Decommissioning at Berkeley Power Station during the 1990s, here one of the sealed boiler vessels is being taken down in preparation for securing the reactor building for long term (typically 100 year) storage prior to eventual dismantling Picture courtesy of Magnox Electric

NUCLEAR DECOMMISSIONING IN THE UK

The safe and sustainable management of radioactive waste has always been one of the major challenges facing countries establishing a long-term nuclear energy programme. Laurence Williams is in a better position than most to report on the progress that has been made in the UK. Until 2008, he was the Chief Engineer of the Nuclear Decommissioning Authority and here he sets the background to the tasks facing the UK nuclear industry and the progress made in decommissioning and clean-up.

The UK is not unique in having to deal with the legacy of an early nuclear energy programme. The US, Russia, France, Japan and many other countries face similar challenges of varying degrees. However, the roots of the UK's nuclear clean-up liabilities go right back to the Manhattan Project – the Second World War project to build the first nuclear weapons.

In 1946, the US passed a law that prevented the transfer of nuclear technology to foreign powers – including the UK – that had actively participated in the development of the Manhattan Project. The UK was, therefore, forced to develop its own nuclear programme. The lack of access to enriched uranium in the early years meant the UK had to use natural uranium fuel, with graphite as the neutron moderating medium, for its military and later commercial electricity generation nuclear reactors. The use of these materials had a major influence on the scale, challenges, and clean-up costs of the UK's nuclear legacy.

The term 'legacy' covers the facilities, nuclear materials and radioactive wastes that have originated from the early nuclear programmes that fall within the public sector civil nuclear liabilities. In terms of volume, the public sector liability covers some 100% of the high-level waste (HLW), 80% of the intermediate-level waste (ILW) and 95% of the low-level waste (LLW) in the current UK radioactive waste inventory (see section titled *Types and Categories of Radioactive Waste*).

The decommissioning of the private sector nuclear reactors operated by British Energy (now owned by the French Utility EDF) will be privately funded and is not addressed in this article. However, the radioactive waste arising from the decommissioning of the British Energy reactors is included in the national radioactive waste strategy. British Energy is responsible for around 12% of the UK ILW inventory and 4% of the UK's LLW inventory.

CIVIL NUCLEAR CLEAN-UP LIABILITIES

The nuclear research and development sites at Harwell, Sellafield, Capenhurst, Springfields and later at Dounreay and Winfrith, housed the facilities to carry out fundamental nuclear research and the production of materials to support the nuclear weapons and later civil nuclear power programmes. Nuclear energy was a new field of science and technology and the production and storage of industrial scale quantities of radioactive material was novel. The pressures of the Cold War and the need to produce plutonium and enriched uranium for the UK's nuclear weapons meant that production took precedence over the management of radioactive waste. These activities were conducted under a cloak of secrecy with initially no independent safety or environmental regulation.

When Calder Hall opened in 1956 on the Cumbrian coast, it became the world's first nuclear power station. As the UK embarked on a major nuclear power programme for electricity production in the late 1950s, it used the Calder Hall design as the basis of the 'Magnox' reactors – the name coming from the magnesium alloy casing surrounding the metallic uranium fuel rod. Between 1953 and 1971, the UK constructed 26 nuclear power reactors of the Magnox type ranging in size from 60MWe to 500MWe.

In total, the UK constructed 41 nuclear power reactors, producing at their peak around one third of the country's electricity needs. The UK also constructed many research reactors, fuel production and prototype reprocessing facilities at its atomic energy research sites at Harwell, Winfrith and Dounreay.

Magnox fuel required reprocessing to recover the plutonium and uranium for reuse. The initial nuclear fuel reprocessing facilities at Sellafield were replaced with larger facilities to deal with the increasing demands from both military and civil programmes. All the facilities associated with this early programme have been decommissioned, shut down or will cease operations in the next decade (see section titled *The UK Nuclear Legacy*).

RADIOACTIVE WASTE MANAGEMENT

In the early days of the programme, the management of radioactive waste was not given the same priority as production and fell short of what would be expected today. The ability to retrieve waste was not considered of vital importance, nor was the process of creating 'passively safe' storage, whereby no active mechanical or electrical systems are needed to maintain the waste in a safe condition.

