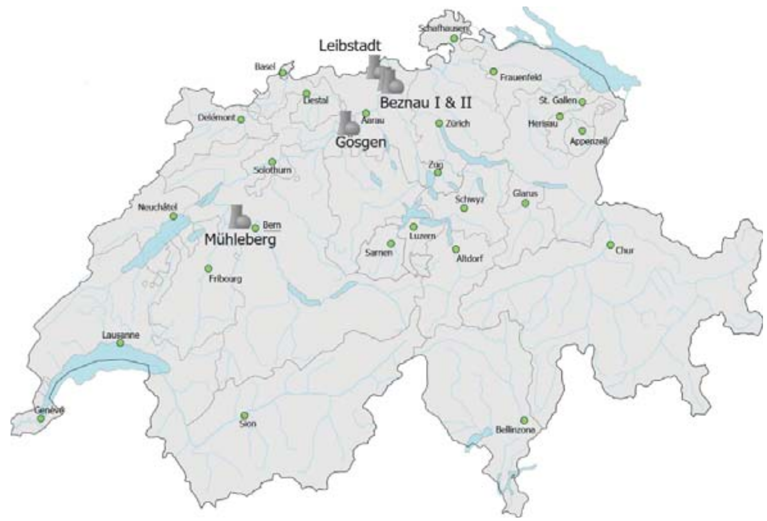
Reactor	Operator	First Power	MWe (Net)	Type
Beznau-1	Axpo Power AG	1969	380	Pressurized
Beznau-2	Axpo Power AG	1971	380	Pressurized
Mühleberg	BKW Energie AG	1972	390	Boiling
Gösgen	Kernkraftwerk Gösgen-Däniken AG	1979	985	Pressurized
Leibstadt	Kernkraftwerk Leibstadt AG	1984	1275	Boiling

Source: World Nuclear Association.

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

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

Figure 1
Map of Switzerland's Five Nuclear Power Reactors



Source: Wikimedia Commons.

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

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

Reprocessing and MOX Fuel

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

Table 2
Historical Reprocessing and MOX Use for Swiss Power Plants

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

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

Nuclear Regulation

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

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

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

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

Methods

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

Findings

In the 1970s, Swiss utilities decided to reprocess their spent fuel and to recycle the separated plutonium in MOX fuel for several reasons. A major factor was the perceived absence of an alternative, direct disposal pathway for spent fuel. Switzerland lacked a national policy concerning SNF until the late 1970s, so NPP operators were ostensibly free to choose between direct disposal and reprocessing. However, in the absence of a national plan for domestic storage of waste, the nuclear utilities viewed exporting their SNF as the only feasible option because it effectively postponed having to deal with nuclear waste domestically. It also avoided the political controversy and potential expense of a domestic reprocessing plant, which

could have inhibited nuclear power. As a result, according to a NOK official, all four Swiss nuclear utilities became "locked into long-term reprocessing contracts, which were at the time, in the mid-70's, the only viable fuel-cycle option for the back end."[20]

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

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

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

Recycling Plutonium in MOX Fuel

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

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

The utility conducted a safety evaluation with HSK, obtaining a license for a maximum of 40-percent MOX in the core (48 of 121 assemblies) of each Beznau reactor.[34] However, the highest percentage of MOX actually loaded in the core of either reactor was 34 percent (41 assemblies) in Beznau-1, in 1992.[35] The percentage of MOX in each core fluctuated substantially over time due to the availability of plutonium and MOX fabrication services (see Appendix 1).[36]

Table 3
MOX Use in Swiss Power Plants

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

Source: Swiss Federal Nuclear Safety Inspectorate (HSK).

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

Economics

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

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

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

Operational Performance

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

At the Beznau NPPs, however, four leaking MOX fuel assemblies, including a total of five defective fuel rods, were identified. The first two breaks in the cladding in 1990 were determined to be caused by debris fretting, resulting from wearing and corrosion by foreign matter. This caused a leakage of

radioactive irradiated fuel into the core's surrounding water, which serves as its coolant and moderator. The primary cause of the three remaining cladding defects, in 1997, could not be determined from visual inspections.[49]

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

Security

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

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

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

Safety

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

Table 4
Safety Evaluation Matrix for MOX Fuel

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

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

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

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

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

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

Waste Management

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

Table 5
Estimated Lifetime Fuel Assemblies to be Discharged

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

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

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

Politics and Public Opinion

MOX fuel was not a particularly contentious topic in Switzerland. The public knew little about MOX fuel and rarely was

consulted in the utilities' decision-making about it. However, the closed fuel cycle clearly was less popular than nuclear power, *per se*. Swiss voters repeatedly rejected proposals to shut down nuclear power quickly, as recently as 2016.[72] By contrast, in a 2003 referendum, they voted to impose a moratorium within three years on SNF reprocessing and MOX recycle – while at the same time authorizing potential new power reactors.

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

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

Summary of Findings

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

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

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

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

Conclusion

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

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

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

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

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

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

Appendix 1

MOX Loading History in Three Swiss Power Plants

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

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

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

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

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

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

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

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

Source: Interview with Dr. Schulz Ralph.

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