Plutonium for Energy?
Explaining the Global Decline of MOX

[EXCERPT]

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MOX in the UK: Innovation but Troubled Production

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

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

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

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

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

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

Methods

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

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

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

MOX Fabrication

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

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

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

MOX Demonstration Facility (MDF)

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

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

Design

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

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

Production and Economics

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

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

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

Security, Safety, and Environment

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

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

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

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

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

Sellafield MOX Plant (SMP)

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

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

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

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

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

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

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

Design

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

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

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

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

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

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

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

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

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

Production and Economics

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

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

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

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

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

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

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

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

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

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

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

Retrofit Plans & Closure

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

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

The economic case for SMP's new rod line was entirely dependent on Japanese demand.[147] In the wake of the Fukushima accident, however, the Japanese government in 2011 announced a phased shutdown of nuclear power plants to reevaluate plant safety and public opinion.[148] This uncertainty led the NDA to permanently shut down SMP in August 2011.[149] The potential Japanese customers had essentially "pulled the plug."[150] British trade unions opposed the closure, especially in light of ongoing discussions about the disposition of UK-owned plutonium as MOX fuel.[151] SMP is now in a mothballed state, and decommissioning might not begin until 2037.[152]

Security, Safety, and Environment

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

A security advantage of SMP's design, which also made production more difficult, was its minimal process hold-up areas. Minimizing buffers between production stages also reduced the

Table 1. SMP Production and Economic Timeline

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

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

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

[b] See narrative above.

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

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

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

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

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

residual plutonium buildup and the risk of criticality accidents. Near-real-time materials accountancy software was used to track material between cleanouts.[157] Although the data falsification at MDF came to light after the design of SMP had been finalized, SMP's design did reduce the possibility of a quality-control data falsification because its inspections were extensively automated, digitally recording the dimensions of every pellet.[158]

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

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

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

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

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

MOX Use in the UK

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

UK Reactor Types

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

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

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

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

Changing Ownership of Nuclear Reactors: 1979 to 2018

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

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

Domestic Sources of Plutonium

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

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

Fast Reactors

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

Magnox Reactors

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

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

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

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

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

Advanced Gas-Cooled Reactors

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

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

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

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

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

Sizewell B PWR

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

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

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

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

Summary of Findings

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

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

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

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

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

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

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

Conclusion

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

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

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

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

Currently, the UK government's preferred disposal option for its over 110 tonnes of domestic-owned separated plutonium is to recycle it in MOX fuel. Since SMP is now shuttered, MOX fuel would have to be fabricated in another facility. A new plant could be built in the UK, or the separated plutonium could be sent to a foreign MOX manufacturer. Non-UK fabrication would require shipping separated plutonium via air or sea, thereby raising significant security concerns, as arose when some plutonium was shipped to France in 2008. In 2015, Areva proposed its Convert

project to build a MOX fuel fabrication plant at Sellafield.[233] However, the proposal did not include any new reactors to use the MOX fuel in the UK, and no current UK nuclear plant developer has expressed interest in using MOX fuel. Two other foreign companies – GE Hitachi Nuclear Energy and Candu Energy – have each offered to build both a new MOX fuel fabrication plant and new nuclear reactors designed to use MOX fuel, but so far there is little domestic enthusiasm.[234]

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

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

Glossary

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

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[158] Laurence Williams, in discussion with the author, February 5, 2018. John Clarke, in discussion with the author, February 6, 2018.

[159] House of Commons Debates, February 16, 2006, vol. 442, col. 2403W.

[160] SMP's lifetime production was 13.8 MTHM; see Table 1.

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[162] Young, "Commercial MOX Fuel Production—the Challenge," 189.

[163] Department for Environment, Food & Rural Affairs and Department of Health, "Re BNFL's MOX Plant at Its Site in Sellafield, Cumbria: Justification for the Manufacture of MOX Fuel," October 2001, 65, http://webarchive.nationalarchives.gov.uk/20030731122447/http://www.defra.gov.uk:80/environment/radioactivity/mox/decision.htm.