For low-level waste (LLW), the management option was for disposal at the National LLW Disposal facility near the village of Drigg in West Cumbria. However, in the early years there was no end solution for intermediate-level waste (ILW) or high-level waste (HLW) and these were initially stored in an untreated form in facilities at Sellafield and elsewhere. The Flowers Report in 1976 recommended geological disposal for radioactive waste. The policy for HLW was surface storage for 50 years to allow the heat generation rate to drop to levels that would allow underground disposal. Safety problems associated with the storage of untreated wastes and the deteriorating condition of the storage facilities caused the Nuclear Installations Inspectorate to demand that some wastes be put in a passively safe state.

The date for an ILW disposal facility continued to slip and the decision in early 1997 to refuse planning permission for a facility near Sellafield to determine the suitability of the site for deep geological disposal meant that the disposal of ILW was no longer a realistic option for the near-term management of radioactive waste. Post 1997, the emphasis changed and greater priority was given to the need to recover all untreated waste and put it in a passively safe state in properly engineered stores.

EARLY DECOMMISSIONING

British Nuclear Fuels, the state-owned company set up in 1970 to manage the UK's civil nuclear fuel cycle activities, embarked on a major decommissioning and radioactive waste management programme in the 1980s. It decommissioned the gaseous diffusion plant at Capenhurst; at Sellafield new waste treatment processes were developed to encase various wastes in cement in robust stainless steel drums that could be safely stored and easily retrieved.

New plants were constructed to convert the liquid fission product wastes into glass and store them in passively safe conditions. Facilities were designed and constructed to remove radioactive wastes from the liquids discharged into the Irish Sea with the wastes encased in cement and stored. Work started on the retrieval of radioactive waste cladding from the reprocessing of Magnox fuel from the large silos at Sellafield and decommissioning of the first reprocessing plant commenced along with other early research and development facilities.

Decommissioning and clean-up became the focus at United Kingdom Atomic Energy Authority (UKAEA) sites in the 1990s. At Windscale (now part of the Sellafield site), considerable progress was made in decommissioning the prototype advanced gas-cooled reactor. Progress was also made on decommissioning various research reactors and associated laboratory facilities at other UKAEA sites. Following a major safety audit at Dounreay in 1998, the UKAEA produced the Dounreay Site Restoration Plan which was the first integrated radioactive waste management and decommissioning programme for a site in the UK.

The power stations at Berkeley and Hunterston A were the first to close down. At Berkeley, once the fuel had been removed, the boilers and ducting were disconnected from the reactor pressure vessel, the machinery at the top of the reactor was removed, the roof was lowered and a weather-tight cladding was erected. This enabled the reactors to be put in a safe storage condition pending final dismantling. The ancillary buildings such as the turbine hall were removed and the area landscaped.

TYPES AND CATEGORIES OF RADIOACTIVE WASTE

Low-level waste (LLW) has a much lower potential hazard than other categories. It still contains some radioactive material and is therefore not acceptable for disposal as ordinary refuse. It usually consists of contaminated equipment and protective clothing from facilities that handle nuclear material, or contaminated materials such as concrete rubble.

Intermediate-level waste (ILW) arises mainly from the reprocessing of spent fuel and from general operations and maintenance at nuclear sites, and can include metal items such as fuel cladding and reactor components, as well as sludge from the treatment of radioactive liquid effluents.

High-level (or heat-generating) waste (HLW) is waste in which the temperature may rise significantly as a result of its radioactivity. This factor has to be taken into account in the design of storage or disposal facilities. In the UK, HLW results from the concentration of the highly radioactive fission products that are separated from uranium during the reprocessing of spent nuclear fuel.

The start of the UK's nuclear power programme: HM the Queen opens Calder Hall Reactor 1, the world's first nuclear power station, in 1956 Image supplied courtesy of NDA

CREATION OF THE NDA

By the end of the 1990s, the lack of progress in the management of radioactive waste and decommissioning was causing concern to the nuclear safety and environment regulators and action was needed to provide a comprehensive solution.

