5 The Legacy of Reprocessing in the United Kingdom

Martin Forwood

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Acronyms

ADL	Arthur D. Little
AGR	Advanced Gas-Cooled Reactor
BWR	Boiling Water Reactor
CoRWM	Committee on Radioactive Waste Management
DRS	Direct Rail Service
BNG	British Nuclear Group
BNFL	British Nuclear Fuels Limited
GWd	Gigawatt-day
HAL	Highly active liquors
HLW	High level waste
HSE/NII	Health and Safety Executive's Nuclear Installation Inspectorate
ILW	Intermediate-level waste
LLW	Low level waste
MDF	MOX Demonstration Facility
MOX	Mixed Oxide Fuel
NDA	Nuclear Decommissioning Authority
NIREX	Nuclear Industry Radioactive Waste Executive
PNTL	Pacific Nuclear Transport Limited
PPI	Parental preconception irradiation
PWR	Pressurized Water Reactor
SMP	Sellafield MOX Plant
THORP	Thermal Oxide Reprocessing Plant
VLLW	Very low level waste
WVP	Windscale Vitrification Plant

About the IPFM

The International Panel on Fissile Materials (IPFM) was founded in January 2006. It is an independent group of arms-control and nonproliferation experts from both nuclear weapon and non-nuclear weapon states.

The mission of the IPFM is to analyze the technical basis for practical and achievable policy initiatives to secure, consolidate, and reduce stockpiles of highly enriched uranium and plutonium. These fissile materials are the key ingredients in nuclear weapons, and their control is critical to nuclear weapons disarmament, to halting the proliferation of nuclear weapons, and to ensuring that terrorists do not acquire nuclear weapons. IPFM research and reports are shared with international organizations, national governments and nongovernmental groups.

The Panel is co-chaired by R. Rajaraman of Jawaharlal Nehru University, India, and Professor Frank von Hippel of Princeton University. The founding members of the Panel include nuclear experts from sixteen countries: Brazil, China, France, Germany, India, Japan, Mexico, the Netherlands, Norway, Pakistan, Russia, South Africa, South Korea, Sweden, the United Kingdom and the United States.

Princeton University's Program on Science and Global Security provides administrative and research support for IPFM.

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Overview

Some 50 years after the Sellafield site, formerly known as Windscale, produced its first plutonium for nuclear weapons, the full extent of the legacy of this early military work and later processing operations is only now becoming clear, both in scale and cost. The UK's politically driven weapons programme of the 1950's, via the two Windscale Pile reactors, saw the remote coastal site in West Cumbria in the north-west of England transformed from a small wartime munitions facility into a burgeoning nuclear complex.

The construction of the four 50-MW(electric) Calder Hall military reactors in the mid to late 1950's – primarily to keep pace with the demand for weapons plutonium – heralded the emergence of the UK's civil nuclear power industry and the establishment of commercial reprocessing. Benefiting from the demise of the area's traditional industries of coal, steel and shipbuilding, Sellafield grew to become West Cumbria's foremost employer, and its operations came to dominate not only the local landscape but also the local economy.

The consequence of the expansion was the creation of mounting stocks of wastes and materials which, in the early development of the site, were produced with no thought about their eventual disposal. Similarly, with scant understanding of their long-term behaviour, radioactive discharges were made to the environment at levels that today are acknowledged as being wholly unacceptable.

The scale and state of this legacy has only recently been fully quantified. This report identifies the current state at Sellafield, the underperforming commercial operations that contribute to its legacy, the clean-up and decommissioning plans for the site, proposals for the management of the stockpiles of separated plutonium and uranium and nuclear wastes, and lastly the overall socio-economic and health impact of the Sellafield enterprise on the local communities.

Despite the legacy and the loss-making commercial operations that contribute to it, reprocessing is allowed to continue with full Government backing even though the original rationale for the operation has evaporated. The future of Sellafield remains undecided, for whilst the site is currently programmed to be decommissioned by 2120, Government support for the construction of a fleet of new nuclear power stations in the UK, and the industry's lobbying for new reprocessing and MOX production facilities could see the plans amended and the site's future extended.

I. Site History

The Sellafield site on the Cumbrian coast in NW England was acquired by the Government as a munitions factory during World War II and transferred to the Ministry of Supply in 1945 for use in the UK's weapons programme. Handed over to the newly formed United Kingdom Atomic Energy Authority (UKAEA) in 1954, ownership was again transferred in 1971 to British Nuclear Fuels (BNFL), a company wholly owned by the Government. Following a re-structuring of that company in 2004, site operations were delegated to one of the company's four main business groups, British Nuclear Group (BNG). In April 2005, ownership of the site was again transferred to its current owners, the Nuclear Decommissioning Authority (NDA) - with BNG contracted to manage all site operations.

The site, covering an area of approximately 2 square miles, has over 200 nuclear facilities, representing some 60% of the UK's total civil nuclear liabilities, and employs a workforce of over 10,000 – 95% of whom live within 30 miles of the site. Operations are regulated by the Health & Safety Executive's Nuclear Installations Inspectorate (HSE/NII), Environment Agency, Office for Civil Nuclear Security, and the Local Authority, which is responsible for planning issues related to the site.

The name of the current site owner, the Nuclear Decommissioning Authority, reflects the change in emphasis – from commercial operations to clean- up – that has been ongoing at Sellafield and other nuclear sites since 2000 when the extent of the UK's nuclear liabilities became more apparent. In 2001, the UK's Secretary of State for Trade & Industry announced to Parliament that BNFL's accounts for that year showed estimated total long-term liabilities of £35Bn ($70Bn) - mostly due to legacy wastes that had arisen at Sellafield prior to the company's formation.[1] These liabilities exceeded BNFL's assets.

Subsequently, in order to radically change the arrangements for nuclear cleanup funded by the UK taxpayer, the Government launched its strategy for action in 2002[2]. This initiated the first stages of formation of a body originally called the Liabilities Management Authority – a title later changed to Nuclear Decommissioning Authority. As a non-departmental public body, the NDA is responsible not only for Sellafield but also for another 19 former BNFL and UKAEA sites.

Since the site's inception over five decades ago, the principal facilities responsible for Sellafield's commercial operations, many now being decommissioned, are shown in Figure 1.

Windscale Piles (1&2) **1950-1957**
Plutonium production for UK's weapons programme. The 1957 fire in Pile 1 (the Windscale Fire) saw both Piles closed and now under decommissioning.

Remaining Pile No.1 Stack

Calder Hall **1956-2003**
Originally used for weapons plutonium (ending in 1995). Also led with electricity production using Magnox-encased uranium-metal fuel.

Windscale Advanced Gas-cooled Reactor (WAGR). **1962-1981**
Prototype of the UK's AGR stations run by British Energy. Now under decommissioning.

A Calder Hall Reactor Building

B204 **1952-1973**
First reprocessing plant. Used for Pile, Magnox and, from 1964, for LWR fuel. Closed in 1973 after major blow-back accident.

B205 **1964-Present**
1500t/yr Magnox reprocessing plant. Closure scheduled for 2016+

WAGR 'Golf Ball'

THORP **1994-Present**
1200t/yr Thermal Oxide Reprocessing Plant for AGR & LWR Fuel. Closure now scheduled for around 2015.

MDF **1993-1999**
MOX Demonstration production Facility. Eight t/yr. Closed following 'falsification' scandal.

THORP –in foreground

SMP **2001-Present**
Sellafield MOX Plant. Capacity now reduced from 120t/yr to 40t/yr. Overseas contracts only.

SMP alongside THORP

Figure 1. Sellafield's Principal Facilities

Source: BNFL & CORE archives

II. Nuclear Transports

The transport of spent reactor fuel by rail from UK power plants and by sea from overseas power stations to feed Sellafield's reprocessing operations has dominated its transport scene since the 1970's. With all contracted spent fuel now delivered, future transports will consist of product and waste returns to overseas customers. Transports of these materials are undertaken by companies wholly or part-owned formerly by BNFL and now by the NDA.

Sea Transports

International Nuclear Services, once a subsidiary of BNG Sellafield Ltd, is now wholly owned by the NDA. Responsible for the international shipment of nuclear materials, INS holds a majority shareholding in Pacific Nuclear Transport Limited (PNTL) with France's AREVA and Japanese utilities as other shareholders. The one BNG/NDA owned International Nuclear Services ship *Atlantic Osprey* currently operates in Atlantic and European waters transporting MOX fuel to Europe, overseas research reactor fuel to the United States, and other nuclear and non-nuclear materials.

The custom-built PNTL fleet currently consists of two working ships, the *Pacific Pintail* and *Pacific Sandpiper*, with the *Pacific Teal* recently decommissioned. At a cost of over £30M ($60M), a new ship *Pacific Heron* has recently been launched in Japan and two more ships are on order from the same Mitsui Shipbuilding & Engineering Co. at the Tamano shipyard.[3] The ships, at around 4500 metric tons and some 30 crewmen each, are registered at their home port, Barrow-in-Furness, south of Sellafield.

Figure 2. The *Pintail*. To deter terrorists, PNTL's *Pacific Pintail* and *Pacific Teal* were each armed in the late 1990's with three 30mm naval canon – the first arming of UK merchant ships since the Second World War. The armament and extra security crew provided by the UK's Civil Nuclear Constabulary (CNC) was a requirement for the shipment of MOX fuel from Sellafield to Japan in 1999 when the *Pacific Teal* acted as escort to the *Pacific Pintail*. The new PNTL ships are expected to be armed in Japan. *Source: CORE archive*

The PNTL ships also transport MOX fuel and HLW from France's La Hague reprocessing plant to Japan.

Rail transports

Direct Rail Services (DRS) was established in 1995 to provide the nuclear industry with a strategic rail transport service. Originally a wholly owned subsidiary of BNFL, DRS is now owned by the NDA.

Operating from number of UK depots, DRS routinely transports magnox and uranium-oxide AGR spent fuel from power stations and submarine fuel from naval dockyards to Sellafield. Low-level waste (LLW) is also hauled by DRS from Sellafield to the LLW facility at the nearby village of Drigg, as are nuclear materials to and from INS ships at the Barrow shipping terminal. DRS also carries non-nuclear freight around the UK, a portfolio likely to increase as UK nuclear power stations close down and are decommissioned.