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[166] Young, "Commercial MOX Fuel Production—the Challenge," 189.

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[168] Nuclear Safety Advisory Committee, "Report from HSE for the Meeting to Be Held July 2007," November 15, 2007, http://www.hse.gov.uk/aboutus/meetings/iacs/nusac/050707/p8.pdf.

[169] "The MOX Plant Case (Ireland v. United Kingdom)," No. 2002–01, Permanent Court of Arbitration, June 6, 2008. Counter-Memorial of the United Kingdom, January 9, 2003, para. 3.7–3.13.

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[174] "In the Dispute Concerning the MOX Plant, International Movements of Radioactive Materials, and the Protection of the Marine Environment of the Irish Sea (Ireland v. United Kingdom)," International Tribunal for the Law of the Sea, 2001.

[175] "In the Dispute Concerning the MOX Plant," Order of December 3, 2001, p. 110, para. 81.

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

[177] "The MOX Plant Case (Ireland v. United Kingdom)," Order No. 6, June 6, 2008.

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

[179] Magnox stands for MAGnesium Non-OXidizing. The cladding was a magnesium–aluminum alloy.

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

[181] Taylor, *The Fall and Rise of Nuclear Power in Britain*, 21–23.

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

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

[184] The Calder Hall Magnox plant at Sellafield was under the auspices of BNFL before the Magnox Electric merger. It closed in 2003.

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

[186] John Simpson, in discussion with the author, February 7, 2018.

[187] Simpson, in discussion with the author, February 7, 2018.

[188] Jensen and Ølgaard, "Description of the Prototype Fast Reactor at Dounreay."

[189] Department of Trade and Industry, "Meeting the Energy Challenge: A White Paper on Energy," May 2007, 204, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/243268/7124.pdf.

[190] "End of an Era," *Nuclear Engineering International*, April 29, 2016, http://www.neimagazine.com/features/featureend-of-era-4879554/.

[191] House of Commons Trade and Industry Committee, "Minutes of Evidence, Thursday 30 March 2000," in *Ninth Report: Proposed Public Private Partnership for BNFL* (HC 1999–2000), 2000, Q. 301, https://publications.parliament.uk/pa/cm199900/cmselect/cmtrdind/307/30702.htm.

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

[193] Health and Safety Executive, "The United Kingdom's National Report on Compliance with the Obligations of the International Convention on Nuclear Safety," Department of Trade and Industry, September 2001, http://www.onr.org.uk/cns2.pdf.

[194] For energy production, the maximum average burnup was around seven MWd/kgHM. For weapons-grade plutonium production at Calder Hall and Chapelcross, the burnup was likely much lower, perhaps 0.5 MWd/kgHM.

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

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

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

[198] Ostensibly this means that there was very limited life left in the Magnox reactors by the year 2000 to make significant operating changes.

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

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

[201] Paul Wilcox, "Use of Plutonium in the UK," in *Mixed Oxide Fuel (MOX) Exploitation and Destruction in Power Reactors*, eds. Erich R. Merz, Carl E. Walter, and Gennady M. Pshakin (Dordrecht, The Netherlands: Springer Netherlands, 1995): 135–37.

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

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[207] BNFL National Stakeholder Dialogue, Plutonium Working Group, "BNFL National Stakeholder Dialogue, Plutonium Working Group Final Report," 33.

[208] Peter Haslam, in discussion with author, February 8, 2018.

[209] "EDF Energy Extends Lives of UK AGR Plants," *World Nuclear News*, February 16, 2016, http://www.world-nuclear-news.org/C-EDF-Energy-extends-lives-of-UK-AGR-plants-1602164.html.

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[211] "For the Longest Time," *Nuclear Engineering International*, June 14, 2013, http://www.neimagazine.com/features/featurefor-the-longest-time/.

[212] Jones, "Nuclear Power Technology."

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

https://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=GB.

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[218] Royal Academy of Engineering, "Nuclear Lessons Learned," October 2010, https://www.raeng.org.uk/publications/reports/nuclear-lessons-learned.

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