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Integrated Waste Management Approach WP 1 Review Report – UK Chapter

Executive summary

This chapter describes the position with respect to irradiated graphite within the United Kingdom (UK). Graphite has been used extensively in the UK nuclear programme, in experimental/Production/Prototype reactors (8), Magnox stations (11) and AGR stations (7). Of the base-load reactors, two Magnox stations and the AGRs remain in operation, whilst the remaining Magnox stations are shut down awaiting decommissioning, in line with the UK "safestore" approach. The UK irradiated graphite inventory is large with a total of over 80, 000 m^3 forecast to arise. At present it is planned that most of this graphite will be routed to geological disposal.

The UK has practical experience of decommissioning graphite reactors gained from work on GLEEP at Harwell and the prototype AGR at Windscale (WAGR). In both cases graphite was retrieved from the cores in air, although the higher radiation associated with WAGR required a higher degree of remote handling.

Revisions

Rev.	Date	Short description	Author	Internal Review	Task Leader	WP Leader
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CHAPTER CONTENTS

1 Introduction

This report describes the position with respect to the UK's graphite waste. Specifically, consideration is given to the legislative and regulatory framework that governs the management of this waste stream. The UK irradiated graphite inventory is large with a total of over 80,000 m^3 of irradiated graphite forecast to arise, and this document outlines this inventory in terms of the use of graphite in UK nuclear reactors. The bulk of the graphite is associated with Magnox and AGR power reactors, with smaller quantities associated with experimental, prototype and production reactors. Only two Magnox stations remain in service.

Whilst retrieval of graphite from the cores of shutdown Magnox reactors has not yet commenced, the decommissioning work on two UK graphite reactors, GLEEP and the Windscale AGR (WAGR), has developed expertise and knowledge. This experience will be of great value to the CARBOWASTE project.

2 Waste Categorisation

A number of conventions/systems are used to categorise wastes in different countries. These generally take into account both the specific activity and the extent to which long lived isotopes are present. In the UK, radioactive waste is classified into one of several categories according to its heat-generating capacity and activity content. These categories, which will be used throughout this document, are generally defined as follows:

High Level Waste (HLW)

HLW is the term used to describe waste in which the temperature may rise significantly as a result of its radioactivity, so this factor needs to be taken into account in designing storage or disposal facilities. In practice this primarily relates to the fission product solutions which are generated from the separation phase of spent fuel recycling and the vitrified product that is generated when these solutions are processed,

Intermediate Level Waste (ILW)

ILW is the term used to describe wastes which exceed the upper boundaries for Low Level Waste (see below), but which do not require heating to be taken into account in the design of storage or disposal facilities,

Low Level Waste (LLW)

LLW is the term used to describe waste which contains radioactive materials other than those acceptable for disposal with ordinary refuse, but not exceeding 4 GBq/te of alpha activity or 12 GBq/te of beta/gamma activity,

Very Low Level Waste (VLLW)

VLLW is the term used to describe waste which can safely be disposed of with ordinary refuse, each $0.1m^3$ of material containing less than 400kBq of beta/gamma activity or single items containing less than 40kBq of beta/gamma activity.

These formal definitions act as useful labels for the materials in question. However the acceptance criteria for disposal facilities will also play a very important role in determining the ultimate fate of these wastes. For example although the upper limit for LLW is defined as 4GBq/te alpha and 12GBq/te beta/gamma the acceptance criteria for the Low Level Waste Repository located in West Cumbria are such that certain wastes which meet the formal definition of LLW can not be disposed of as the waste acceptance criteria specify lower limits e.g. on certain alpha emitting isotopes. Furthermore there is a cumulative limit on the amount of C-14 that can be disposed of at the current LLW repository. Therefore the current baseline plans are based on geological disposal for the major part of the UK graphite.

These waste categories are particularly relevant to the disposal of irradiated graphite in the UK, where the irradiated graphite generated from reactor decommissioning programmes is projected to account for as much as 1/3 of the total volume of ILW requiring geological disposal. Any waste treatment process that could reduce the activity content of irradiated graphite sufficiently to enable it to be disposed of to a facility with a lower waste classification (e.g. reclassification from ILW to LLW) could substantially reduce costs. The marginal cost of disposal is typically lower for LLW disposal in a near surface facility than ILW disposed of in a geological disposal facility. In addition the costs of LLW handling and management are typically lower than those for wastes with higher specific activities.

3 The UK Legislative and Regulatory Framework

In the UK, the responsibility for radioactive waste management is shared between the Government, the regulator and the producers of the waste. The Government decides on matters of overall policy; the regulators ensure that the policy is implemented; and the producers of the waste must manage it in ways which meet the regulatory requirements. Accordingly this section describes current Government policy relating to long term waste management and the regulatory framework

3.1 The Development of Government Policy

This section presents a summary of current Government Policy in respect of the long term management of radioactive wastes and describes how this has evolved in recent years.

In July 1995 the Government published a Review of Radioactive Waste Management Policy [1] . At this point Government policy for long term management of the various categories of materials was as follows:

Intermediate Level Waste (ILW)

Government favoured a policy of geological disposal and considered that the site investigation programme then being pursued by United Kingdom Nirex Ltd (Nirex) should continue. It was further noted that a final decision on geological disposal would depend on the establishment of a sound safety case, the granting of planning consent and compliance with regulatory requirements

High Level Waste (HLW)

Government restated its long-held position that vitrified High Level Waste should be stored for a period of at least 50 years to allow short-lived radionuclides to decay and heat generation to reduce, without any decisions being made about how the waste should be managed after that period.

Spent Fuel

Government accepted that spent fuel should not be categorised as a waste and reaffirmed its policy that the question of whether or not to reprocess should be a matter for the commercial judgement of the owner.

Nirex was established more than 25 years ago and was, at that time charged with developing a geological disposal facility for ILW and that fraction of LLW that was unsuitable for near surface disposal. Nirex applied for planning permission to develop a Rock Characterisation Facility in Cumbria to evaluate the suitability of the geology to host such a repository. However in March 1997 the planning application for this facility was finally refused.

In 2001 Government launched a national debate with the aim of developing and implementing a UK nuclear waste management programme which inspires public support and confidence. A consultation was launched with the publication of a White Paper [2].In 2003, following the initial stage of this consultation process, Government established a new advisory body, the Committee on Radioactive Waste Management (CoRWM). CoRWM was tasked with continuing the programme of public engagement and making recommendations on the long term management of the full range of radioactive materials, including not only ILW, but also HLW and such elements of other strategic materials as may subsequently require disposal. This included spent fuel and any element of the separated uranium and plutonium stocks as may eventually be declared to be surplus to requirements.

CoRWM published its recommendation to Government in 2006 [3]. Its report contained a series of 15 recommendations. There were 3 main themes to these recommendations which can be summarised as:

- Geological disposal is currently the best form of long term management for the UK's higher activity radioactive waste;
- There should be a commitment to the safe and secure interim storage of the waste during the period it will take to plan and construct the geological disposal facility; and
- The UK should look to develop partnership arrangements, linked to appropriate involvement and benefit packages, with local authorities/communities as a means of securing facility siting.

The first recommendation is the most relevant to this document and is reproduced in full below:

- Within the present state of knowledge, CoRWM considers geological disposal to be the best available approach for the long-term management of all the material categorised as waste in the CoRWM inventory when compared with the risks associated with other methods of management. The aim should be to progress to disposal as soon as practicable, consistent with developing and maintaining public and stakeholder confidence.

The Government has welcomed these recommendations and put in place arrangements to implement them. There have been two key changes:

The first is that the programme to develop a geological disposal facility in the UK has been widened from consideration of only ILW to encompass all of the higher active materials that may require disposal (including vitrified HLW, spent fuel and any separated uranium or plutonium that may require disposal).

The second is that CoRWM has been reconstituted to deliver its revised mission of providing independent scrutiny and advice relating to the implementation of policy relating to the long term management of radioactive wastes.