Figure 3. Spent Fuel Transport. Whilst UK spent fuel is transported in 50 ton cuboid flasks secured inside rectangular steel transport cabins, overseas fuel arrives in the UK in cylindrical flasks - typically in Excellox, Castor or TN flasks weighing up to 100 tons, and is transported uncovered on the rail journey to Sellafield. The rail link and casks were identified as a target by the IRA in the 1980's. *Source: CORE archive*

With all imports of overseas spent fuel now completed, 230-330 tons of spent fuel continue to be transported by rail to Sellafield each year from UK's AGR power stations for storage or reprocessing at THORP.[4] Based on the original 2012 THORP closure date, AGR fuel arriving at Sellafield after May 2006 was to be stored, as there was insufficient cooling time for that fuel to be reprocessed by 2012.[5] The new 2015 closure date for THORP suggests that more AGR fuel could be reprocessed.

Rail transports of Magnox fuel to the site have recently been greatly reduced from 621 tons in 2005/06 to 150 tons up to November 2007/08.[6] Because of receipt and reprocessing problems at Sellafield (see 'Magnox Reprocessing,' below), fuel that would normally be transported to Sellafield from closed stations under decommissioning is instead stored in-reactor on those sites.

III. Commercial Operations

Civil reprocessing has been the backbone of Sellafield's operations since the 1960's. Together with the more recent commercial production of MOX fuel, such operations account for the majority of all the NDA's commercial revenues. Despite their importance, data on plant performance is not always readily available directly from the operators for reasons of commercial confidentiality, and has to be gleaned from a number of sources. Contractual and financial information is even harder to come by for the same reason.

Reprocessing – Past, Present and Future

The first reprocessing plant (B204) opened in 1952 to extract plutonium from Windscale Pile fuel as part of the UK's weapons programme. Shut down in 1964, when the new Magnox reprocessing plant B205 was opened, the plant's head-end was re-opened in 1968 and adapted to dissolve oxide fuel, with the resultant liquor transferred for chemical separation to B205. With only some 60 tons of oxide fuel dissolved over the next five years, the head-end experiment was abandoned and the plant closed in 1973 following a major 'blow-back' accident. The experiment represented BNFL's sole experience in reprocessing oxide fuel prior to the opening of the Thermal Oxide Reprocessing Plant (THORP).

Magnox Fuel Reprocessing

The new Magnox plant (B205), with a nominal capacity of 1500 tons/yr, conducted both military and civil reprocessing campaigns, the former consisting of fuel from Sellafield's Calder Hall reactors and the sister reactors at Chapelcross in Scotland, and the latter fuel from the UK's other power stations and from Italy's Latina and Japan's Tokai Magnox reactors. Early year operation saw annual throughput exceeding 1000 tons regularly, but levels fell substantially in the mid 1990's – the result of the Government's 1995 decision to end military reprocessing and more frequent outages required for the ageing plant to be refurbished. (See Figure 4.)

Some 47,000 tons of Magnox spent fuel – a metal fuel comprised of natural uranium with traces of iron and aluminium contained within a magnesium-based cladding alloy – is estimated to have been reprocessed at Sellafield since operations began.[7]

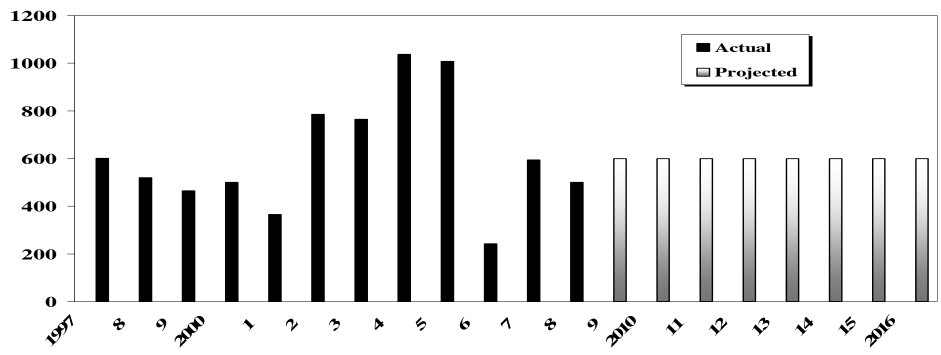


Figure 4. Magnox Reprocessing Throughput (tons per year)

Source: BNFL Sellafield Ltd and NDA

B205 remains Sellafield's most polluting plant in terms of environmental discharges. While the high discharge levels of the 60's and 70's have abated, their legacy remains in significant local concentrations of radioactivity (see 'Discharge' section below).

A 1998 directive of the Commission for the Protection of the Marine Environment of the North-east Atlantic requires 'progressive and substantial' discharge reductions.[8] The aim is to reduce discharges, emissions and losses of radioactive substances to levels where, by 2020, the additional concentrations in the marine environment above historic levels resulting from such discharges, emissions and losses are close to zero. The directive led to the subsequent BNFL announcement of B205's closure around 2012.[9] Based on BNFL's projected shut-down of all but two of the UK's Magnox power stations by 2010, and with 12,000 tons of fuel still to reprocess, B205 faced the target of reprocessing at least 1000 tons/yr to meet its 2012 closure date, a major challenge given the plant's age and recent performance.

The expected inability to meet the challenge was confirmed by the NDA in 2007.[10] Blaming plant problems and logistical difficulties in receiving fuel from those power stations under decommissioning, B205's life has now been extended to 2016 or later. With an estimated 6000 tons of fuel still to be reprocessed, the NDA expects B205 to operate at some 600 tons per year till 2016.[11]

In the event of an irreparable failure within the plant, alternative fuel management options have been considered. A principal but temporary contingency measure, already in use because of the logistical problems mentioned above, is the storage of fuel within shutdown reactors. Other options include:

- Reprocessing the metallic fuel through THORP;
- Developing dry fuel routes out of the reactors, constructing a packing facility and stores in which to store fuel on an interim basis in drums filled with inert gas; and

- For already wet fuel, which corrodes rapidly, building fuel packing facility and stores and encapsulating the fuel in concrete in drums.

These options, apart from in-reactor storage, would be time consuming and costly, however, and are unlikely to be implemented.[12]

THORP Oxide Reprocessing

In 1977, with the advent of the UK's new generation of AGR plants, BNFL's plans for a new Thermal Oxide Reprocessing Plant (THORP) were put to a Public Inquiry (the Windscale Inquiry). Expecting to capitalise on the then projected worldwide expansion of nuclear power, and to provide plutonium for fast breeder reactor programs, Government approval for THORP was given in 1978, by which time earlier negotiations with overseas customers had already been firmed up to full contract status.

Following much Parliamentary debate, construction of the spent-fuel storage ponds began in the 1980's to receive the already contracted overseas fuel. Construction of THORP was completed by 1992, by which time the cost had escalated from an estimated £300M ($600M) in 1978[13] to £2.3Bn ($4.6Bn).

THORP's contracts were of three types: pre-1976 at fixed price and pre-1976 at cost-plus, both with no waste return clause, amounting to some 1500 tons in total, and post-1976 at cost-plus with waste return, estimated at 4600 tons.[14] Payment by overseas customers for their post-1976 contracts is understood to be undertaken in three tranches – a capital fee of 60% of the total cost of contract while THORP was being built, and an operations fee of 25% of the balance on fuel delivery to Sellafield, with the remaining 75% of the balance upon the reprocessing of the fuel.[15]

This arrangement resulted in THORP's construction costs virtually being paid 'up-front' by overseas customers and with minimal use of loans or internally generated cash by BNFL. The arrangement, which included not only customers paying their share of construction costs but also storage fees, inflationary cost increases, decommissioning costs and the return of materials recovered by reprocessing, are described as being highly favourable to BNFL.[16]

After highly charged public consultations and legal challenges, approval to operate the plant was given in 1993 – even though by that time the original rationale for THORP had all but evaporated. No worldwide expansion of nuclear power had materialised, the fast breeder reactor programme was in limbo, stocks of natural uranium were more abundant, and customer support for reprocessing was already declining. Approval for THORP was based largely on its completed construction, a secured 10-year order-book and the jobs it would provide. THORP's future therefore depended on its 'recycling' performance and BNFL's ability to operate the complex plant to specification, and to win new business.

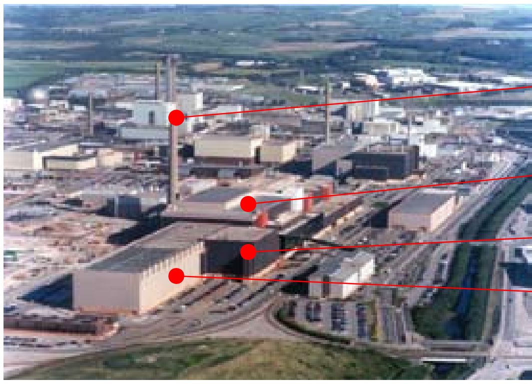


Figure 5. THORP *Source: BNFL*

With a design throughput of 1200 tons/yr and with base-load orders for 7000 tons secured – two-thirds from overseas – the first fuel (AGR) was sheared in March 1994. Describing THORP at the time as the jewel in Sellafield's crown, BNFL claimed the plant would make a financial profit of £500M ($1000M) over the base-load period. Table 1 shows THORP's base-load contract status as at 1994,[17] the post-base-load orders and the timescale in which the fuel was to be reprocessed.

German utilities, as THORP's sole overseas post-base-load customers had originally contracted 1500 tons for that period, but withdrew 550 tons within months of THORP's opening. The German post-base-load orders are understood to have been subsequently further reduced from the 787 tons to a little over 100 tons.