The lack of a coordinated national approach to radioactive waste management and decommissioning meant that the cost of decommissioning and clean-up could not be defined. In April 2005, the UK Government established the Nuclear Decommissioning Authority (NDA) as the national body to coordinate the management of decommissioning and the associated management of radioactive waste.

The involvement of private sector contractors at the 19 licensed nuclear sites owned by the NDA was at the heart of the Government's decommissioning strategy and, to enable this, the existing nuclear industry had to be reorganised .

ESTIMATING COSTS

Uncertainty surrounding the cost of the nuclear decommissioning and clean-up programme was one of the main reasons for setting up the NDA. To address this issue the NDA adopted the US approach of Life Cycle Baselines (LCBL) to help quantify the costs and required the site licence companies to produce an LCBL for each site. The LCBL defines the scope of work to be done, the schedule and the cost.

Assumptions had to be made regarding radioactive waste disposal timescales and final state of each site. The 2005 LCBL estimate gave the discounted cost of decommissioning and clean-up as £30.6 billion. This increased to £37billion in 2006-07 and the NDA's latest estimate, which includes the discounted cost for the deep geological disposal facility, is £44.1billion.

THE UK NUCLEAR LEGACY

The UK Nuclear Legacy (which falls under the responsibility of the public sector civil nuclear liabilities and managed by the NDA) includes:

- around 1,100m^3 of high-level waste; 190,000m^3 of intermediate-level waste and an estimated 2,970,000 m^3 of low-level and very low-level waste (see chart below)
- remaining several thousand tonnes of spent fuel from the Magnox power stations
- UK stockpile of separated plutonium and reprocessed and depleted uranium
- hundreds of nuclear facilities to be decommissioned and demolished
- clean-up of the ex-UKAEA sites at Harwell, Winfrith, Springfields, Windscale, and Dounreay
- clean-up of the ex-BNFL sites at Sellafield, Capenhurst, Springfields, Calder Hall (four reactors), and Chapelcross (four reactors)
- clean-up of the 18 reactors at the Magnox power station sites at Bradwell, Berkeley, Dungeness A, Sizewell A, Hinkley Point A, Trawsfynydd, Hunterson A, Oldbury, and Wylfa.

VOLUME OF NUCLEAR WASTE IN THE UK AT 1 APRIL 2007 (m^3)

Site owner	HLW	ILW	LLW	Total
NDA	1,090	190,000	2,970,000	3,160,000
Ministry of Defence	0	12,400	63,400	75,800
British Energy	0	28,900	123,000	152,000
Others	0	4,700	33,600	42,200
Total	1,090	236,000	3,190,000	3,430,000

from *The 2007 UK Radioactive Waste Inventory Main Report* published by the Nuclear Decommissioning Authority (2008)

PRIORITIES

The type, complexity and hazard potential of the facilities at the NDA sites varies enormously and, as the NDA does not have an unlimited budget, it has had to prioritise its funding. The NDA has given its highest priority to hazard reduction in order to reduce risk to both current and future generations.

The main hazards come from the radioactive wastes that are 'potentially mobile'. Potentially mobile wastes are those in the form of liquids or sludge that could be dispersed into the atmosphere if their containment was lost. Waste that has been conditioned to be put it in a passively safe state via encapsulation in glass or cement is not easily dispersible and hence not considered as potentially mobile. The latest NDA data shows that around 22% of waste by volume and 93% by activity is currently in a potentially mobile form.

However, not all the hazards are at Sellafield. Priority is also being given to defuelling the shut down Magnox reactors as this removes over 99% of their radioactive inventory. At Dounreay, there are also potential hazards resulting from radioactive waste arising from the fast reactor reprocessing facilities and from the liquid metal coolants.

HAZARD REDUCTION

At Sellafield, the main hazards come from what are referred to as the 'legacy ponds and silos' and the storage of the liquid fission products in tanks. Waste in the silos is highly radioactive, non-homogeneous, and has complex chemical composition. When waste was placed in these silos there was little consideration given to how it would be retrieved.