3.1.1 Nuclear Decommissioning Authority

The other major change relating to long term waste management arrangements was set out in the publication 'Managing the Nuclear Legacy' [4] in which the Government announced its intention to establish a Nuclear Decommissioning Authority (NDA) to take responsibility for the liabilities on civil public sector nuclear sites. This responsibility includes setting the strategy for decommissioning and waste management programmes, which are likely to cost billions of pounds and extend for decades into the future. The NDA was established under the Energy Act 2004 and came into being on April 1st 2005. The NDA mission is to deliver safe, sustainable and publicly acceptable solutions to the challenge of nuclear clean-up and waste management. The NDA now owns all of the civil public sector sites in the UK and was initially given the following specific responsibilities:

- the operation, pending the commencement of their decommissioning, of designated nuclear installations;
- the decommissioning of those and other designated nuclear installations;
- the cleaning-up of designated nuclear sites;
- the operation of designated facilities for treating, storing, transporting or disposing of hazardous material;
- the treatment, storage, transportation and disposal, in designated circumstances, of hazardous material; and
- the decommissioning of designated installations comprised in NDA facilities.

In 2006 it was announced that ownership of the shares in Nirex had been transferred to the NDA. Thus the NDA now also has a responsibility to develop geological disposal facilities capable of safely accepting the full range of materials requiring geological disposal.

3.2 The Role of the Regulators

The UK has a strong and effective regulatory regime for the management of radioactive waste, including storage. The following agencies are key in this respect.

3.2.1 Health and Safety Executive (HSE)

The Health and Safety Executive is the statutory body responsible for the enforcement of health and safety law on nuclear sites in Great Britain. HSE is the licensing authority for nuclear installations in Great Britain and, through its Nuclear Installations Inspectorate (NII), regulates the nuclear, radiological and industrial safety of nuclear installations.

3.2.2 Environment agencies

The Environment Agency (EA) is responsible in England and Wales for the enforcement of environmental protection legislation in the context of sustainable development. It authorises and regulates radioactive and non-radioactive discharges and disposals to air, water (both surface water and groundwater) and land. The equivalent body in Scotland is the Scottish Environment Protection Agency (SEPA) and in Northern Ireland this function is carried out by the Environment and Heritage Service within the Department of the Environment (DoENI).

The Environment Agency' has also established a Nuclear Waste Assessment Team (NWAT) which provides specialist technical support within the Environment Agency on the management and disposal of radioactive waste in England and Wales. Its main aim is to ensure that radioactive wastes will be disposed of in the most appropriate manner in order to protect the public, the wider environment and to contribute to the UK's aim of sustainable development. The team interacts closely with nuclear licensees, Government departments and the NDA. Much of their work is carried out in partnership with colleagues in the Health and Safety Executive (HSE) and the Scottish Environment Protection Agency (SEPA), ensuring coherence throughout.

3.2.3 Nuclear Installations Inspectorate

The main legislation governing the safety of nuclear installations in the UK is the Health and Safety at Work etc Act 1974 (HSWA 74)[5] and the associated relevant statutory provisions of the Nuclear Installations Act 1965 (as amended)[6]. One licence condition requires that adequate arrangements are made and implemented for the decommissioning of any plant or process that may affect safety, and that adequate arrangements are made for the production and implementation of decommissioning programmes for each plant. Furthermore, the licensee is required to provide adequate documentation to justify the safety of proposed decommissioning and, where appropriate, provide this documentation to the Health and Safety Executive. By these provisions, the Nuclear Installations Inspectorate (NII) has the power to require each licensee to supply it with the details of the programmes of its decommissioning proposals. If the HSE (NII) is not satisfied with research industry is undertaking, it can carry out its own research and/or commission others to undertake the work and recoup the costs from industry.

In 2006 the HSE published a series of Safety Assessment Principles for Nuclear facilities which are currently available on the HSE web site[7]. Some of these principles relate to decommissioning; these can be summarised as follows:

- Facilities should be designed and operated so that they can be safely decommissioned.
- A decommissioning strategy should be prepared and maintained for each site and should be integrated with other relevant strategies.
- Decommissioning should be carried out as soon as is reasonably practicable taking relevant factors into account.
- A decommissioning plan and programme should be prepared and maintained for each nuclear facility throughout its life-cycle to demonstrate that it can be safely decommissioned.
- The facility should be made passively safe before entering a care and maintenance phase.
- Throughout the whole life-cycle of a facility the documents and records that might be required for decommissioning purposes should be identified, prepared, updated and retained.
- Organisational arrangements should be established and maintained to ensure safe and effective decommissioning of facilities.

3.2.4 The Role of the Environment Agencies

The Environment Agency (EA) takes a leading role in protecting and improving the environment in England and Wales while the Scottish Environment Protection Agency (SEPA) has similar responsibilities in Scotland. These responsibilities include enforcing the Radioactive Substances Act 93 and the Environment Act 1995. This means that these agencies are responsible for authorising any disposal, discharge or off-site transfer of radioactive waste.

This takes the form of granting authorisations for existing facilities such as the Low Level Waste Repository located in West Cumbria as well as arrangements associated with any potential future geological disposal facility.

Under section 7 of the Environment Act 99, the Environment Agency or SEPA may provide advice, including includes advising HSE on the long-term disposability of conditioned waste, and ensuring waste is managed in a sustainable way, taking into account long-term environmental considerations.

In addition, the Environment Agencies scrutinise the concepts that the Nuclear Decommissioning Authority's Radioactive Waste Management Directorate (NDA(RWMD)) has developed for assessing the disposability of waste packages to ensure that these concepts are fit for purpose.

Under the terms of a Memorandum of Understanding the Environment Agency or SEPA consult HSE and will not authorise the disposal of radioactive waste without taking full and meaningful account of any health and safety issues raised.

Prior authorisation must be obtained for the disposal of radioactive waste. An applicant for authorisation must provide a detailed consideration of environmental impacts of disposal. Authorisations issued by the Agency for operating facilities place numerical limits on the quantities of radioactive waste, which can be disposed. They also require the 'best practicable means' be used to minimise the quantities of waste disposed of, and to minimise the radiological effects of disposals on members of the public and the environment.

The EA oversees how nuclear licensed sites dispose and plan to dispose of their radioactive waste by granting site authorisations to the operators who run them. Operators of these sites must have an authorisation from the EA or SEPA to dispose of their waste. These authorisations set out limits and conditions on the amount and way they dispose of their waste and cover all radioactive waste disposals including discharges to air and water, and transfers of wastes The EA and SEPA also assess sites to ensure they're not exceeding their limits and releasing as little radioactive waste as possible into the environment.

3.3 The Responsibility of the Site Licensees

Currently there are a number of nuclear licensed sites in the UK operated by a range of licensees. Their statutory responsibility is to ensure they comply with legislation and regulatory requirements largely via the site licence, for example the Licensees:

- Have sole and absolute responsibility for the nuclear safety at a licensed site;
- Must be in control of day to day licensable activities on the site;
- Must have, and have taken steps to retain, adequate capability within their own organisation to understand the safety requirements of all their activities and those of any contractor; to take responsibility for managing safe operations; and to set, interpret and ensure achievement of safety standards, i.e. must be an intelligent customer;
- Have a legal duty to comply with all licence conditions;
- Must make and implement adequate arrangements to control any change to their organisational structure and resources which may affect safety;
- Retain absolute legal responsibility for the nuclear safety of activities on site until there has ceased to be any danger from ionising radiation from anything on the site or the legal responsibility has been transferred to another corporate body.

A licence, once granted, applies throughout the lifetime of an installation from manufacture, construction, commissioning, operation, modification, through to eventual decommissioning and demolition.

It is the responsibility of the licensee to prepare programmes for decommissioning. There is a specific requirement for these under Licence Condition 35 attached to each nuclear site licence. This condition also gives the NII the power to require the arrangements and programmes to be submitted to it and the power to approve them or parts of them. Once approved, the licensee can not deviate from them without NII's approval.

4 Graphite in UK Nuclear Reactors

This section details nuclear reactors in the UK containing irradiated graphite, provides an estimate of the quantities of i-graphite and describes the design of those reactors containing graphite which will eventually require decommissioning.