Customer	Fuel	Baseload	Post-Baseload	Baseload Schedule
		tons	tons	
United Kingdom	AGR	2158	2512	1994-2003
Japan	LWR	2673		1995-2003
Germany	LWR	969	787	1995-2003
Switzerland	LWR	422		1996-2003
Italy	LWR	143		2003
Spain	LWR	145		2002-2003
Sweden	LWR	140		2003
Nederlands	LWR	53		2002
Canada (research)	HWM	2		2003
Reserved		*295*		
Total		7000	**3299**	

Table 1. THORP's Baseload Customers

After a projected slow ramp-up period, THORP was to achieve 900 tons/yr in the sixth year of operation (1999) with fuel burn-up ranging from 3.1 to 24.0 GWd/MTU for AGR fuel, 7.4 to 28.8 for BWR fuel, and 16.9 to 40.0 for PWR fuel – with higher burn-up fuels reserved for later years of the base-load.[18]

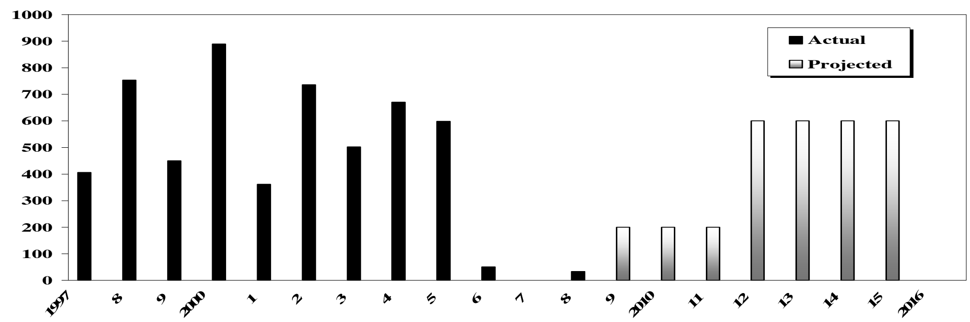


Figure 6. THORP Throughput, tons reprocessed at end of each financial year

Source: BNFL Sellafield Ltd and NDA

As can be seen in Figure 6, throughput has neither been reliable nor to specification – with just over 5000 tons completed during the first ten years of operation. Contributing to schedule slippage have been a range of equipment failures and accidents including acid spills, pipe leaks and blockages and problems with the plant's sole high-level waste evaporator. By the end of the official base-load period, with plant closure scheduled for 2010/11 "with all contracts completed,"[19] THORP was running some two years late. No new orders were secured and none are currently in the pipeline.[20]

Further delay was yet to come – in the form of a major accident in April 2005, which saw 22 tons of dissolved fuel and nitric acid (18,000 litres) leak from fractured pipe-work into the plant's Feed Clarification Cell over a 9-month period.

This accident has significant implications for the plant's future viability. After an almost 3-year closure and engineering modifications to the damaged Cell, within which the dissolved liquors are normally measured for volume and concentration of dissolved plutonium and uranium prior to transfer for chemical separation, THORP's schedule has slipped by at least 5 years and overseas customers face the prospect of their fuel now being reprocessed by around 2015 – some 11 years late. The new closure date reflects not only the extended accident closure but also a projected reduction in throughput.

BNFL's Board of Investigation into the accident pointed to human failure as the major contributory factor, with the workforce ignoring warning signals and alarms over many months. The Report also warned that "given Sellafield's history of such events there remained a significant chance of further plant failures occurring in the future."[21]

Whilst normal operations would see the use of two accountancy tanks in the Feed Clarification Cell, modifications enforced by the accident have resulted in just one accountancy tank being used in the future – the damaged tank and associated pipe-work being bypassed. This effectively reduces THORP's Head-End throughput from a nominal 7 tons/day to around 3 tons/day and ensures that the plant will never again operate as originally designed.[22] Other constraints that will further limit THORP's progress include:

- A cautious ramp-up after a 3-year closure;
- Planned outages – 5 identified for "significant plant maintenance and project activities"[23]
- Unscheduled stoppages;
- Reprocessing of "difficult fuels which pose particular challenges;"[24]
- Reprocessing overseas spent MOX fuel, requiring some plant configuration changes; and
- Lack of high-level waste evaporative capacity up to 2010.

Despite this prospect, and with just 5729 tons reprocessed at the time of the accident,[25] the Government and NDA remain committed to returning THORP to full operation in order to complete all existing contracts – estimated at around 3900 tons: 800 tons of overseas light-water reactor fuel[26] and 3100 tons of AGR fuel.

Completing overseas contracts is the principal driver behind THORP's re-start because of their revenue potential and, conversely, what are claimed to be significant financial penalties for contract cancellation. In the event of cancellation, the NDA has outlined the alternative options for overseas fuel management as:[27]

- Retaining overseas fuel in the UK and making alternative arrangements to discharge the contract conditions e.g. "virtual reprocessing" (see below);
- Return fuel to its country of origin; and
- Send fuel overseas for third-party reprocessing.

With fuel return and third-party reprocessing already all but ruled out on technical and logistical grounds, the retention of fuel at Sellafield with contract re-negotiation is the only realistic option in the event of THORP's irreparable breakdown.

For AGR fuel, the alternative is permanent storage rather than reprocessing. Reprocessing AGR fuel on its own (when not co-reprocessed with overseas fuel[28]) is uneconomic.[29] No financial benefit to the NDA is gained by reprocessing the fuel, payment being made for delivery to Sellafield only.[30] The original contacts for AGR fuel included a volume that was to be stored rather than reprocessed, and any fuel that remains un-reprocessed in the 5-year period prior to THORP's new closure date of 2015 will be added to that volume.

Regulatory consent for THORP's phased re-start was given in January 2007, and the reprocessing of a test batch of 33 tons of AGR fuel was completed 9 months later.[31] A second batch of AGR and overseas LWR fuel had to be abandoned in January 2008 with no fuel sheared, following the mechanical failure of the elevator system that lifts fuel from the spent-fuel Feed Pond into the Head End. With the elevator's wire ropes now replaced, processing the 100 tonne batch was re-started in March 2008.

The eventual return to full operation will be delayed over the next few years by the lack of high-level-waste evaporative capacity until a new evaporator comes on line in 2010, and further hampered by the restrictions listed above.

Despite this, the NDA projects a future annual throughput of some 600 tons. Time will tell whether THORP is able to meet what many consider to be an unnecessary and costly challenge. An interesting comparison can be made from Table 2 below which shows the throughput of the French UP2 and UP3 reprocessing plants at La Hague, both of which have a nominal annual capacity of 800 tons, and that of Sellafield's THORP plant, which has a nominal capacity of 1200 tons per year.[32] Both UP3 and THORP came on line in 1994, and UP2 in 1990.

	1994	1995	1996	1997	1998	1999	2000	Total
UP3	700	801	819	820	822	713	387	**5062**
UP2	259	758	850	850	775	849	810	**5151**
THORP	65	208	408	753	450	890	362	**3136**

Table 2. Throughput at THORP and La Hague

MOX Fuel Production and the Sellafield MOX Plant (SMP)

Between 1963 and 1988, a total of some 20 tons of MOX fuel was produced at Sellafield. This included 3 tons of LWR MOX and some 18 tons for the fast breeder programs. While Magnox-derived plutonium was used initially, plutonium recovered from the Protoype Fast Reactor at Dounreay in Scotland was later used as well.[33]

Production was subsequently put onto a more commercial footing in the site's MOX Demonstration Facility (MDF), a facility jointly owned by BNFL and Atomic Energy Authority Technology. Designed to produce PWR MOX fuel and using the BNFL-developed "short-binderless" approach to fuel pellet manufacture, MDF opened in 1993 with an annual production capacity of 8 tons/year. With no MOX use in UK reactors, orders were secured from Switzerland, Germany and Japan.

Over a six-year period (1994-1999) MDF produced a total of just 32 MOX fuel assemblies which, at about 500 kg per assembly, represents about 16 tons of fuel over the five-year period, far short of the MDF 8 tons/year nominal capacity. But worse was to come in what became MDF's last order, in the form of 4 MOX fuel assemblies for Japan's Takahama power plant. Dispatched by sea under armed escort to Japan in 1999, the consignment had barely reached its destination before it was revealed by a Sellafield whistle-blower that the Quality Assurance data accompanying the fuel had been falsified by bored night workers.

The MOX Falsification Scandal, as it became known, had severe repercussions for Sellafield, including the resignation of BNFL's Chief Executive, the sacking of workers, a halt to future business negotiations by Japan, and a £133M ($266M) compensation payment to the customer.

Closed down for inspection by the regulators following the incident, MDF was banned from further commercial production by the Nuclear Installations Inspectorate in 2001. The falsified Japanese MOX fuel was returned to Sellafield at UK expense in 2002 and today languishes in a Sellafield storage pond.

In parallel with MDF's opening in 1993, BNFL developed plans to construct the 120 tonne/year Sellafield MOX Plant SMP.[34]

Figure 7. Sellafield MOX Plant. SMP was completed in 1997 at a cost of £470M ($940M). Built adjacent to THORP, and with a design life of at least 20 years, SMP was designed to produce LWR fuel assemblies via the use of two parallel process lines with common powder receipt and fuel assembly areas. *Source: BNFL*

Constructed with the aim of achieving 'a balance between plutonium arisings in THORP and SMP's ability to turn it into fuel,'[35] SMP was designed to produce a wide range of PWR and BWR fuel at enrichments of up to 10% fissile plutonium.[36] Only PWR fuel has been produced to date in SMP at a plutonium concentration in uranium of around 5-6 percent.

As with THORP, a number of legal challenges and public consultations preceded SMP's opening. The final consultations focussed on BNFL's economic case for SMP – a case heavily dependent on securing MOX contracts with Japan. When the first plutonium was introduced into SMP in April 2002, no Japanese orders had been secured. Japan's utilities were still smarting from the MDF Falsification Scandal. Firm orders were limited to small European orders.

The Arthur D Little (ADL) consulting company undertook an assessment of the BNFL economic case for the U.K. Government, and its conclusions published in July 2001showed SMP to have a net positive value of £199M ($398) – with the first deliveries of MOX fuel to Europe scheduled for 2002.[37] SMP's £470M ($940M) construction costs were treated by ADL as "sunk costs" and were ignored in arriving at its value figure.

It was evident from the early days of plutonium commissioning that SMP was struggling to operate to design. As described in a subsequent 2006 ADL report for the NDA, SMP's production capacity had by that time been downgraded from 120 tons to 40 tons/yr.[38] Beset by operational difficulties, the plant's operators have not yet been able to demonstrate to the NDA that the plant will be able to sustain continuous operation at the level needed to meet customer requirements.

