RADIOACTIVE GRAPHITE MANAGEMENT AT UK MAGNOX NUCLEAR POWER STATIONS

G. HOLT
British Nuclear Fuels plc,
Berkeley, United Kingdom

Abstract. The UK nuclear power industry is predominantly based on gas-cooled, graphite moderated reactors with their being 20 operating and 6 shutdown Magnox reactors. The radioactive graphite issues associated with the Magnox reactors relate mainly to the reactor core graphite but, at two of the stations, there is also another graphite waste stream which results from the handling of their particular design of fuel elements which incorporate graphite fittings.

The decommissioning plan for the Magnox reactors is to apply the Safestore strategy in which the defuelled reactors will be maintained in a quiescent state, e.g. to gain benefit from radioactive decay, with their dismantling being deferred for a period of time. In preparing for and developing the decommissioning strategy detailed studies have been undertaken on all relevant aspects. These have resulted in, for example, extensive information on the graphite radioactive inventories, the condition of the graphite throughout the quiescent deferral period, safety assessment, and, dismantling, waste management and disposal plans.

Significant work has also been undertaken on the management of the graphite fuel element debris that has accumulated at the two stations. For example, work is well advanced at one of the stations to install equipment to retrieve this waste and package it in a form suitable for eventual deep geological disposal.

1. INTRODUCTION

The UK nuclear power industry is predominantly based on gas-cooled, graphite moderated reactors with there being 20 operating Magnox reactors (plus 6 other Magnox reactors that are now shutdown) and 14 Advanced Gas-Cooled Reactors (AGRs), in contrast to the single UK pressurised water reactor. Following the most recent restructuring of the UK nuclear industry all of the Magnox stations are now the responsibility of British Nuclear Fuels plc (BNFL). This paper focuses on radioactive graphite issues related to the UK Magnox reactor sites.

The 26 UK Magnox reactors are located on 11 different sites around the UK with 7 sites being in England, 2 in Scotland and 2 in Wales. Of these, 6 reactors on 3 sites have been shutdown and are undergoing the process of decommissioning. Although all these reactors are of the Magnox type, their detailed designs do vary quite significantly, e.g. in size and layout. The majority of the reactors are of steel pressure vessel construction but at 2 sites the reactors have concrete pressure vessels.

The principal source of radioactive graphite on the Magnox reactor sites is the reactor core graphite which serves the function of a neutron moderator and reflector. However, in addition to this, on 2 sites, there is an additional source of radioactive graphite (graphite fuel element debris) which results from their particular design of fuel elements

The issues associated with these source of radioactive graphite that are associated with the UK Magnox reactors are presented below.

2. GRAPHITE FUEL ELEMENT DEBRIS

The fuel elements for Magnox reactors comprise natural uranium rods contained within a magnesium alloy (Magnox) metal can. The detailed designs of the fuel elements vary from station to station and include various external features. On most fuel element designs these features consist of Magnox metal ‘splitters’ or ‘lugs’ to assist gas flow and heat transfer. However, at Berkeley the fuel element design also includes graphite struts and at Hunterston A a graphite sleeve. Following removal of the irradiated fuel elements from the reactors, the splitters and lugs, and the graphite struts and sleeves are removed from the elements prior to them being transported off site for reprocessing at Sellafield. The Magnox and graphite fuel element debris removed from the elements is retained on the reactor sites and throughout the operating lifetime of the reactors it has been accumulated and stored within concrete vaults on the reactor sites.

The two stations where this graphite fuel element debris waste stream has arisen are now shutdown and action is being taken to retrieve and treat this waste in a manner suitable for eventual disposal. At Berkeley the graphite fuel element debris is mixed with other, mainly Magnox, debris removed from the elements. There is approximately 1000 m^3 of this mixed fuel element debris accumulated within vaults at Berkeley, with about 90% of this being graphite. At Hunterston A there is approximately 1700 m^3 of graphite debris which has generally been stored segregated from the other Magnox debris. The graphite fuel element debris is classified as intermediate level radioactive waste (ILW) and for radiological protection purposes requires shielding and remote handling.

A number of options for treating this graphite waste stream have been considered with the two main process options being incineration and encapsulation. The incineration option has the advantage that it results in a significant reduction in waste volume. Studies into this option have been performed, including actual incineration trials. This work demonstrated that the incineration option is feasible and can be performed safely, and resulted in an outline design being prepared. However, the work also identified a number of difficulties.

A key requirement for successful incineration is that the feedstock material is appropriate and acceptable. The graphite fuel element debris, particularly at Berkeley, does contain other material than just graphite. One constituent is Magnox metal which if left in the feedstock could result in conflagrations within the incinerator. Development work has shown that it is very difficult to remove Magnox so as to reduce its content to the 0.5% acceptable level. The waste also contains some metallic components with high Cobalt content which results in high radiation dose rates. This has an impact on the materials handling, shielding and radiological protection requirements on the plant.