4.1 The Current Situation

The total number of reactors that are to be decommissioned in the UK is currently in excess of 50. This comprises commercial nuclear plant, plutonium production reactors, experimental reactors and material testing reactors (MTR). Of these, 45 reactors contain irradiated graphite and these are detailed in Table 1 together with their current status. The commercial nuclear plant and the Windscale Pile plutonium production reactors contain the most significant quantities of irradiated graphite. The two Windscale Pile reactors each contain approximately 2,000 tonnes of graphite. The commercial Magnox and AGR reactors account for in excess of 70,000 tonnes of graphite in their structures alone. Some of these reactors also have additional irradiated graphite arising from graphite fuel sleeves. Table 2 details the forecast arisings of volumes of irradiated graphite for the UK. Figure 1 is a map of the UK showing the location of the commercial nuclear plant (with the exception of Dounreay which is the UK's former site for fast reactor research).

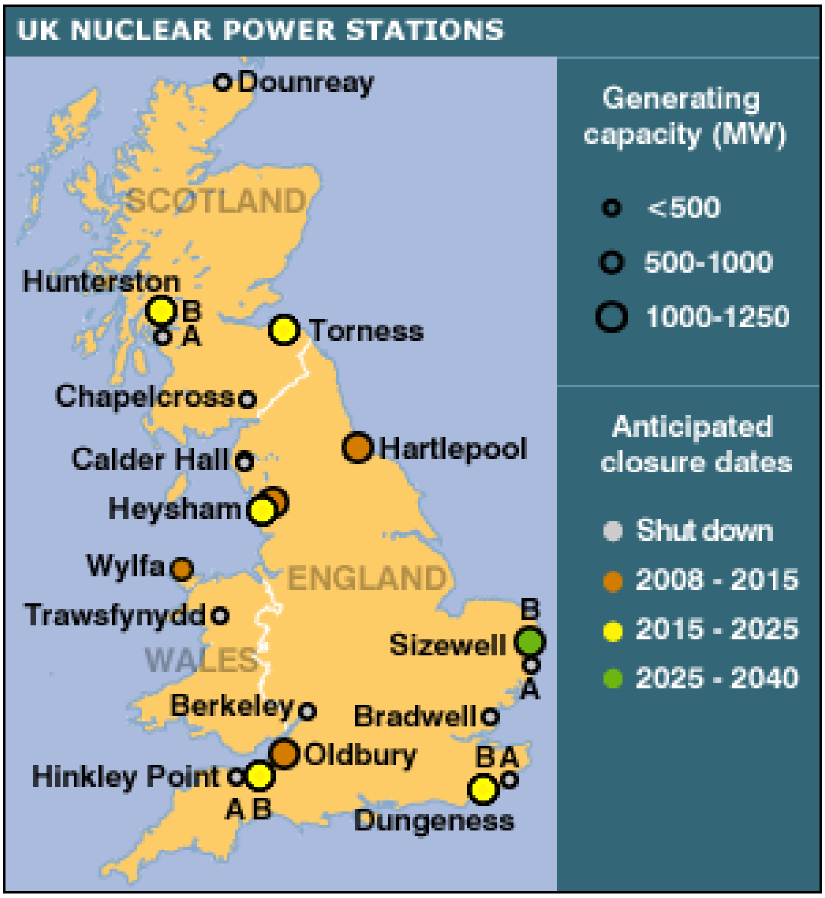

Figure 1: Map of the United Kingdom showing the location of commercial nuclear reactor sites and Dounreay

Table 1: Summary of UK Nuclear Reactors Containing Graphite

Reactor	**Operation began**	**Operation ceased**	**Output per reactor MWe**	**Status**
Experimental, Production and Prototype Reactors				
GLEEP	1947	1990	3 kWt	Decommissioned
BEPO	1948	1968	6 MWt	Shutdown
DIDO	1956	1990	26 MWt	Shutdown
PLUTO	1957	1990	26 MWt	Shutdown
DRAGON	1962	1975	20 MWt	Shutdown
Windscale Pile 1	1950	1957	180 MWt	Shutdown
Windscale Pile 2	1950	1957	180 MWt	Shutdown
WAGR	1962	1981	33	Partly decommissioned
Magnox Reactors				
Calder Hall	1956	2003	50 (x 4) (D)	Shutdown
Chapelcross	1959	2004	49 (x 4) (D)	Shutdown
Berkeley	1962	1989	150 (x 2) (D)	Shutdown
Bradwell	1962	2002	121 (x 2) (D)	Shutdown
Hunterston A	1964	1989	180 (x 2) (D)	Shutdown
Hinkley Point A	1965	2000	250 (x 2) (D)	Shutdown
Trawsfynydd	1965	1991	250 (x 2) (D)	Shutdown
Dungeness A	1965	2006	275 (x 2) (D)	Shutdown
Sizewell A	1966	2006	290 (x 2) (D)	Shutdown
Oldbury	1967		300 (x 2) (D)	Operating
Wylfa	1971		590 (x 2) (D)	Operating
Advanced Gas-Cooled Reactors				
Dungeness B	1983/85		545 (x 2) (A)	Operating
Hartlepool	1983/84		595 (x 2) (A)	Operating
Heysham 1	1983/84		580 (x 2) (A)	Operating
Heysham 2	1988		615 (x 2) (A)	Operating
Hinkley Point B	1976		430 (x 2) (A)	Operating
Hunterston B	1977		420 (x 2) (A)	Operating
Torness	1988		625 (x 2) (A)	Operating
Period of operation and current status (D=design, A=actual at December 2008)				

Table 2: Forecast of graphite waste volumes arisings in the UK

Waste Type	Description	Stock (m^3)	2007 (m^3)	2007-2029 (m^3)	2030-2059 (m^3)	2060-2099 (m^3)	Post 2100 (m^3)	Total Volume (m^3)
ILW	AGR Graphite Fuel Assembly Components	4278	233	3759	0	0	0	8037
ILW	Decommissioning : Graphite	0	0	0	0	229	14999	15228
ILW	FED Graphite	2362	0	0	0	0	0	2362
ILW	Final Dismantling & Site Clearance : Graphite	0	0	0	0	13038	24024	37062
ILW	Fuel Stringer Debris - Graphite	237	9	170	0	0	0	306
ILW	Fuel Stringer Debris - Graphite & Associated Metals	125	6	78	0	0	0	203
ILW	Fuel Stringer Debris - Graphite and Associated Metals	130	6	81	0	0	0	211
ILW	Graphite Samples	0.1	0	0	0	0	0	0.1
ILW	Graphite/THTR Waste	89	0	0	0	0	0	89
ILW	WAGR Stringer Graphite Debris - Conditioned	35	0	0	0	0	0	35
ILW	Windscale Pile1 and Pile 2 Graphite and Aluminium Charge Pans	0	0	2964	0	0	0	2964
LLW	Decommissioning : Graphite	0	0	0	0	57	4784	4841
LLW	Final Dismantling & Site Clearance : Graphite	0	0	0	0	795	7220	8015

(ILW: Intermediate Level Waste, LLW: Low Level Waste, FED: Fuel Element Debris, THTR: Thorium-based High Temperature Reactor) – source: 2007 UK National Inventory

There is a total of around 80,000 m^3 of irradiated graphite waste forecast to arise in the UK, of which around 80% is ILW and 20% is LLW. This includes legacy waste from the Harwell DRAGON project and other UK research programmes.

As shown in Table 1, there are currently two Magnox stations (each with two reactors) and seven AGR stations (each with two reactors) continuing to generate power commercially in the UK.