The report noted that production had fallen further behind schedule through recurring problems with plant operability. Pointing to equipment breakdowns and flow bottlenecks, ADL stated that with a potential throughput of "only a few tons of plutonium per year at best," and with "the prospect of fully automatic operation now only a remote possibility" – SMP's net value had seriously eroded.

Licensed by the U.K. Government[39] to fabricate MOX fuel from plutonium "separated from foreign customers spent fuel in THORP and which belongs to them,"[40] no MOX pellets, rods or assemblies were produced until 2004.[41] The delay led to a number of orders being sub-contracted to fabricators in Belgium and France and the first four assemblies completed in SMP were finally delivered to Switzerland in June 2005 – more than three years after the first plutonium was introduced into the plant.

Further deliveries of 4 assemblies were made in 2006 and 2007. The true level of this underperformance can best be gauged by comparison with the NDA's forecast that 145 assemblies would be built in the fiscal years 2005/06 and 2007/08.[42] Government figures show that, after failing to produce any fuel in its first two years of operation (2002/03-2003/04) SMP produced 0.3 tons in 2004/05, 2.3 tons in 2005/06 and 2.6 tons in 2006/07[43] – a poor performance for a 120 tonne/yr capacity plant, even allowing for the planned cautious ramp-up to full operation.

Despite starting a new campaign of powder and pellet production for a German customer twelve months ago, following the completion of the Swiss order in 2006, no finished MOX fuel assembly had been completed for that customer by March 2008. Citing a bottleneck in SMP's fuel rod production section, plant operator Sellafield Ltd has admitted a further falling behind of overall production.

Deliveries of MOX fuel assemblies for European customers are made by road from Sellafield to local docks under armed police escort and loaded onto the NDA ship *Atlantic Osprey* which carries an armed escort.

Figure 8. Transport of MOX Fuel Assemblies *Source: CORE archive*

In addition to SMP's production problems, changes have now had to be made to its licensing arrangement, which permitted only overseas plutonium recovered in THORP to be used for fuel fabrication. The lack of sufficient stocks of overseas plutonium recovered in THORP to feed even SMP's limited requirements resulted in an NDA proposal to use UK-owned plutonium instead.

Under a system of Advance Allocation, plutonium from the UK stockpile is made available "where appropriate" to overseas customers in lieu of the plutonium still to be recovered from their un-reprocessed fuel. Customer ownership of the spent fuel and UK ownership of the plutonium would be swapped, with the UK taking permanent responsibility for the fuel with the customers receiving equivalent quantities of plutonium from the UK stockpile. A limited public consultation took place in June 2007.[44] Government approval was given five months later.[45]

The arrangement, deemed by the NDA to be a temporary measure until THORP re-opens, is considered by many to represent "virtual reprocessing" whereby no actual reprocessing takes place but the products required to be returned to customers under are drawn from existing stockpiles. If fully employed, this option could fulfil all outstanding overseas contracts through the use of UK stockpile materials and with no need to re-start THORP.

SMP was supposed to operate in tandem with THORP, obviating the need for overseas plutonium to be exported in any form other than in MOX fuel. The plant's poor performance has resulted, however, in a number of MOX orders having to be sub-contracted to French and Belgian fabricators. As outlined in a BNFL brochure, the plutonium used by the European fabricators in fulfilling the sub-contracted business must be replaced by plutonium from Sellafield stocks.[46] A February 2008 license approval secured by France's AREVA to receive plutonium dioxide from Sellafield indicated that a transport of plutonium dioxide from Sellafield to France was expected shortly.[47]

IV. Products of Reprocessing

Plutonium

The UK's plutonium stocks have almost doubled since 1997[48] and, as the Table below shows, now stand at 100+ tons. The material is considered to be an asset of "zero value"[49] and its potential status as either a waste product or a future energy asset currently remains unresolved. The most recent published information on stocks is shown below.[50]

Plutonium Stocks at 31/12/06 (tons)	2006	2005
1. Unirradiated separated plutonium in	102.9	101.1
product stores at reprocessing plants.		
2. Unirradiated separated plutonium in the	1.2	1.2
course of fabrication.		
3. Plutonium contained in unirradiated MOX fuel.	1.9	2.0
4. Unirradiated separated plutonium held elsewhere.	1.0	1.0
Plutonium included in **1-4** above and belonging to foreign bodies.	26.5	26.5

Table 3. UK Plutonium Stocks at end of years 2005 and 2006

If all current reprocessing contracts are completed, the stockpile is estimated to increase to 133 tons, of which some 100 tons will be UK derived and 33 tons from foreign fuel. Included in the current UK civil stockpile is an estimated 4.4 tons of military origin plutonium, a majority of which remains under Ministry of Defence ownership either in weapons or in reserve stocks.[51] The military component is unlikely to increase as the Magnox military plutonium-production reactors (Calder Hall and Chapelcross) have closed.

All plutonium from foreign spent fuel is to be returned to overseas customers in the form of MOX fuel. Not all of the projected 33 tonne total has yet been contracted for MOX-fuel production. Indeed, not all overseas spent fuel has been reprocessed. With some overseas customers having no plans to burn MOX fuel in their reactors (Spain, Italy and the Netherlands), alternative arrangements for their plutonium are currently under assessment, including the possibility of "third party" use.

Magnox-derived plutonium dioxide is stored in aluminium inner cans, each holding about 5.5 kg of plutonium. THORP-derived plutonium dioxide is stored in steel triple packs, each containing about 7.5 kg of plutonium. The packaged material is currently stored at Sellafield in stores purpose-built for Magnox derived plutonium, and in the THORP plutonium product store which doubles as a buffer store for feeding the SMP. Plutonium management is subject to international safeguards administered by Euratom and – for Japanese plutonium – the IAEA.[52]

Given regulatory concerns on the ageing of existing stores and the risks presented by some of the materials therein,[53] plans were laid for a replacement facility and a new store. The Sellafield Product & Residues Store with a design life of 50 years extendable to 100 years is currently under construction. With a nominal design capacity of some 9600 plutonium canisters it will receive plutonium from the reprocessing plants and from SMP, and provide replacement storage for the older stores.

The use of MOX fuel in Magnox reactors is precluded because of the imminent closure of the stations, and in British Energy's AGR stations because of the lengthy reactor modifications that would be required as well as safety reviews and a possible public inquiry. The use of MOX fuel in the UK's single PWR power reactor at Sizewell (capable of a 30% MOX loading) is also ruled out on economic grounds by its owners, British Energy. Though there are therefore no plans to use MOX fuel in the UK's current reactors, the possibility of building a MOX burning reactor at Sellafield as a means of reducing the site's plutonium stockpile is one of a number of options being assessed.

Other alternative management options for plutonium are being considered on the basis that long-term storage is politically unattractive because of risk of theft. The principal scenarios currently under review include:

- Immobilisation as waste – the stockpile (excluding overseas plutonium) declared as waste and conditioned for geological disposal using techniques of cementation, vitrification, ceramification or low-spec MOX;[54]
- Part Immobilisation – some of the stockpile converted (using techniques above) to a stable form that would not discount future recycling options, the remainder immobilised as waste; and
- High-spec MOX – the stockpile converted to MOX fuel. This would utilise an estimated 95% of the stockpile (5% deemed unsuitable because of chemical contamination). This option is only considered viable with the construction of new reactors.

With no timescale set for decisions to be taken on the fate of UK stockpile, the main recommendation of the recent Royal Society report is that Government develop and implement a management strategy for the stockpile as an integral part of its energy and radioactive waste policies. Among the immediate priorities suggested are:[55]

- No further separation of plutonium once current contracts are completed;
- All weapon-grade plutonium transferred to the civil stockpile should be blended down to limit the effects of theft; and
- Fabrication capacity at SMP must be increased to convert the stockpile to less easily dispersed MOX fuel pellets.

Uranium

As with the UK's plutonium stockpile, its stocks of uranium in various forms are either assets or liabilities, depending on the market price of uranium and the relative costs of treating it as a waste, of storing it or of processing to bring the material to market. The current stockpile is shown in Table 4.[56]

Uranium Stocks as of December 31 (tons)		2006	2005
Total civil depleted, natural and low enriched uranium in the civil nuclear fuel cycle (tons).		93,000	86,400
includes components:	i) tails uranium hexaflouride	25,000	
	ii) Magnox depleted uranium	30,000	
	iii) THORP product uranium	5,000	
Total HEU (20% enrichment or more) at civil reactor sites, enrichment & fabrication plant etc.		1441 kg	1490 kg

Table 4. UK Uranium Stocks at end of years 2005 and 2006

In addition to the current civil HEU stocks, in 2006, the UK reported that it possessed 21.9 tons of military HEU,[57] much assumed to be in spent submarine fuel. There were an estimated 50 spent submarine cores in pond storage at Sellafield at that time; the number of cores was projected to increase to some 90 cores by 2020 containing around 8.5 tons HEU.[58]

The uranium product recovered by reprocessing Magnox spent fuel is stored in drums, each holding about 800 kg of oxide. Drums are stored at Sellafield and at Capenhurst in Cheshire. THORP uranium product is stored in drums, each containing about 180 kg of oxide. Over 550 tons of THORP product uranium, in the form of uranium trioxide, has been transported to Russia since 2000 on behalf of overseas customers for further processing and fuel fabrication, with transports scheduled to continue well into the next decade.[59]

V. Nuclear Waste Management at Sellafield

A majority of all UK waste is held at Sellafield in a number of wet and dry facilities and comprises wastes of all levels. Sellafield-held wastes have arisen from reprocessing operations on the site since the early 1950's from both military and civil programmes.

Table 5 below shows the volume in cubic meters of all those unconditioned wastes currently held at Sellafield and those projected to arise between 2005/06 and 2119/20.[60] The intermediate-level waste (ILW) and low-level waste (LLW) volumes include contaminated land at Sellafield.