The incineration trials that were performed demonstrated that graphite is not readily incinerable. In order to initiate and achieve complete combustion of the graphite it was found necessary to size reduce the feedstock material to approximately 25mm size thus introducing an additional process step. The issues associated with the radiological impact of the discharges (e.g. of C14) from the plant were also addressed but, at the time of the study, they were not considered significant for the quantities of graphite fuel element debris involved. However, since this assessment, there has been an increased emphasis on reducing and not adding to existing radioactivity discharges.

In comparison with incineration the other main process option of encapsulating the graphite fuel element debris is less challenging technically and radiologically, although of course it does not achieve the significant waste volume reduction of incineration. The encapsulation process simply requires the waste to be placed, without any pre-treatment such as sorting, into drums and a cementitious grout to be added to produce a stable and passively safe waste form suitable for eventual disposal.

Following a comparison of the treatment options for the graphite fuel element debris it was decided to adopt the encapsulation process. The installation of plant to retrieve and process the waste in this way at Berkeley is now well advanced and plans are progressing to install similar plant at Hunterston A in the near future. At present in the UK there is no final disposal route for the drummed ILW resulting from the encapsulation process. The drummed encapsulated waste will therefore be placed into stores constructed on the reactor sites pending the availability of a national disposal route.

3. REACTOR GRAPHITE

The predominant source of radioactive graphite on Magnox reactor sites is the reactor core graphite. Some basic data on the size and weight of core graphite associated with the various reactors is presented in Table 1. This indicates that in total there is 50,650te or 36,600 m^3 of graphite associated with the UK Magnox reactors.

TABLE 1: REACTOR GRAPHITE DATA

Reactor Site	**No. of Reactors**	**Net Design Output/reactor MW(e)**	**Graphite Moderator and Reflector**		
			Diameter (m)	**Height (m)**	**Weight (te)**
Berkeley	2	138	14.6	9.1	1938
Bradwell	2	150	13.8	9.4	1931
Calder Hall	4	42	11.0	8.2	1164
Chapelcross	4	42	11.0	8.2	1164
Dungeness A	2	275	15.2	8.5	2237
Hinkley Point A	2	250	14.9	8.8	2475
Hunterston A	2	160	15.4	8.5	2150
Oldbury	2	300	14.2	9.8	2061
Sizewell A	2	290	15.7	9.4	2237
Trawsfynydd	2	250	14.6	8.3	1900
Wylfa	2	590	18.7	10.3	3740

Total number of reactors	26
Total volume of graphite for all reactors	36,600 m^3
Total weight of all reactors	50,650 te

The reactor graphite is a decommissioning waste stream as the reactor design is such that it is not removed or removable during the operational life of the plant. As the graphite is an integral part of the reactor it can only be considered as part of the overall decommissioning strategy for the complete reactors, i.e. the biological shield, reactor pressure vessel, core support structure and reactor core. The options for and the details associated with the decommissioning of the Magnox reactors have been subject to thorough study over about the last 20 years and the results of some of this work is indicated below.