The UK Magnox reactors are now owned by the Nuclear Decommissioning Authority (NDA) with the sites operated formerly under contract by a single licensee Magnox Electric. In October 2008, two new licensee companies were created from Magnox Electric to maintain and operate (where appropriate) the UK Magnox reactor fleet. Magnox North has responsibility for Magnox plant located at Chapelcross, Hunterston A, Oldbury, Trawsfynydd and Wylfa. Magnox South has responsibility for Berkeley, Bradwell, Dungeness A, Hinkley

Point A and Sizewell A. Calder Hall is covered by the Sellafield site license and is managed under contract by Sellafield Ltd. The AGR reactors are owned and operated under license by British Energy

4.2 UK Graphite Moderated Reactor Design

Within the UK, graphite has been used as a moderator and reflector material for the reactors listed in Table 1. In some plant, graphite and other carbon materials have been used for fuel sleeves and other components. In the case of graphite sleeves, material is periodically removed during operation (from Chapelcross and from all the AGRs), segregated from the fuel and stored. During the lifetime of such plant, significant volumes of graphite will accumulate and will ultimately need treatment along with structural material. Carbon blocks have also been used in some reactor designs as shield walls and this may have some impact upon decommissioning activities.

This section focuses on the design details of the Magnox reactor cores and reflectors. Brief descriptions are provided for the non-commercial nuclear reactors (GLEEP, BEPO, the Windscale Piles and WAGR). Some general design details for the AGRs are also included. Descriptions of the relatively small (in terms of graphite inventory) DIDO and PLUTO Material Test Reactors (MTRs) and the DRAGON prototype high temperature reactor have been omitted.

The Graphite Low Energy Experimental Pile (GLEEP) at Harwell was the first reactor in Europe. It was an air-cooled graphite moderated reactor used for initial investigations into how to make a reactor work and later as an international standard for materials testing and calibration. Figure 2 shows a view of the pile during construction in 1947. The core structure contained approximately 550 tonnes of graphite in the form of basic prismatic bricks with chamfered corners providing channels for the fuel. The whole structure has been completely dismantled, as described in section 5.1 below.

Figure 2: View of the GLEEP moderator under construction at Harwell

British Experimental Pile '0' (BEPO) was used mainly for isotope production, general irradiations, chemical engineering experiments and as a source of neutrons for nuclear measurements. It was an air-cooled graphite moderated reactor containing approximately 863 tonnes of graphite. Initial decommissioning has been carried out and BEPO is now being kept in a safe care and maintenance regime before dismantling. Figure 3 shows a view of the reactor during its period under operation.

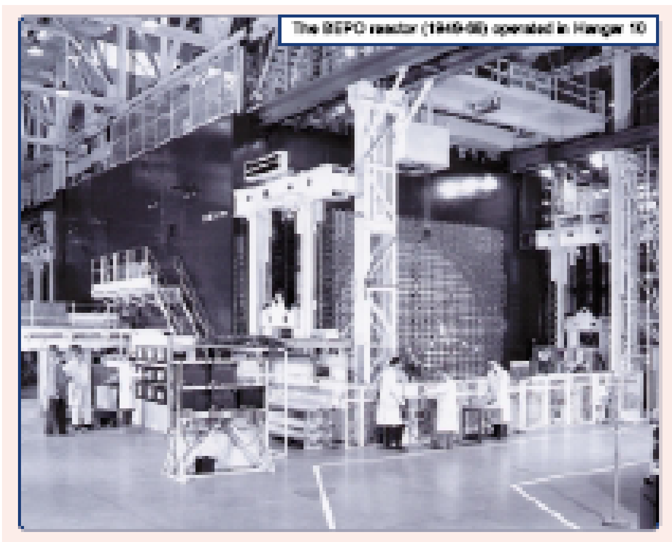

Figure 3: View of the BEPO reactor at Harwell

The Windscale Piles were primarily used to produce plutonium for the UK nuclear defence programme. Each reactor consists of approximately 2000 tonnes of graphite blocks in an octagonal stack, 15 metres in diameter and 7.5 metres long. The graphite blocks were pierced horizontally by fuel channels with the piles being cooled by air fed from two blower houses. Both reactors were shut down following a fire on Pile 1 in 1957 and have been subsequently kept in safe care and maintenance. The presence of damaged fuel in Pile 1 presents extremely demanding decommissioning challenges.

The cores in the first power producing UK Magnox reactors were designed with only a limited amount of information available regarding the anisotropic dimensional change behaviour of graphite. Consequently, as more information was gained, improvements to reactor core design were made. These changes are briefly described, as they will have an impact on decommissioning operations.

The primary graphite used for the construction of the Magnox reactor cores was PGA graphite (Table 3). The coke used for the production of the graphite was referred to as 'needle' coke because of the needle like appearance of the grains after crushing. The method of forming the basic shape of the graphite blocks involved extrusion. This method had the effect of preferentially aligning the grains and hence the crystallite basal planes in a direction parallel to the direction of extrusion. As a result, the properties of the graphite are anisotropic (or more specifically orthotropic, meaning that properties in the plane perpendicular to the extrusion direction are isotropic). A less pure graphite from an earlier stage of the same manufacturing process (Pile Grade B) was used for reflector components (side reflector and upper and lower reflector layers, depending upon design).

Table 3 UK Magnox reactor graphites

Graphite type	Principal raw materials	Manufacturer	Components
AGXP	Petroleum coke. No information on source of binder pitch and impregants. Extruded graphite.	Electrometallurgical Company, Welland, Canada for Calder Hall and Chapelcross.	Side reflector bricks and tiles.
Pile Grade A (PGA)	Needle petroleum coke and coal tar pitch binder. Coke from Shell refinery at Pernis, Holland. Binder pitch from Ford Motor Company at Dagenham and refined by North Thames Gas. No information on source of impregnants. Extruded graphite.	British Acheson Electrodes Ltd (BAEL) for Berkeley, Bradwell R2, Calder Hall, Chapelcross, Hinkley Point A, Hunterston A, Sizewell A, Trawsfynydd, Wylfa and Anglo Great Lakes Ltd (AGL) for Bradwell R1, Dungeness A, Hunterston A, Oldbury.	Moderator bricks, tiles and sleeves. For some designs, upper and lower reflector bricks. Keys associated with bricks of same material.
Pile Grade B (PGB)	Needle petroleum coke and coal tar pitch binder. Coke from Alberta oil fields and refined at Sainia, Canada, and from Shell refinery at Pernis, Holland. Binder pitch from Ford Motor Company at Dagenham, refined by North Thames Gas. No information on source of impregnants. Extruded graphite.	British Acheson Electrodes Ltd (BAEL) for Berkeley, Bradwell R2, Calder Hall, Chapelcross, Hinkley Point A, Hunterston A, Sizewell A, Trawsfynydd, Wylfa and Anglo Great Lakes Ltd (AGL) for Bradwell R1, Dungeness A, Hunterston A, Oldbury.	Side reflector bricks and tiles. For some designs, upper and lower reflector bricks. Keys associated with bricks of same material.

In the earliest Magnox reactors, Calder Hall and Chapelcross, the core is made up of layers of square cross-section bricks of side slightly smaller than the lattice pitch of 203 mm, with the extrusion direction along the brick axis. An isometric view of the Calder Hall reactor is shown in Figure 4. The reflector region around the core was built with no inter-brick gaps since irradiation effects in this region were considered to be negligible. Garter restraints (in the form of compensating beams) were placed around the periphery at the same height as the tile layers which meant that the tiles were fully constrained and the lattice as a whole would expand as graphite in the long tile direction (in effect radially). The compensating beams were designed to have a coefficient of thermal expansion close to that of graphite and so always provided the necessary restraining forces at the core boundary. The core does however expand at a different rate relative to its support structure and therefore the columns were mounted on ball bearings to cater for the differential.