The retrieval of these wastes from the silos presents a considerable engineering challenge. Once retrieved, the waste will be immobilised in cement within stainless steel drums. The current NDA programme for the removal of waste from these silos is under review but the 2006-07 LCBL indicated that retrieval would be complete around 2027.

Open air ponds were used for interim storage of nuclear fuels pending reprocessing. One pond, constructed in the early 1960s, has had a troubled history and still contains a large number of nuclear fuel rods and considerable quantities of radioactive sludge. The removal of fuel and sludge from this pond is being given a high priority. The current NDA programme will provide for the removal of 90% of the sludge by 2018. The 2006-07 LCBL shows all legacy wastes will be retrieved, packaged, and stored by 2040. *(Continued on page 50.)*

Intermediate level waste is encapsulated in cement in robust stainless steel containers, for long term storage pending disposal. This cutaway shows simulated conditioned ILW in a stainless steel container courtesy Sellafied Ltd

RADIOACTIVE WASTE STORAGE PRINCIPLES

Low-level waste in half-height ISO containers are placed in vaults at the National LLW Repository near Drigg in West Cumbria © Sellafied Ltd

Radioactive waste pending disposal is currently stored in a variety of forms and facilities. Much of the waste is stored in an untreated form but the aim is to eventually store all waste in a passively safe state and in a form that can be easily retrieved by future generations when disposal facilities are available.

LLW is currently placed in steel ISO containers and on arrival at the disposal site the containers are filled with cement grout to provide long term structural stability in the disposal vaults.

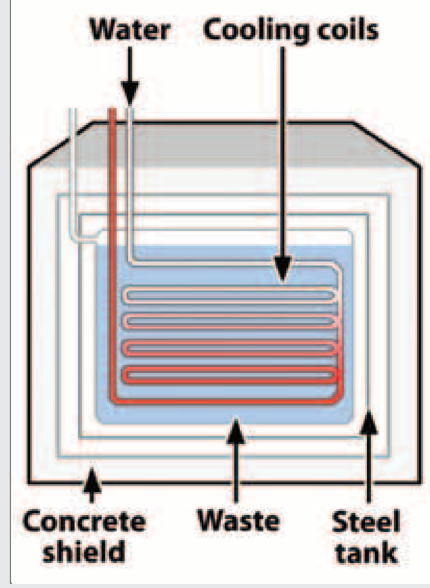
The preferred solution for ILW is to encapsulate the waste in a cement matrix contained in robust, high quality stainless steel drums. The sealed drums provide long-term containment for the waste and are placed in specially engineered stores using remotely operated handling machinery. These stores provide high-integrity protection for the safety of the workers and the public.

HLW resulting from heat generating fission products is stored in liquid form in stainless steel tanks protected by massive concrete structures that provide biological shielding from the intense gamma radiation. To put these wastes into a passively safe state, the liquors are dried using a calcining process and the solid fission products are then mixed in molten glass. The molten glass mixture is poured into robust stainless steel canisters and sealed when the glass has solidified. The canisters are placed in a long-term store that has been engineered to allow natural convection cooling.

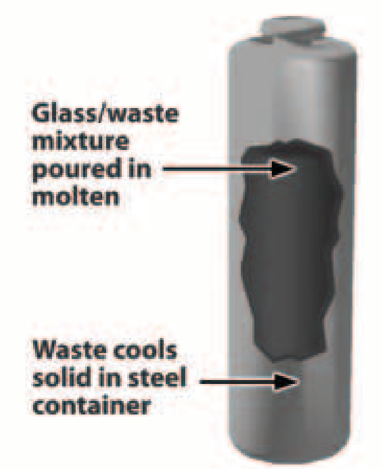
The current solution for interim storage of radioactive materials in the cores of the Magnox reactors is to adopt the 'Safestore' strategy. Stage 1 of the strategy is the removal of fuel followed by a care and maintenance preparation period where mobile wastes are conditioned ready for interim storage, redundant facilities are removed and remaining buildings, including the reactor buildings, are put in a suitable state. This stage removes some 99% of the radioactivity from the reactor.