Sellafield	HLW	ILW	LLW
Total lifetime waste arisings	1380	101,800	1,800,000

Table 5. Radioactive Wastes at Sellafield (in cubic meters)

High Level Waste (HLW)

The majority of Sellafield's heat-generating HLW is in liquid form held in cooling tanks within the site's HLW complex. The complex consists of 21 numbered stainless steel tanks, commissioned between 1955 and 1990. All tanks are designated to receive the highly active liquors (HAL) from either magnox or oxide reprocessing, and employ a 'one-in-four' spares policy. Current HAL arisings are now routed to the newer tanks, with older tanks being taken out of commission.

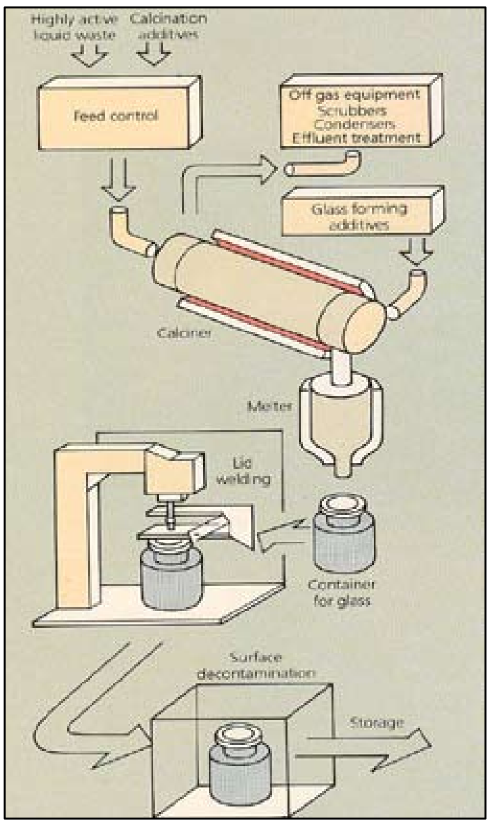
As cooling tank coil failures increased and concern mounted over the system's vulnerability to an accidental release of tank inventories and to acts of terrorism, regulatory pressure was applied to BNFL to reduce stocks of liquid HLW. In 2001, with a stock level of some 1570 cubic meters, the Health and Safety Executive's Nuclear Installation's Inspectorate (HSE/NII) issued a Specification (a legal requirement) that formalised the reduction programme, capped the total volume that could be held and required annual reductions to a buffer level of 200 cubic meters by 2015. In 2007, with stocks standing at 1225 cubic meters, a revised Specification was issued.

With vitrification as the sole option for converting the liquid HLW to a passively safe form, meeting the Specification is wholly dependent on the performance of Sellafield's Windscale Vitrification Plant (WVP), as is the return of vitrified product to overseas customers on time.

Vitrification

Based on a French process, the WVP began operation in 1991 with two production lines that were projected to produce between them 600 containers of vitrified product per year.[61] The process involves HAL being evaporated and dried in a calciner and the resultant dry powder mixed with a glass matrix. Heated at around 1150 degrees C, the molten product is poured into the stainless steel containers, each holding some 360 kg of a product mix containing varying 'blends' of oxide and magnox HAL.[62] On average, two WVP product containers are produced from 1 cubic meter of HAL.[63]

Since operations began, both lines have been plagued with a range of technical problems – principally the failure of the melter crucibles due to thermal shock and their frequent and time-consuming replacement, and pipe blockages between WVP's transfer tanks and the lines. The flow-sheet below shows the process. From the accompanying production figures, it can be seen that the 600 cans per year target from 2 lines has been missed by a wide margin. The failure of the plant to keep pace with the constant feed of HAL from both Magnox and THORP reprocessing resulted in the opening of a third vitrification line in 2002.



WVP Production Rate

Year	Containers
90/91	45
91/92	114
92/93	113
93/94	267
94/95	332
95/96	216
96/97	246
97/98	336
98/99	328
99/00	152
00/01	131
01/02	120
02/03	333*
03/04	341*
04/05	478*
05/06	482*
06/07	322*
07/08	400* (target)

* *from 3 production lines*

Figure 9. Windscale Vitrification Plant *Source: BNFL*

Following the HSE/NII's 2001 Specification, BNFL was warned that, in order to keep HLW volumes within the Specification, the regulators would not hesitate to use their powers to stop THORP operations.[64] WVP's poor performance has already resulted in several temporary closures of THORP and necessitated vitrification assistance from French rivals at La Hague.

Vitrified product containers are placed in Sellafield's Vitrified Product Store. The store, which can hold up to 7960 containers in four vaults, is expected to be full by 2013.[65] With some 9000 containers expected to be produced over the lifetime of existing reprocessing contracts, the return of HLW containers to overseas customers is becoming a priority. The first overseas return (to Japan), already re-scheduled numerous times from the 1990's, is now due to take place later in 2008. Shipments to all overseas customers are scheduled to continue until 2016/17 (see Table 6).

HLW – Waste Substitution

All post-1976 overseas reprocessing contracts include the option for all wastes to be returned. The retention in the UK of overseas low-level waste (LLW) was approved by the Government, however, in 1995.[66] Approval for the retention of foreign intermediate-level waste (ILW) was linked to the availability of a UK waste repository, but the failure to site the anticipated repository led to a Government decision in 2002 to de-link the retention of overseas ILW from the availability of a repository. Admitting the expected high cost and logistical complexity of returning overseas ILW stocks, a proposal for "waste substitution" was put to public consultation in 2004.[67]

Subsequent Government approval "in principle" for the substitution proposal will result in all overseas ILW being retained in the UK and only the vitrified HLW being returned together with an additional volume of HLW which, in total, would contain the radiological equivalence of the overseas wastes retained in the UK. The principal benefits of the proposal are claimed to be its environmental neutrality, the reduction in numbers of transports (see Table 6 below[68]) and the revenue to the UK from managing the retained overseas wastes.

Destination	Type of Waste	With Substitution	No Substitution
Europe	HLW	8	7
Europe	ILW	0	50
Japan	HLW	11	10
Japan	ILW	0	23

Table 6. Number of Overseas Waste Transports

Intermediate Level Wastes (ILW)

Unlike HLW, ILW is defined as waste not requiring its heat-generating capacity to be taken into account in the design of storage or disposal facilities.[69] Sellafield's ILW comprises fuel-element cladding and assembly fittings, maintenance scrap and spent fuel storage equipment, slurries and flocs from liquid effluent treatment. It also includes plutonium-contaminated material.

Stocks of Sellafield ILW were estimated at 57,500 cubic meters in 2004,[70] a large proportion of which were unconditioned. They account for approximately 73 percent of the UK's total ILW volume,[71] and are conditioned by encapsulation in a cement-based material within 500 liter drums. The drums are stored on site in a series of Encapsulated Product Stores.

Providing the policy of waste substitution is enacted, some 5,000 cubic meters of overseas ILW[72] will be retained along with UK stocks at Sellafield, and will be stored on site for at least the next four or five decades – the earliest the country's underground repository is expected to be built and operational.

Plutonium Contaminated Material (PCM)

Smaller items are wrapped and placed in mild steel drums. Larger items, such as glove-boxes are sealed in crates before being placed in storage. Sellafield's Waste Treatment Complex is designed to assay the plutonium contaminated material and then compact and encapsulate it in a cement grout within 200 litre stainless steel drums. Tens of thousands of such drums are stored in a series of Engineered Drum Stores pending the availability of a UK repository.

Low Level Wastes (LLW)

LLW from Sellafield accounts for around 71% of total UK holdings of radioactive waste, measured by volume.[73] It is transported, largely by rail, to the UK's national LLW repository near the village of Drigg six miles south of Sellafield. Owned by the NDA and operated under contract by UK Nuclear Waste Management Ltd (UKNWM) – a consortium led by URS Corporation – Washington Division, the facility was opened in 1959 and also receives LLW from other nuclear sites and from small users including medical and research wastes. From 1959 to 1995, an estimated 800,000 cubic meters of LLW was disposed by 'tumble-tipping' into clay lined open trenches that were subsequently capped.[74] Following Government recommendations in 1986, tumble-tipping was gradually abandoned, and a concrete–lined Vault (Vault 8) came into operation in 1988.

Plutonium contaminated wastes (now classified as ILW) were also disposed of in the 1960's in ten former World War II munitions magazines that are now being emptied and demolished to make way for a second LLW Vault. The current Vault 8, with a LLW storage capacity of 200,000 cubic meters and with current spare capacity of 28,000 cubic meters – equivalent to around 1000 further containers – is expected to be full in 2008.[75]

Prior to its transfer from Sellafield to the LLW repository, wastes are consigned either to 200-liter sacrificial drums or 1-cubic-meter sacrificial boxes for super-compaction in the Waste Monitoring and Compaction Plant to reduce volume. The resulting "pucks" are placed in half-height intermodal shipping containers and grouted. Non-compactable waste is also routed for grouting in the containers and large items consigned separately and grouted as discrete items in Vault 8.

Local Authority planning permission has been granted for the construction of the new Vault 9 with a capacity of some 110,000 cubic meters (5500 containers).[76] Newly appointed contractors UKNWM believe the site's operational life can be extended by a further 20 years, taking its closure date to around 2070, when a new UK site will have to be located.

VI. Clean-up and Decommissioning

The Nuclear Decommissioning Authority (NDA) took ownership of Sellafield and other nuclear sites in the UK in April 2005, charged with the specific remit "to ensure the nuclear legacy is cleaned up safely, securely, cost-effectively and in ways which protect the environment for the benefit of current and future generations."[77] Heralded as promoting a step-change from "business as usual" on nuclear sites to clean-up and decommissioning, the NDA was widely welcomed as a provider of the long overdue remediation of nuclear industry sites throughout the UK.

Despite the extent and complexity of its original remit, the NDA has subsequently been charged with overseeing the disposal of UK's nuclear wastes in an underground repository and, as owner of a number of nuclear licensed sites, has become involved in UK Government plans to build new reactors in the UK. Its support for continued reprocessing at Sellafield as a source of revenue is hard to reconcile with its clean up remit given reprocessing's capacity to produce wastes and its polluting effect on the environment. Similarly, the NDA's involvement as both waste producer and waste disposer is seen to be in direct conflict with the international principle of total independence between producers and disposers.