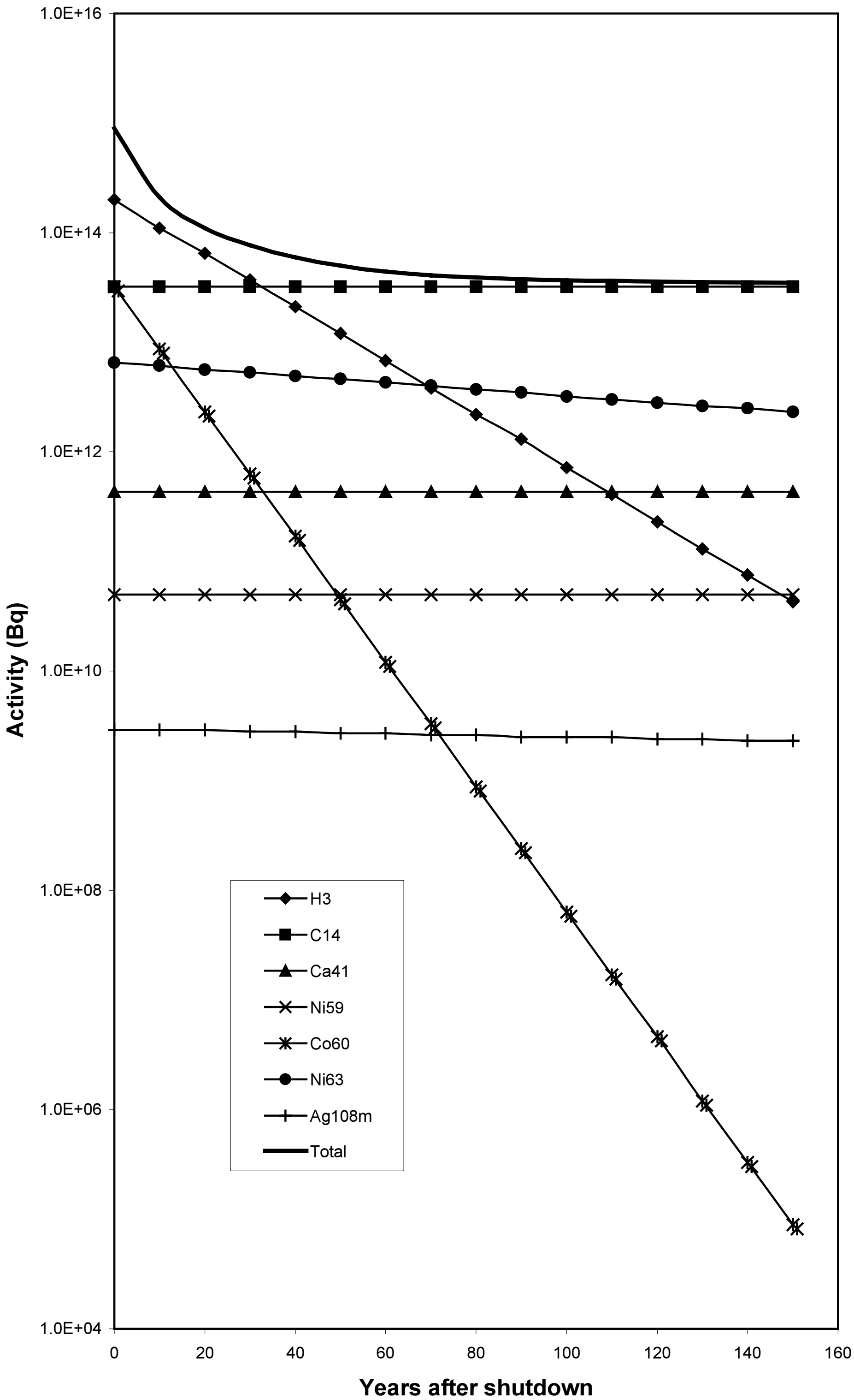

FIG. 1. Radioactive inventory of principal nuclides associate with reactor graphite.