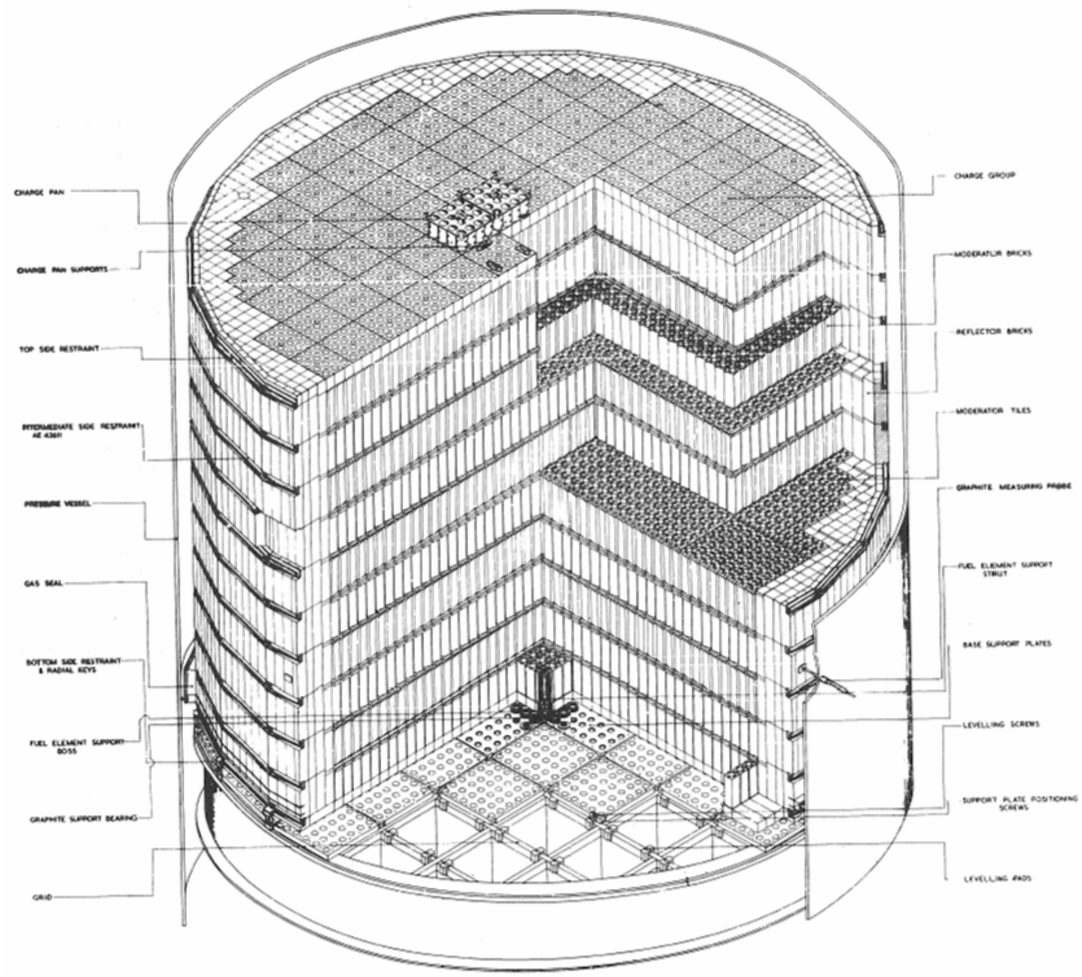

Figure 4: Isometric view of the Calder Hall reactor[8]

The bricks are approximately 800 mm in length and are interleaved with two layers of rectangular tiles having their extrusion axes placed horizontally and parallel with the long sides. The bricks and tiles in each column are located relative to one another by means of cruciform keys on the bricks and tiles as shown in Figure 5. In this way, the moderator bricks are located in their correct lattice position by the tiles and, because they have sides which are slightly shorter than the lattice pitch, have a gap around their vertical sides to accommodate the predicted lifetime growth of the graphite.

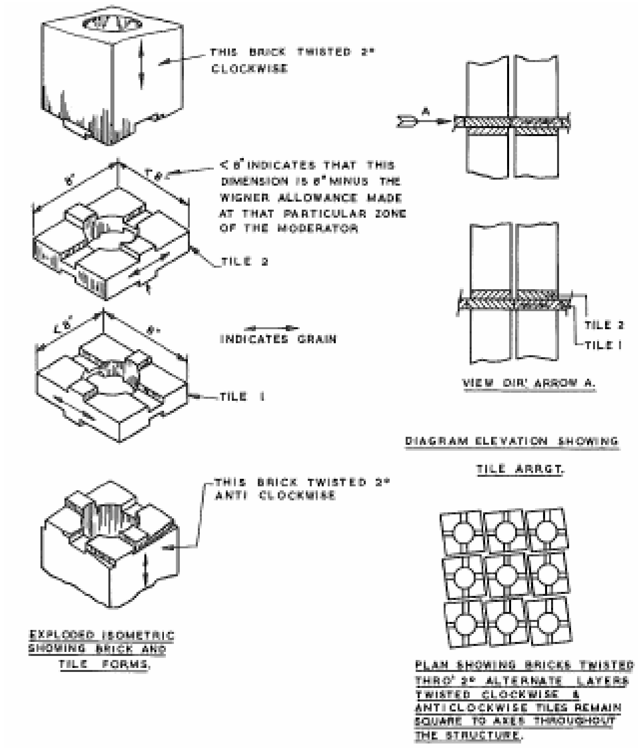

Figure 5: Isometric showing brick and tile forms and keying arrangement for the Calder Hall reactor design[8]

Although allowances were made for the different expansion/shrinkage rates between tiles and bricks and between parallel and perpendicular expansion to the extrusion axis, it was discovered later that PGA graphite actually shrunk in the direction parallel to the extrusion axis. It was realised that gaps would consequently open up between the tiles and so permit lateral movement of individual columns, which could affect cooling and control rod insertion. At the time that this behaviour became apparent, the graphite bricks for Berkeley, Bradwell and Hinkley Point A cores were at an advanced stage of machining. A decision was therefore made to incorporate zirconium pins in deep horizontal holes drilled into the bricks and/or tiles to maintain lateral alignment. Zirconium has a low neutron absorption cross section and therefore the small penalty of slightly reduced reactivity was considered acceptable. The arrangement adopted for Bradwell, in which the zirconium pins were located in the bricks, is illustrated in Figure 6.

The Trawsfynydd design was less advanced and a single tile at each brick junction utilising radial keys on the 90°and 45° axes was adopted. After Trawsfynydd, the brick and tile method of maintaining channel lattice alignment was abandoned, in favour of a full brick radial keying arrangement as illustrated in Figure 7. This is further illustrated in Figure 8 which shows the Oldbury core under construction.

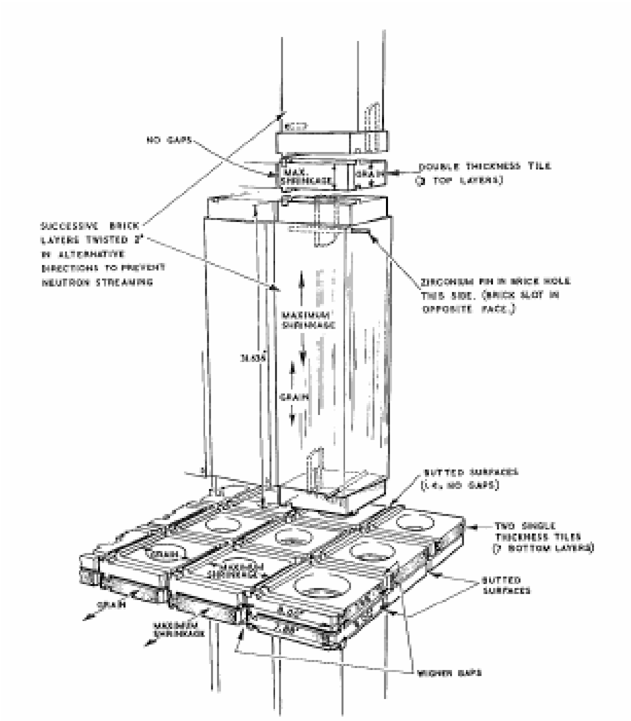

Figure 6: Arrangement of bricks and tiles in Bradwell graphite core[8]