The NDA's income is sourced from a mix of grant-in-aid from its sponsoring Government Department – now the Department of Business, Enterprise and Regulatory Reform (DBERR) – and monies generated from commercial activities including reprocessing, MOX fuel production, nuclear-material transport and electricity generation from the UK's two remaining Magnox power stations. Expenditure is divided between all sites on a basis of hazard prioritisation based on three factors:[78]

- The hazard level of the stored materials;
- The age and condition of the facility in which the material is stored and how well the behaviour of the material is understood; and
- The ongoing environmental effects of the facility or inventory if no action is taken.

Priorities

The NDA's 'number one' clean-up priority is defined as decommissioning and cleaning up the higher-hazard facilities at Sellafield and Dounreay[79] to bring about the hazard reduction needed to make these sites safe for future generations.[80]

At Sellafield, the priority is focused primarily on what are described as the Legacy Ponds and Silos, each providing individual remediation challenges in terms of activity levels, chemical behaviour and sludge materials. The key facilities are the Pile Fuel Storage Pond, the Magnox Fuel Storage Pond, the Magnox Cladding Wet Storage Silos, and the Dry Storage Silos.

The Pile Fuel Storage Pond – an open pond built between 1948 and 1952 – was used for storing the de-canned fuel elements from the Windscale Pile reactors and the swarf from the fuel's outer casing. Used as an ad hoc waste store in 1962, operations in the pond ceased in the early 1970's.

The inventory now consists of sludges from corroded swarf, small quantities of fuel, and redundant equipment. The pond contains a significant proportion of biologically derived material such as guano, algae and wind-blown debris.

The Magnox Fuel Storage Pond, which operated from 1959 to 1985, was used for the storage of fuel prior to reprocessing – with the fuel's de-canning taking place in the pond. Today's inventory consists of quantities of degraded magnox fuel, other "Miscellaneous Beta-Gamma Wastes" (MBGW) sludges from corroded Magnox cladding ("swarf"), and the old decanning equipment itself. Numbered as building B30 (and referred to by those who worked in it as the "dirty thirty") radiation levels within the facility are such that working time is limited to less than one hour per day, and in one area to two to three minutes.

Radiation levels and poor water clarity have made the provision of a comprehensive pond inventory impossible, though it is estimated to include some 1.3 tons of plutonium, 400 kg of which is contained in corroded fuel lying on the bottom of the pond as sludge. BNFL's inability to provide inventory detail led to an infringement of a 2004 European Commission requirement in 2004 that directed BNFL ensure that Euratom inspectors had full access to the material to check its nature and quantity.[81]

Figure 10. Magnox Fuel Storage Pond *Source: BNFL*

The Magnox Cladding Wet Storage Silos are comprised of four adjacent concrete silos, the first of which began operation in 1964, and the last in 1983. Used primarily for the underwater storage of magnox cladding swarf arising from the removal of the fuel's outer casing prior to reprocessing, waste emplacement in the silos ceased in 2000.

The Dry Storage Silo operated from 1952 to 1964 and the inventory includes aluminium swarf, Windscale Pile reactor fuel, swarf from magnox fuel, graphite and other MBGW.

While the above Legacy Ponds are prioritised in terms of hazard reduction at Sellafield, the NDA is also focusing currently on isolating redundant pipework and plant systems to reduce hazard, and on reducing stocks of high activity liquors in the HLW tanks.[82]

The Cost of Cleanup

In 2002, the total cost of cleaning up all sites now owned by the NDA was put at £48Bn ($96Bn)[83] of which Sellafield accounted for £27.5Bn ($55Bn).[84] The latest estimate shows the total liability costs for all NDA sites to have risen to an estimated £73Bn ($146Bn) at 2007 prices, with Sellafield costs now put at £46.3Bn ($92Bn).[85] Further increases are expected. The distribution of these costs between sites is shown below:

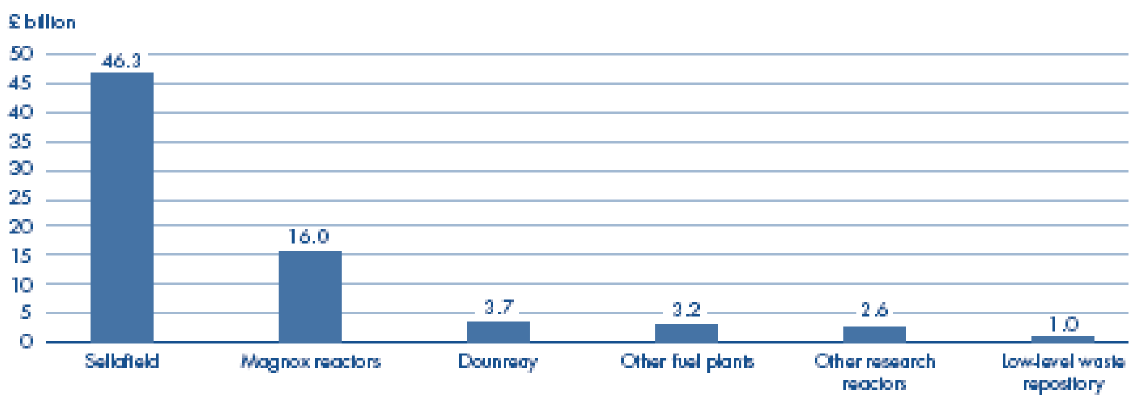


Figure 11. Total Decommissioning Liability Costs. *Source: National Audit Office Report, January 2008*

The expenditures and income for Sellafield since 2005, when the NDA took ownership of the site, are shown in Table 7 which follows, along with NDA's total budget for all sites for each year.[86] It can be seen that expenditure at Sellafield annually accounts for almost 50 percent of the entire NDA budget for all sites. Further, despite the arrival of the NDA in 2005 and the step-change from business as usual to decommissioning and cleanup, the costs of commercial operations on the site heavily outweigh those expended on decommissioning and cleanup programs.

Year	All sites Total Budget[a]	Sellafield			
		Expenditures[b]		Total Expenditure	Total Income[c]
		Commercial	Decommissioning		
	£Bn ($Bn)	£M ($M)	£M ($M)	£M ($M)	£M ($M)
2005/06	2.20 (4.40)	727.4 (1454.8)	290.5 (581.0)	1017.9 (2035.8)	771.8 (1543.6)
2006/07	2.20 (4.40)	901.7 (1893.4)	300.5 (601.0)	1202.2 (2404.4)	807.0 (1614.0)[d]
2007/08	2.47 (4.94)	865.2 (1730.4)	305.0 (710.0)	1170.2 (2340.4)	979.0 (1958.0)[e]

Table 7. Costs of Operation and Decommissioning at Sellafield.

Notes: a. Consists of Government grant-in-aid payment and commercial operations revenue
b. Includes both capital and labour costs.
c. Income includes projected revenue from reprocessing, transports, MOX fabrication
d. A shortfall of £112M ($224M) from THORP and SMP was subsequently recorded for the year
e. The projected income includes anticipated overseas customer "waste substitution"

While the NDA's total annual budget for all sites has remained relatively static, expenditures at Sellafield have risen since 2005/06 – a rise attributed largely to a "better understanding" by the NDA after three years in office.

The rise has resulted in some programmes at lower-hazard sites being put on hold or delayed. Defuelling programmes, for example, at those Magnox power stations under decommissioning, have had to be put back, and Calder Hall fuel is to be stored in-reactor until 2012. The resultant delays to transporting fuel from these stations to Sellafield for reprocessing has necessitated a life extension of at least four years to the site's Magnox reprocessing plant. An added impediment for the NDA is the uncertainty of the annual revenue from commercial operations, particularly THORP reprocessing and MOX fuel production, whose facilities are described as "ageing and unreliable."[87]

Sellafield Site End-State

Most of the NDA's other 19 sites are expected to be cleared of existing facilities and the land decontaminated in around 80 years time.[88] Sellafield's commercial facilities are scheduled to have ceased operation by around 2020.[89] Clearance of the site is expected to be completed by 2120,[90] but parts of the site are likely to remain under indefinite institutional control in the form of licenses and management controls imposed by institutions not yet defined at this time. The current end-state plan for Sellafield takes no account of the possibility of new reactors being built on the site or of the construction of a new reprocessing or MOX plant.

Planning the programme of work required to achieve end-state status falls within the NDA's portfolio. As such, ongoing reviews are conducted by the NDA to see whether timescales can be reduced or opportunities provided to reduce costs or deliver other benefits. Reviews of the end-state process will be carried out every 5 years through public consultation involving the Sellafield Site Stakeholder Group, the Regulators, Site Licence Companies and others. The current process envisages the site split into 5 zones, each of which is tested against a range of management options. No preferred option for the site has yet been selected.

One major constraint to the site's end-state is the uncertainty about the volumes of contaminated soil that will need moving. Present estimates suggest a total of some 20 million cubic meters (LLW and VLLW) – some likely to be at a depth of 30 metres.[91] LLW volumes from decommissioning work also include significant tonnages of concrete, asbestos, lead, ferrous metals, combustible materials and lesser volumes of oil and mercury.

VII. Nuclear Waste Disposal

After a series of failed attempts over three decades to locate a permanent disposal facility for the UK's nuclear waste, a concerted programme was launched in 1987 by the newly formed Nuclear Industry Radioactive Waste Executive (NIREX), a body owned by and acting on behalf of the UK nuclear industry and tasked with finding a 'deep disposal facility' for ILW and LLW. The NIREX remit did not include HLW which was to be stored for at least 50 years at Sellafield. From an initial list of 537 potential sites within the UK and subsequently from a shortlist of 12 sites, a site in the Sellafield area was finally selected. With the exception of Sellafield and the second preference at Dounreay in Scotland, the location of all other sites was kept secret and only publicly divulged in 2005.