Stage 2 of the strategy is to construct an intruder- and weather-proof structure around the reactor building to provide long term passively safe storage of the radioactive materials in the reactor core. The third stage covers the dismantling and complete removal of SafeStore buildings, the packaging of the remaining radioactive materials for direct disposal and the clean-up of the site. The timescale for the completion of the whole process will depend on many factors, including the availability of a geological repository but the aim is to provide safe storage for around 100 years.

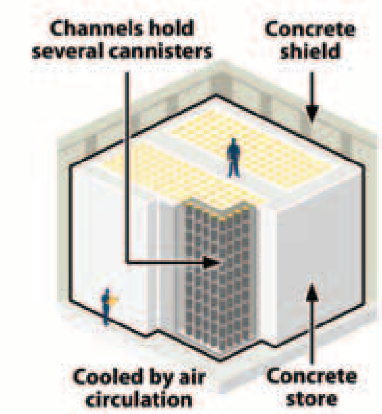
Liquid HLW is contained in robust stainless steel tanks with multiple cooling systems for interim storage…



…before being mixed with glass and sealed in high quality stainless steel cannisters…



…for long-term storage above ground pending eventual disposal



Schematics drawn by Simon Roulstone

The reprocessing of fuel from the Magnox reactors is a major part of the hazard reduction programme and the NDA Magnox Operating Programme is being used to coordinate the activities required to ensure that all Magnox fuel is reprocessed within the expected life of the current reprocessing plants.

At Dounreay, considerable progress has been made in reducing the hazard from the sodium coolant used in the Prototype Fast Reactor. The sodium destruction plant at Dounreay has effectively destroyed all the bulk sodium with no significant impact on the environment. The earlier Dounreay Fast Reactor used an alloy of sodium and potassium (NaK) as a coolant but this is heavily contaminated with fission products. A process to decontaminate and destroy this material has been developed and the 2006-07 LCBL shows the destruction of the NaK coolant by 2010.

Reprocessing of the research reactor and fast reactor fuels at Dounreay was much smaller than that at Sellafield but again the fission products were stored in liquid form in tanks. The fission product concentration in these tanks is not as great as at Sellafield and UKAEA developed a process to encapsulate these wastes in cement rather than use a vitrification process to encase it in glass. This has been very effective and considerable progress has been made in emptying the storage tanks. The 2006-07 LCBL shows the encapsulation process being completed by 2017.

FUTURE CHALLENGES

Decommissioning and clean-up of the NDA sites will take many decades. This will require a comprehensive approach to the storage of radioactive waste (see *Radioactive Waste Storage Principles*). The initial priorities in the next 10 to 20 years must be hazard reduction and the storage of all radioactive waste in a passively safe state. This will not be easy and will require the UK to maintain its nuclear fuel cycle skills and knowledge to sustain a viable decommissioning and clean-up programme.

The management of the UK's plutonium and reprocessed/depleted uranium stocks will also be a challenge. As an energy source for future nuclear electricity generation, they represent a valuable asset. As a waste they represent a considerable liability.

Removal of a redundant uranium storage flask from a storage pond at Sellafield © NDA

BIOGRAPHY – Laurence Williams FREng

Laurence Williams was the NDA's Chief Engineer and the Director for Nuclear Safety, Security and Environment until 2008. Prior to joining the NDA, Laurence was Her Majesty's Chief Inspector of Nuclear Installations and had a long and distinguished career as a nuclear safety regulator. He currently advises the European Bank for Reconstruction and Development on nuclear safety, radioactive waste management, and decommissioning.

The dismantling of the Magnox reactors will provide many engineering challenges, especially if early clearance of the sites is required. However, there is no point in dismantling these reactors unless there is somewhere to dispose of the waste because the SafeStore concept adopted for the Berkeley reactors represents safe and cost-efficient storage for the radioactive wastes in these reactors.

The provision of disposal facilities for ILW and HLW radioactive wastes will be a challenge but they are essential if the NDA is to deliver cost effective decommissioning and clean-up.

Further reference

Nuclear Decommissioning Authority: www.nda.gov.uk

Committee on Radioactive Waste Management: www.corwm.org.uk