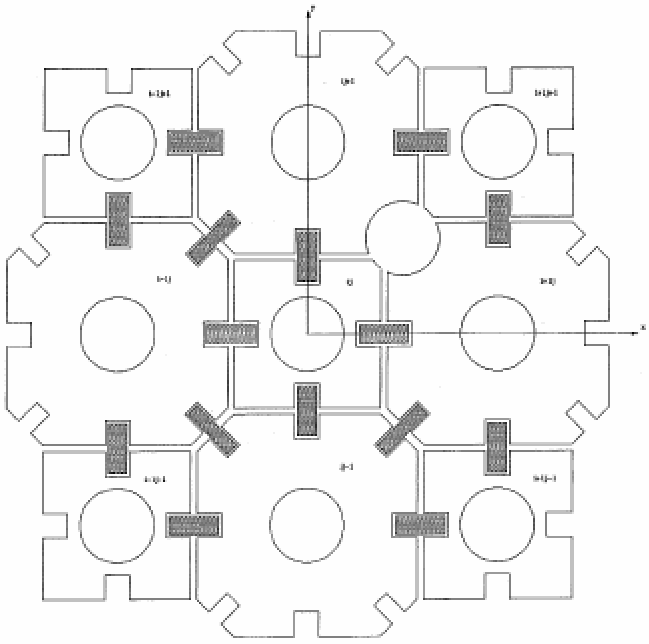

Figure 7: Keying arrangements in later Magnox core design (octagon and square bricks)

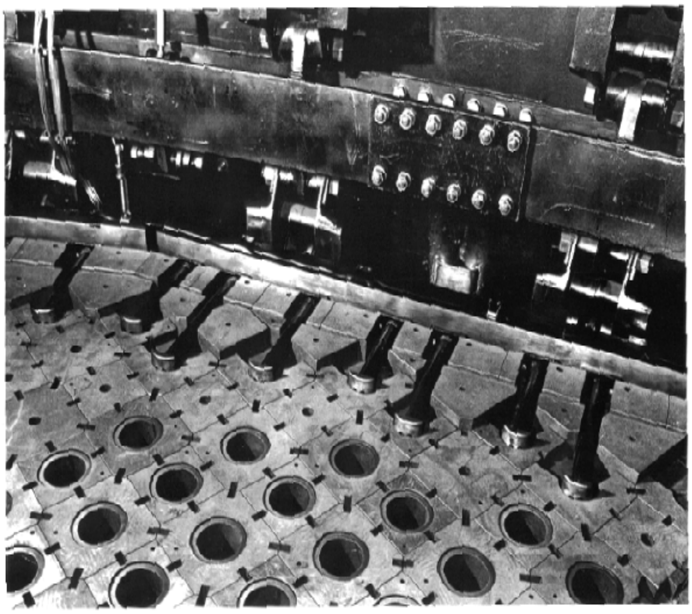

Figure 8: View of the Oldbury reactor core during construction showing the radially-keyed octagon-square brick arrangement

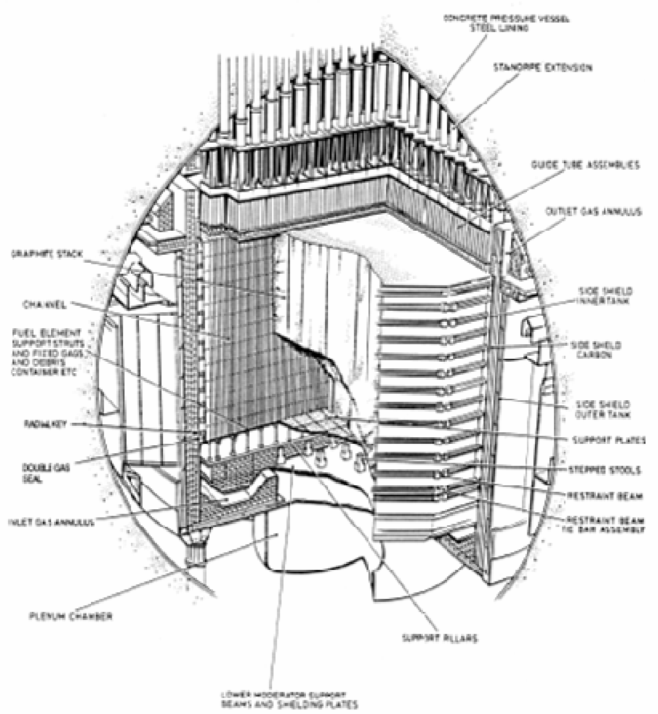

Figure 9: Isometric view of the Wylfa reactor

An isometric view of one of the Wylfa reactors is shown in Figure 9. The core consists of 13 layers of brick arranged as shown in Figure 7 and Figure 9. The moderator and surrounding graphite shell is approximately 18.6 m across the flats with a height of approximately 10.3 m. The moderator structure contains 6156 columns comprising over 80,000 graphite bricks. This was the final reactor design in the evolution of the Magnox stations.

Windscale AGR (WAGR) was designed as the prototype for the fleet of commercial AGRs operated by British Energy. The core was constructed from Pile Grade A (PGA) graphite. The bricks making up the core were rectilinear blocks, 230 mm in square cross section and length 800 mm. Within the active core, fuel bricks were made by introducing a 150 mm diameter channel up the length of the bricks. As will be described in section 5.2 below, the core has been entirely dismantled and transferred to concrete sealed boxes for temporary storage on the Sellafield site.

The AGR reactor design that evolved from the Magnox reactor design (such as at Heysham 2) achieved higher power densities by increasing channel gas outlet temperatures. This was engineered through a re-entrant flow design that maintained graphite and steel support structures within acceptable limits. The reactor inlet gas flow passes up the channels in the moderator bricks in an annulus between the bricks and a graphite sleeve surrounding the fuel. At the top of the core, the gas is forced down over the fuel within the graphite sleeves and then back to the heat exchangers. This design concept could be accommodated by a smaller graphite structure. An AGR core typically comprises an inner cylinder of moderator graphite (in 10 or 11 layers) surrounded (top, bottom and side) by reflector graphite. The bricks are approximately circular in plan with a diameter of about 460 mm and a height of about 850-900 mm. They are arranged in columns on a square lattice. The small bricks (Figure 11 and Figure 12) are about 190 mm square arranged in columns in interstitial positions.

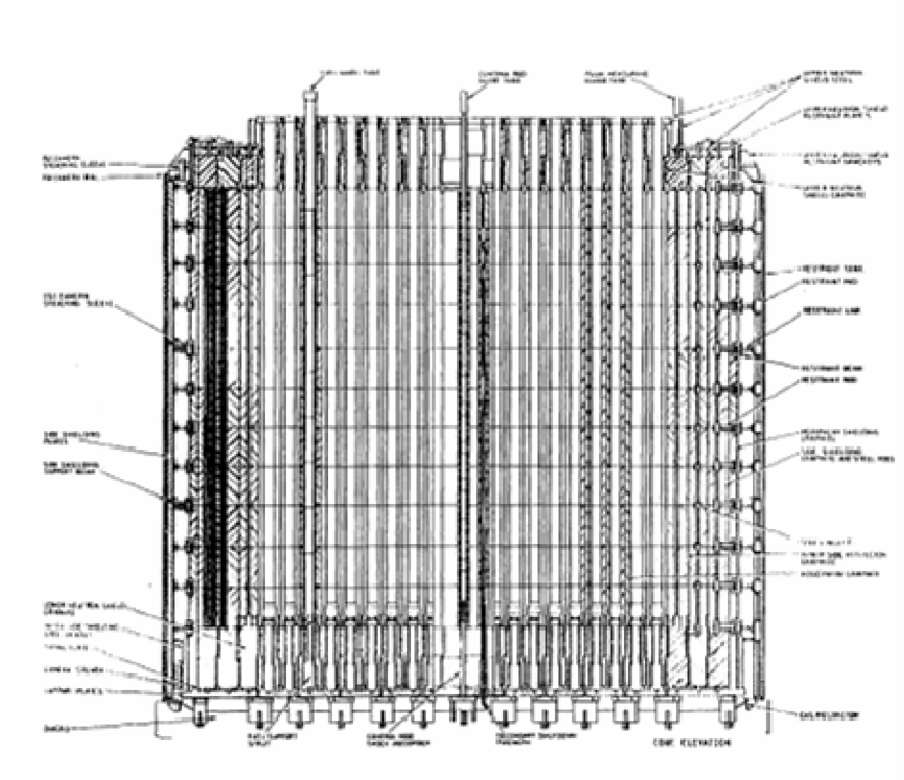

Figure 10: Section through Heysham 2 and Torness reactor core[9]