Following a comprehensive programme of surface investigation and borehole drilling, an application to construct a facility between the Sellafield site and the adjacent boundary of the Lake District National Park was rejected at a Public Inquiry by the Inquiry's lead inspector in 1996 on the grounds that it was unsuitable in terms of the complex nature of its heavily faulted volcanic rock, its groundwater flow and a flawed site selection process. This major set-back to the industry's preferred option of deep disposal effectively 'wiped the slate clean' and required a completely new approach to waste disposal to be adopted by the UK and resulted in the formation of a new body the Committee on Radioactive Waste Management (CoRWM) in 2003. The defunct NIREX is now subsumed into the NDA as part of its new Radioactive Waste Management Directorate.[92]

CoRWM, as an advisory body, was charged with establishing an inventory of UK radioactive wastes and materials and an option or combination of options that would provide a long-term solution for the disposal of HLW and ILW (LLW and site selection were not within the remit). After wide-ranging public consultation, the inventory was completed in 2005 and an options list in mid-2006. The preferred option was identified as:[93]

- In the long-term, disposal of waste deep underground –"geological disposal;"
- Robust interim storage, given the several decades necessary to implement geological disposal;
- An equal partnership between government and potential host communities based on a willingness to participate; and
- The immediate creation of an oversight body to begin the process of implementation.

The key elements of this "fresh start" by CoRWM and its advice to Government that deep geological disposal offered the best option for waste disposal, include the new concept (for the UK) of the need for wide public acceptance of and involvement in any disposal plans through a system of volunteerism whereby communities would offer their respective areas as host to the repository in return for a substantial package of financial support from Government. Whilst the official call for such volunteers has not yet been made, Sellafield's local authority Copeland Borough Council has expressed strong interest despite the 1996 rejection of the local geology. Opponents of the proposal, who see the support packages as little more than bribery, consider it premature to call for volunteers before their prospective host geology has been shown suitable for deep disposal.

Taking account of the uncertainties as to whether some nuclear materials – specifically spent fuel, plutonium and uranium – may eventually be classified as wastes, CoRWM's Baseline Inventory, measured in eventual projected volume and radioactivity around year 2120, is shown below:[94]

Type	Packaged volume (cubic metres)	Radioactivity (terabecquerels)
HLW	1290	39,000,000
ILW	353,000	2,400,000
LLW (non-Drigg)	37,200	<100
Plutonium	3270	4,000,000
Uranium	74,950	3000
Spent nuclear fuel	8150	33,000,000
Total	477,860	78,000,000

Table 8. Baseline Radioactive-Waste Inventory in 2120

Source: Committee on Radioactive Waste Management

CoRWM has also projected the likely increase to the above volumes resulting from a programme of new reactor build in the UK. Based on the operation of ten AP1000 reactors and assuming no reprocessing and all plutonium and uranium incorporated into MOX fuel, the ILW volume would increase to 508,650 cubic meters (2.5% increase), spent fuel to 40,000 cubic meters (400%) and the overall radioactivity to 207 million terabecquerels (265%).

In October 2006, the Government accepted CoRWM's recommendations, and committed to a reconstituted CoRWM that would carry out the planning and development of the geological disposal option through volunteer communities, geological investigation in those areas and eventual site selection. The reconstituted CoRWM was appointed in October 2007. Stages of the future process are tabled below.[95]

Stage	Time	Period (years)	Main activities
1-4	2006-2016	10	Establish organisations and screening criteria, partnerships and packages
5	2016-2035	19	Site investigation and selection
6	2035-2045	10	Planning permission for repository and construction
7	2045-2110	65	Emplacement (assumes co-disposal)
8	2110-2120	10	Closure

Table 9. Stages of Repository Development

VIII. Radioactive Discharges

A major component of Sellafield's legacy is due to the daily discharges of radioactive gases and liquids released to the air and the sea. The liquid effluent is discharged at a rate of some 2 million gallons per day. While the industry can rightly claim that today's discharges are a fraction of those of the first three decades of Sellafield's operations, those historic releases included numerous long-lived materials including plutonium-239 with its radioactive half-life of 24,400 years.

The topic of Sellafield's discharges covers a spectrum of issues too wide and detailed for this report, and an overview summarising the current position is therefore provided. While the effects of the site's discharges are most severe in the immediate locality, their impact stretches far afield. For example, Sellafield's discharges of krypton-85 from both reprocessing plants, released at around 100,000 TBq annually (with THORP contributing a significant majority of the discharge) are monitored in Miami. Similarly technetium-99 has been found at high levels in lobster in Norway's pristine fishing grounds,[96] and other materials detected in Arctic waters around Greenland and the northern coast of Canada.[97]

For the U.K., the Environment Agency describes the Sellafield reprocessing plant as the main source of liquid radioactive discharges to the environment. Historic radioactivity from Sellafield can be detected around most of the coastal area of the U.K.[98]

With the help of mother nature in the form of the weather elements, it is unsurprising that discharged plutonium and other radioactive materials find their way back to dry land where they can be found, for example in house-dust along the coastline and further inland, and in children's teeth where concentrations are strongly correlated with distance in miles from the Sellafield site.[99]

Despite the overall 100-fold reduction in releases, radiation dose rates to local community residents (seafood eaters) have, in some cases, increased by 75% since 2000 – a reflection of greater seafood consumption rather than an increase in concentrations of radioactivity in seafood, but nevertheless a warning that reduced discharges do not necessarily result in lower doses to humans.[100] Similarly, while overall discharges have decreased (partly due to recent reprocessing inactivity) some individual elements show recent annual increases.

A case in point is the presence of Americium-241 in local sediments. It emits alpha and gamma radiation and has a radioactive half-life of 458 years. Its increase, as a decay product of Plutonium-241 (13 year half life) already discharged, is also blamed on its remobilisation in the marine environment. The plot below shows the reduction in Americium-241 discharges and its increasing presence in West Cumbrian sediments around Sellafield.[101]

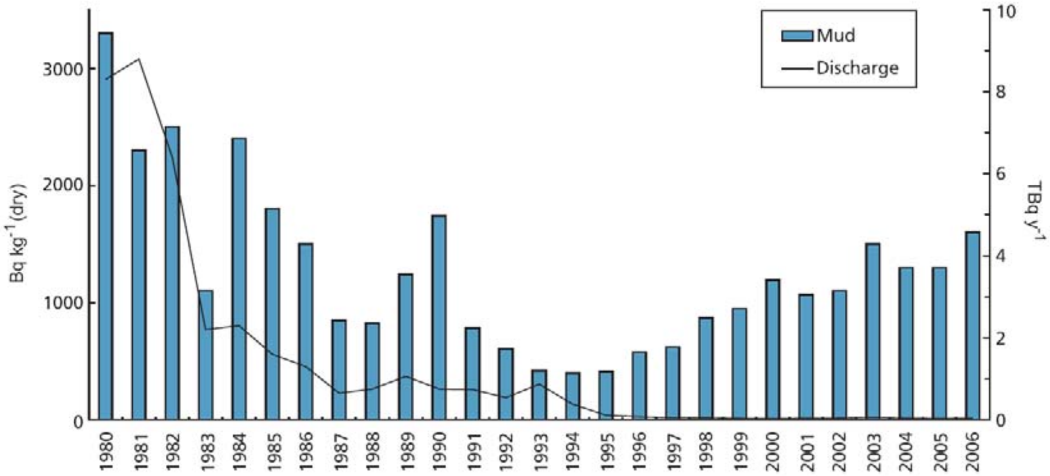


Figure 12. Americium-241 in West Cumbrian Sediments

Source: UK Environment Agency

The persistence nature of two long-lived radionuclides in the environment,[102] especially plutonium, is shown in the graph below.[103]

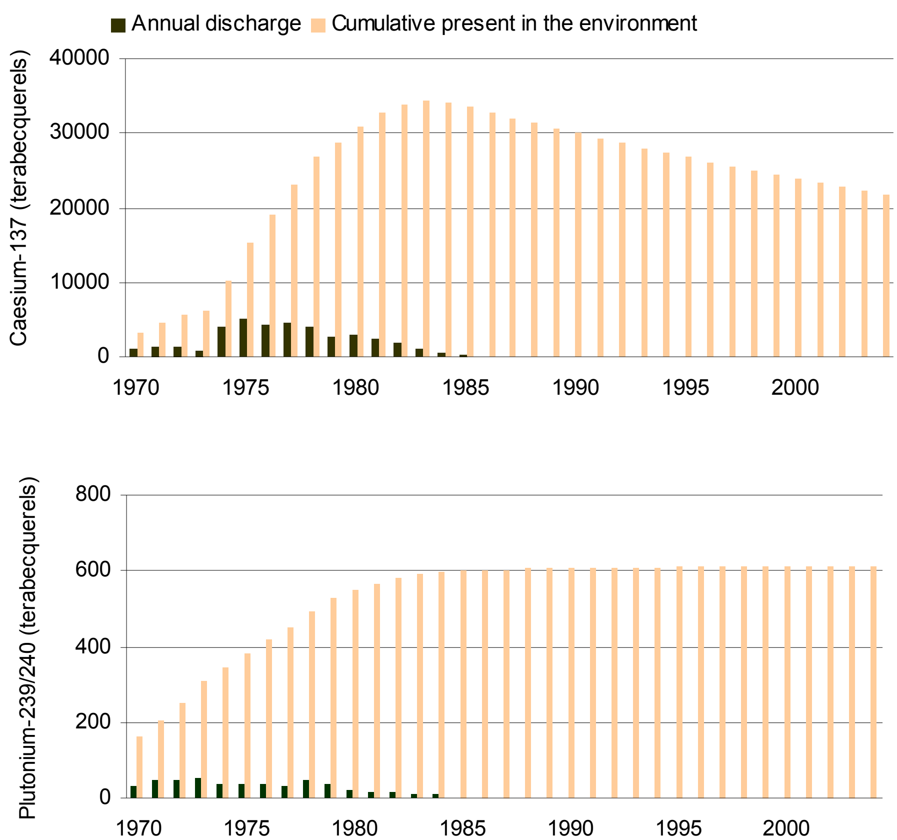


Figure 13. Radioactive Discharges from Sellafield, 1970-2004

Source: UK Environment Agency.

Health Impact and Implications

While the scale of Sellafield's discharges can be quantified with a certain level of confidence, no such certainty can be given to their health impacts. In particular, the relationship between Sellafield's operations and discharges, and the increased incidence of childhood cancers in the locality remains unresolved today. A summary of the current situation is provided below.