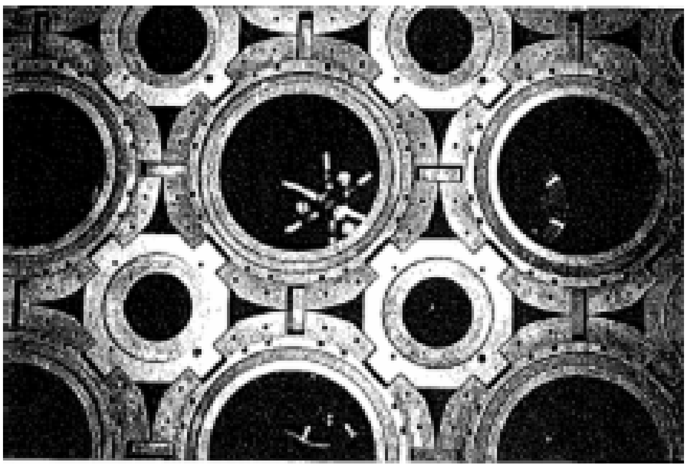

Figure 11: Keying arrangements in AGR core design[10]

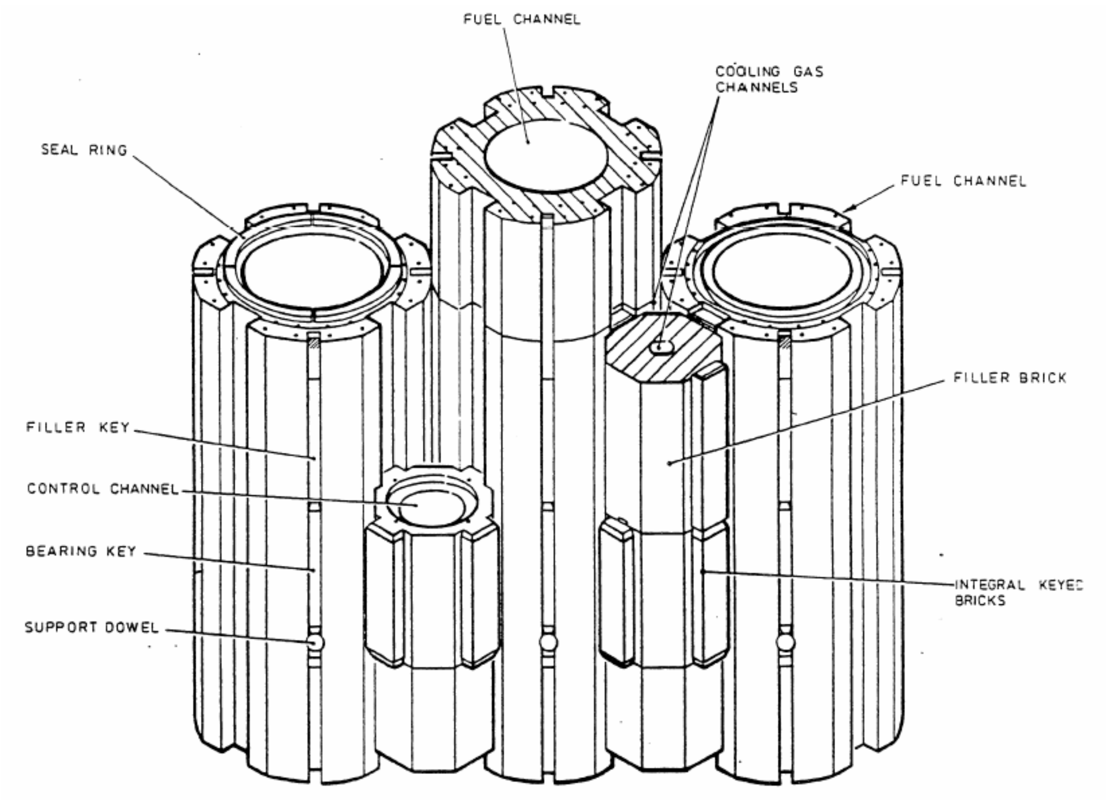

Figure 12: Schematic of AGR brick keying arrangement[10]

Two types of graphite are used in AGR cores. The permanent components are made from Gilsocarbon graphite, which used natural Gilsocarbon cokes as filler particles and flour (fine particle coke) impregnated with pitch to produce near-isotropic properties. The moderator bricks use graphite that is double impregnated, while the reflector and shielding bricks use graphite that is single impregnated. The fuel sleeves are made using needle coke particles double impregnated with pitch to produce slightly denser, near-isotropic graphite.

4.3 Other Materials Associated with the Graphite Core

Although reactor cores contain a significant quantity of graphite, other materials including steels also feature within the structures. Control rods, flattening bars and fuel stringer components are present and will need to be removed prior to dismantling of the graphite structure. However, other components such as Magnox sealing rings, thermocouples, wires connecting bricks and zirconium pins used to secure graphite bricks in some Magnox reactors cannot be removed prior to core disassembly and will have to be handled at the same time as the graphite.

The irradiation of steels in a neutron flux results in activation of alloying elements and impurities and the waste management strategy for steel will be similar to that for graphite. The key issues relate to heat production and radiation dose due to the activation products cobalt-60, iron-55, and nickel-63. Generally, for normal carbon steels, the dominant activation product for heat and dose is ^{60}Co. Although the care and maintenance (C & M) period will reduce the activity of graphite and steels, it is important to understand the chemical composition of steels used inside the reactors as special grades or alloys may introduce unusual radionuclides which could be important contributors to heat, dose and other aspects of the waste management strategy.

5 Decommissioning of UK Nuclear Reactors

The predicted timescales for the completion of decommissioning of UK plant span more than 100-years in total. Some of these reactors have been closed for some time, for example, Windscale Piles 1 & 2 (Figure 13). The Magnox stations have been following a planned closure programme over recent years and two remain in operation (Wylfa and Oldbury). Berkeley power station (Figure 14) was the first of the Magnox stations to start the decommissioning process. All AGRs are currently operating and will continue to generate electricity for some years.

Several reactors have already been decommissioned in the UK, including:

- small research reactors;
- University Research Reactor (URR) near Manchester ;
- TRIGA reactor at ICI Billingham ;
- ARGONAUT, the Scottish Universities Research Reactor

The decommissioning of GLEEP and Windscale AGR (WAGR) are of direct relevance to the Carbowaste project. The experience gained and, in particular, the retrieval techniques used to recover the graphite from these reactors is highly relevant to the Carbowaste project.

Figure 13: Windscale Pile Chimneys

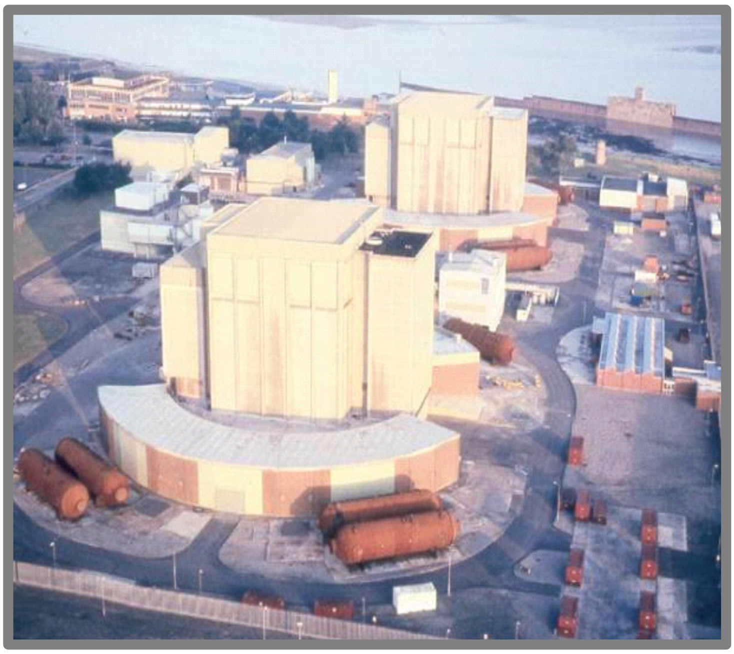

Figure 14: Berkeley Reactor Buildings

5.1 Decommissioning of GLEEP

GLEEP was a low energy research reactor on the Harwell site. It was decommissioned about 4 years ago and this involved removing about 13500 irradiated graphite blocks with a total mass of about 550 tonnes (the average weight of a graphite block ~40 kg). The blocks were of a simple design with chamfered corners to allow fuel insertion between the blocks. In the decommissioning process the blocks were removed from the reactor using a three-point drill and tap procedure to accommodate lifting eyes. The blocks were initially lifted in to a basket on the top of the graphite core (16 blocks per basket) and the basket lifted out of the reactor confines using a polar crane. Outside the reactor, vacuum lifting was employed to transfer blocks from the basket to a roller table via the monitoring station. The roller table was used to feed blocks into a crushing plant. The crushed graphite (<50mm fragment size) was drummed awaiting an acceptable disposal route. Most of this graphite has since been thermally treated in a commercial incinerator. This was observed to reduce the tritium and carbon-14 levels in the graphite, the balance having been discharged.

5.2 Decommissioning of WAGR

The WAGR reactor (Figure 15) was the UK prototype for the advanced gas cooled reactor programme. It produced 33MW(e) and ran from 1963 to 1981.The graphite core was contained within a 6 m diameter, 6 m high carbon steel pressure vessel and was cooled using carbon dioxide.

Figure 15 WAGR Reactor

Access to WAGR was by removal of the reactor head and thermal shield and then installation of a dismantling machine from which could be fixed various masts and tools for completely remote operations. The design of the dismantling machine commenced in 1982 and was used for the first time in 1999. The machine has been used for 9 separate campaigns, including the removal of the core graphite. The graphite was predominantly recovered using a ball grab suspended from a 3 tonne hoist which dropped down the fuel channel located on the blocks central vertical axis. Other items of graphite were also recovered using a ‘drill and tap’ lifting tool, again suspended from the 3 tonne hoist. Miscellaneous graphite waste was retrieved via a

Schilling manipulator deploying a variety of tools including, but not limited to, jaws, a yard brush and waste bins.

The WAGR graphite inventory comprised an active core and a surrounding wall of reflector blocks. A number of recovery techniques used or considered included a drill and tap technique, a ball-race (ball grab) device that could be inserted down the hole (for the fuel elements or control rods) in the graphite blocks and vacuum lifting. Approximately 80 graphite blocks located in the two thermal columns outside of the pressure vessel but within the bio-shield were recovered using hydraulic grabs that gripped at the bottom each block and separated each block from the adjacent block on the next row down (this was needed as each row was doweled vertically to the rows above and below). This tool was deployed from a cantilever beam lifting tool suspended from the 3 tonne hoist. The cantilever was required to reach the thermal columns which were located under the corbel, which prevented direct vertical access by the crane. Graphite that was too weak for lifting by the above methods tended to break up and fall to the lower tundish inside the reactor pressure vessel. The area contained operational waste and decommissioning waste from earlier campaigns, including, but not limited to, steelwork, asbestos and thermocouples. This miscellaneous waste was mainly recovered using a brush and shovel technique deployed from the Schilling manipulator.
Retrieved graphite blocks from the core were placed in half height waste baskets after sentencing surveys were taken. Two half height waste baskets would be then placed into a WAGR concrete box (a custom made concrete box with castings to accept a lid once full). The top half height waste basket containing graphite would be then fitted with an anti-flotation plate and filled with grout. Once set, the box would be capped with the lid and moved into temporary storage next to WAGR.

For WAGR, totally remote operations were required due to the enclosed location and radiation environment of the reactor vessel. Later campaigns also had large amounts of asbestos to retrieve and package. Once retrieved, items of waste passed through a sentencing cell where they were remotely monitored to obtain radiation readings, prior to being placed in baskets. Full baskets were then remotely lifted into boxes which were then grouted using an automated system. Only once the box lid was installed, did the box leave restricted areas.

5.3 Decommissioning Strategy for Magnox Stations

The current plan for decommissioning the Magnox stations is outlined in the NDA strategy document [11], and described in more detail in the individual lifetime plans for each site. This approach is illustrated in Figure 16 . The individual Magnox stations are at different stages of this process. Both Oldbury and Wylfa are still in operation, generating electricity whereas Berkeley is the most advanced in terms of decommissioning having ceased operation in the early 1990s.

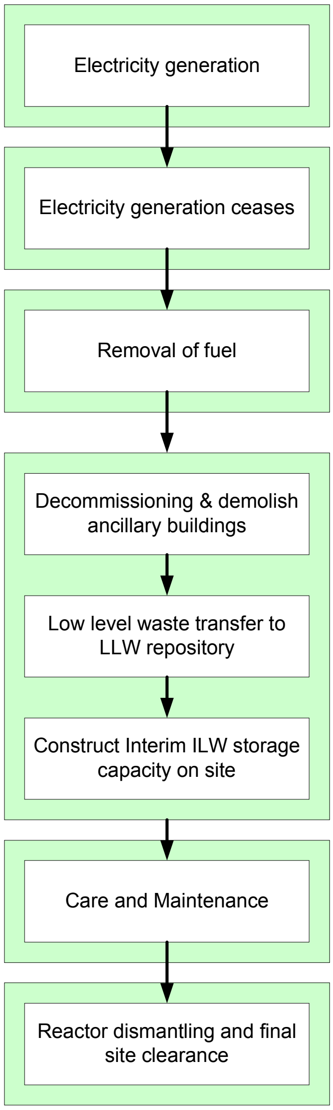

Figure 16 Magnox Decommissioning Phases

The general approach after the cessation of electricity generation at a station is;

- Defuelling the reactors, this removes around 99% of the radiological hazard from the site.
- Preparing for a care and maintenance regime, involving the decommissioning and demolition of ancillary buildings, disposal of low level waste to the low level waste repository and construction of new (interim) intermediate level waste storage capacity locally on the site for storage of retrieved operational and decommissioning ILW.
- Care and maintenance (C & M)
- Dismantling of reactors and ultimately site clearance

The current strategy is based on a preparation for care and maintenance period of 20 to 25 years and care and maintenance between 80 and 100 years. This approach is often referred to as the “safestore” strategy or sometimes the so called ‘3 box strategy’ (on the basis that during the care and maintenance phase, only the two reactor buildings and the ILW store remain in place). The current plan assumes ultimate disposal of the graphite in an ILW repository.
The decommissioning strategy, involving an extended care and maintenance phase, was originally adopted to allow time for shorter lived isotopes within the reactor buildings to decay, reducing dose rates to a level that would permit “hands on” dismantling and minimising the volume of ILW requiring disposal. However the counter argument is that extended care and maintenance period leaves dismantling and disposal activities to future generations.

Whilst this is the current strategy, the NDA strategy [12] referred to two potential innovative approaches that were under consideration at that time, to test the business case for accelerating the decommissioning operations. Firstly, a British Nuclear Group Innovation project which was based on experience in Spain, and involved accelerating the preparations for care and maintenance by retrenching all radiological activities into one area of the site and storing operational ILW on an interim basis within the reactor buildings. It was believed then that this approach could achieve care and maintenance status in around 5 years, at a lower cost than the base case strategy. This approach still required a care and maintenance period of 80 -100 years.
The second approach under consideration was based on the French approach, where they aim to complete decommissioning in 25 years, storing ILW on their sites until long term solutions are available.

6 Graphite Characteristics

Details of the UK Magnox graphite characteristics / data are contained in the separate Nuclear Graphite Overview chapter document.

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