The ongoing and contentious debate is largely focused on the identification in the 1980's of a higher than normal incidence of childhood leukaemia in Sellafield's dormitory town of Seascale just a mile south of the site. The Black Inquiry, set up to investigate the case, concluded that while radiation was the only established environmental cause of leukaemia known at that time, significant uncertainties about discharge levels precluded a connection with radiation being made.[104] The subsequent Gardner Report found that children born in Seascale to fathers working at Sellafield who had received certain levels of pre-conceptual radiation dose faced an eight times higher risk than normal of contracting leukaemia or Non Hodgkins lymphoma.[105]

This finding of Parental Preconception Irradiation (PPI) was nevertheless rejected by a London High Court, on the grounds of lack of supporting evidence, in a case brought by families who sought to establish the link between radiation exposures to Sellafield workers and illness in their children.[106] Two later studies were to confirm PPI, and a study by the Health & Safety Executive subsequently found the incidence of childhood cancer in Seascale to be some 14 times the national average and twice that of other West Cumbrian areas with a significantly increased risk to children whose fathers had worked at Sellafield before 1965.[107] A later report by the Committee on Medical Aspects of Radiation in the Environment confirmed a continuing excess of childhood cancers in 0-24 year-olds in Seascale between 1984 and 1992.[108] It also found that no excess was observed during 1900-1945, before Sellafield's establishment, and that data for 1955-1983 showed a continued excess that was "highly unlikely" to be due to chance.

Despite all these findings, and making full use of the earlier High Court ruling, BNFL continues to claim today that Sellafield had been given a "clean bill of health," a claim rooted in a series of research studies commenced in 1988 that point to a virus causing childhood leukaemia.[109] This 'Population Mixing Theory' suggests that because many nuclear facilities are situated in isolated rural areas, the local inhabitants are more vulnerable to a virus imported by an in-flux of "non-locals" employed in building and operating those sites. With no virus identified, doubts have been expressed as to whether such a large relative risk persisting over more than three decades could be wholly attributed to population mixing.[110]

Sellafield workers, while also the subject of inconclusive research, are supported by their own compensation scheme – the industry-wide Compensation Scheme for Radiation Linked Diseases. The scheme "pays out" for a range of radiation induced illnesses on the basis of a 20% probability that their disease resulted from their work. It is felt somewhat ironic by those who do not work at the site and live outside the perimeter fence that no such recognition is given to their own cases.

IX. Nuclear Power in the UK

Nuclear power currently provides around 18% of the UK's electricity. It is generated at ten power stations, all but one with twin reactors: the last two Magnox stations, seven with Advanced Gas-Cooled Reactors (AGRs), and one station with a single PWR. The majority are scheduled for closure by the early 2020's. The one PWR station (Sizewell) is due for closure in 2035. The Magnox fleet is owned by the NDA, and the AGRs and PWR by British Energy.

Magnox	**Capacity (MW)**	**Published Lifetime**
Oldbury A1, A2	434	1967 - 2008
Wylfa 1,2	980	1971 - 2010
AGR		
Heysham I/1, I/2	1,150	1989 - 2014
Hinkley Point B1, B2	1,220	1976 - 2016
Hunterston B1, B2	1,190	1976 - 2016
Dungeness B1, B2	1,110	1985 - 2018
Hartlepool A1, A2	1,210	1989 - 2018
Heysham II/1, II/2	1,250	1989 - 2023
Torness 1.2	1,250	1988 - 2023
PWR Sizewell B	1,188	1995 - 2035

Table 10. U.K. Operating Nuclear Power Plants

Source: Department of Business, Enterprise and Regulatory Reform

All spent fuel from existing UK power stations is already contracted for reprocessing with the exception of Sizewell PWR fuel and an estimated 3000 tons of AGR fuel that is destined for long-term storage. Additional spent fuel will arise if new reactors are built in the UK. Based on the construction of ten new AP1000 PWR's with a 60-year lifetime, BNFL has projected a further spent fuel arising of 14,000 tons.[111]

Citing a future 'energy gap' when a majority of the power stations close, the need for CO_2 reductions and seeking greater future security of supply, the Government has recently given its approval for a programme of new nuclear-power reactors.[112] This paves the way for utilities to submit plans for an undefined number of new stations to be built, operated and decommissioned entirely at the utilities' expense. No reprocessing of fuel from these stations is currently envisaged.

Applications for reactor design assessment were submitted in 2007 by a number of consortia. The four short-listed designs, currently under "Generic Design Assessment" by the Health & Safety Executive (HSE) and the Environment Agency, are Atomic Energy of Canada Limited's ACR-100, the Electricité de France/AREVA European Pressurized-water Reactor, GE-Hitachi's GE ES-Boiling Water Reactor and the Westinghouse Advanced Pressurized Water Reactor 1000. The assessments are expected to take around 3 years.

In its most recent pronouncement in support of a new build, the Government has confirmed that the construction of new stations should proceed on the basis that their spent fuel will not be reprocessed.[113] Given the Government and nuclear industry's propensity to making U-turns on policy, however, the possibility of some future reprocessing should not be ruled out.

X. Conclusion

After five decades of operation, the costs and extent of the environmental contamination and the accumulation of nuclear wastes, separated plutonium, and other materials associated with the United Kingdom's reprocessing program have become apparent. This legacy that today haunts the program and in particular its main site, at Sellafield, is a result of a historic lack of public accountability, a failure to independently scrutinise financial and operational projections, and the promotion of reprocessing over all other spent fuel management options.

The direct cost of clean-up at the Sellafield site in West Cumbria is today put at £73Bn ($146Bn). This may well be an underestimate, with the final cost now projected by a senior director of the Nuclear Decommissioning Authority (NDA) to be several billions higher. The final reckoning is unlikely to be known before another half century when the disposition of existing wastes and other materials is expected to have been completed. Over its lifetime, Sellafield operations are expected to generate almost 2 million cubic meters of radioactive waste.

The UK reprocessing program has produced an accumulated separated plutonium stock of over 100 tons as of the end of 2006. It is considered to be an asset of "zero value" and it is as yet undecided whether the UK will treat it as a waste product or a future energy asset. The stockpile will increase to 133 tons if current reprocessing contracts are completed. Some 100 tons will be from UK-origin spent fuel and 33 tons from foreign fuel. The plutonium from foreign spent fuel is to be returned to overseas customers as MOX fuel.

Many of Sellafield's outstanding environmental and waste problems might have been mitigated at a much earlier stage – or indeed need not have risen at all – if a less cavalier approach had been adopted by the U.K.'s reprocessing industry in the early years. An accurate assessment of the financial and other costs of the resulting legacy was always a secondary consideration.

During the last two decades of the twentieth century, successive UK Governments – heavily briefed by the industry – continued to promote reprocessing at a time when it was demonstrably in decline throughout the world. Based on their testimony to various departmental select committees over the years, U.K. Government Ministers gave unstinting support to operational ventures at Sellafield even though the viability of those operations was known to be highly suspect and to have little justification. The go-ahead for many major projects at Sellafield, such as the THORP reprocessing plant and the Sellafield MOX fuel fabrication plant, simply ratified decisions already taken by Government before public consultation on the projects.

With hindsight, a very different course could have been taken some twenty years ago, amid growing concerns at home and abroad about reprocessing and the recognition of the need to diversify the West Cumbria region's economy. Despite paying lip service to this need, plans for the THORP reprocessing plant were vigorously pursued by British Nuclear Fuels Limited (BNFL) in the knowledge that its operation, and subsequently that of the Sellafield MOX Plant, would lock West Cumbria into further years of dependence on Sellafield operations and add more wastes and separated plutonium to the stockpile. Investment monies that were secured, ostensibly for diversification, inevitably found their way into ventures that supported the industry, if not directly into Sellafield's hands. As a result, little diversification has taken place and with THORP's and SMP's future hanging in the balance, events have now travelled full circle with urgent calls once more for a more balanced local economy.

Acting as judge and jury, and as the golden shareholder for government-owned BNFL, Ministers responsible for Sellafield not only shaped policy but also protected a business that was financially imploding. In 2000, the UK government belatedly realised that BNFL and its Sellafield operations were technically bankrupt. This led directly to the formation of the Nuclear Decommissioning Authority (NDA).

Whilst its name and original remit engendered some hope that past lessons had been learned and a new era of clean up and decommissioning was being ushered in, the NDA was made dependent for its revenue on income from THORP reprocessing and the Sellafield MOX plant's fuel production to help offset clean-up costs. The NDA has found itself with a significantly reduced income from these operations over the last three years, and the plants themselves are now recognised by the Royal Society and government committee sources to be unreliable. With little prospect of significant improvement in these operations – certainly in the near-term – the NDA must either secure extra funding from an already unwilling government Treasury Department, or make yet further cut-backs to its cleanup and decommissioning program.

Given its apparent inability to secure funding from a more reliable source, the NDA's overall approach to meeting its work program is increasingly questioned. Ostensibly to maximise financial returns to the UK taxpayer, the NDA refuses to rule out the possibility of further reprocessing contracts, whether from the US or elsewhere. Thus, the agenda of the NDA is at risk of being driven more by the needs of its contractors and the whim of government than by the vital requirement to solve existing high-level waste and plutonium stockpile problems.

There are few signs that the industry has learned from its fifty years of experience. Successive owners and operators of Sellafield showed a woeful level of miscalculation in terms of estimating plant construction and operating costs or build times. It is also clear from BNFL's Board of Investigation into the 2005 THORP accident that the workforce still considers itself to be an elite body above reproach.

The renewed push for reprocessing, driven by the reprocessing industry's pursuit of its long-term vested interests and supported by short-term governments as a way to secure the future of nuclear power, would be to the detriment of the public economic and environmental interests and the effort to reduce global stocks of nuclear-weapon materials.

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About the Author

Martin Forwood joined CORE in 1985 and took over as Campaign Coordinator in 1989, the position he holds today. CORE was founded in 1980 by a group of residents opposed to the import of overseas spent fuel through local docks. The Group has since campaigned at home and overseas on all aspects of BNFL's operations at Sellafield, with a focus on reprocessing.

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