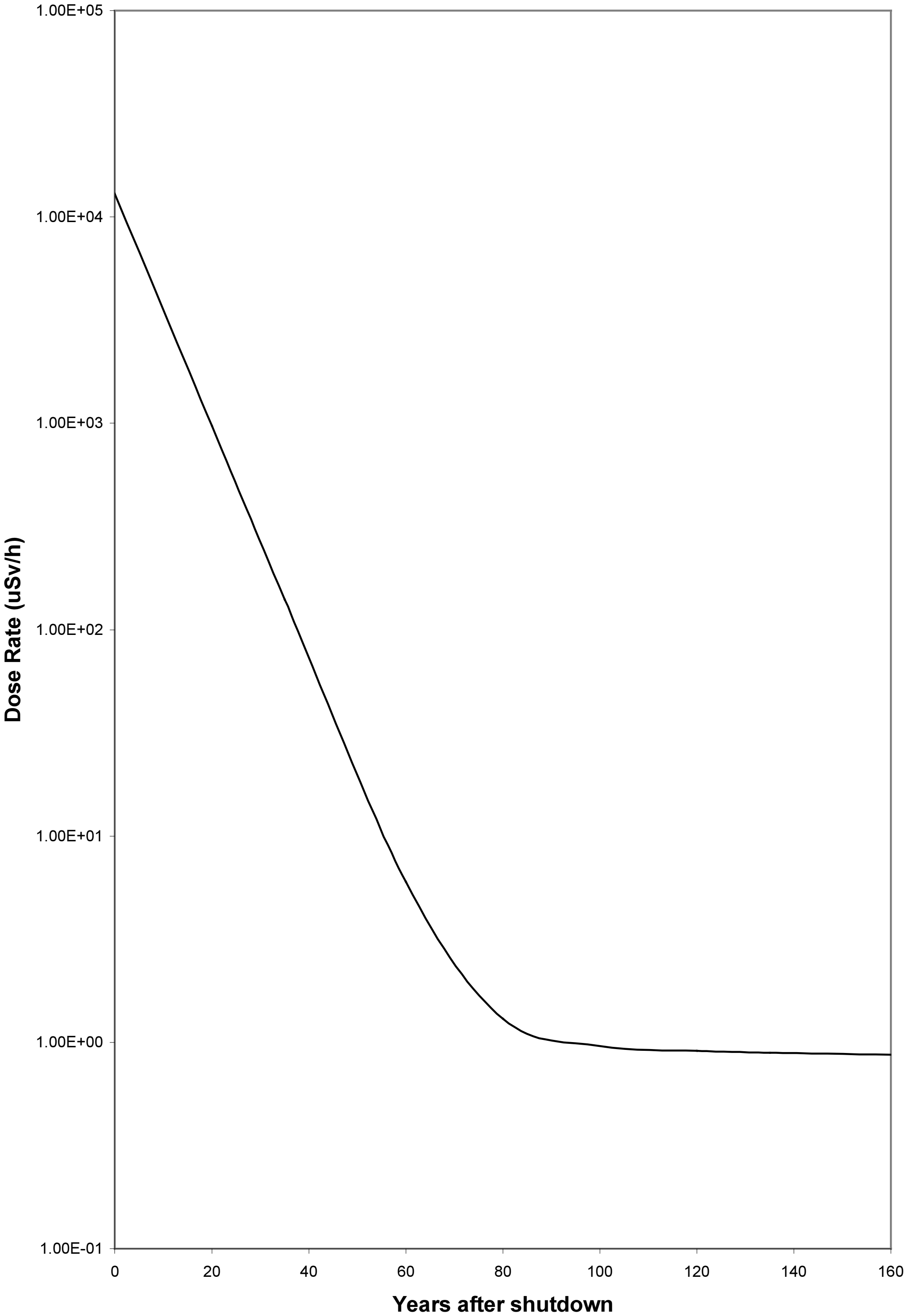

FIG. 2. Dose rates resulting from reactor graphite.

3.1. Radioactive Inventory

In order to successfully develop reactor decommissioning strategies and plans it is necessary to have a good understanding of the physical and radioactive inventory of the reactor materials. Significant attention has therefore been paid to determining such an inventory for each of the UK Magnox reactors. Detailed inventories have been derived by studying the engineering drawings, modelling the reactors and performing neutron activation calculations to determine the radionuclide content and activity level of each component of the reactors, including the graphite. Key input data for these calculations is the elemental composition of the materials and this has been determined by a programme of sampling and analysis of representative and actual materials.

The activation calculations have provided activity data related to 30 radionuclides for each reactor component and material type from which it is possible to see how the radioactivity content varies over time following reactor shutdown. Figure 1 provides activation inventory information on reactor graphite associated with one of the Magnox reactors for some of the key radionuclides. The results from the activation inventory calculations have been used to determine the radiation dose rates within the reactor and to show how these vary over time following reactor shutdown. Typical dose rates within the reactor resulting from the reactor graphite are shown in Fig. 2. There is an ongoing programme to validate these calculations by taking actual dose rate and gamma spectrometry measurements on a number of the reactors and the results obtained so far are very encouraging.

3.2. Reactor Dismantling

To access the reactor graphite to make it available for appropriate treatment and disposal it is necessary to dismantle the reactor. Detailed studies have been performed into how this could be done. The initial studies that were performed considered the complete dismantling of the reactors within about 20 years of station shutdown. This showed that it is technically feasible to perform the work at this time with available technology despite the complexity of having to perform the majority of the work with remotely operated equipment due to the high radiation dose rates associated with the reactor materials.

Further studies indicated that there are some potential benefits to be gained by dismantling the reactors on a later timescale, e.g. because radioactivity decay results in reduced radiation dose rates and radioactive waste arisings. Furthermore, for the graphite moderated reactors internal reactor dose rates will, over time, reduce to levels where man access into the reactors is permissible and it will not be necessary to use complex remotely operated equipment. Extensive work has been done to study this option of delaying reactor dismantling and this has demonstrated that it is a feasible option which can be undertaken successfully and safely.

The actual techniques, e.g. for cutting and materials handling, used in dismantling the reactors will remain the same regardless of the time when the dismantling is undertaken. Generally the only variable will be the degree to which remote operations will need to be used to apply the techniques. With respect to reactor graphite, the cores are made up of a stack of graphite blocks and dismantling will be the reverse of the original construction, e.g. removal block by block in a sequenced manner. The blocks have holes passing through them that form the fuel channels. These holes can be used during dismantling to allow the insertion of a mandrel for lifting purposes.

3.3. Decommissioning Strategy

The key variable associated with selecting the most appropriate decommissioning strategy option for Magnox reactors is the time at which dismantling should proceed. As stated above, reactor dismantling could be performed promptly (within about 20 years after reactor shutdown) or alternatively it could be delayed for a period. The main technical factor relevant to dismantling timing is radioactivity decay. As indicated by Figs 1 and 2, radioactivity levels and radiation dose rates reduce over time with the initial, relatively rapid, reduction in the first decades being dominated by Co60 decay. After a time the long lived radionuclides begin to dominate radiation levels and the rate of reduction falls dramatically. Figure 2 shows this happening, for graphite, after about 80 years or so after shutdown. If the full family of decay curves for all the reactor materials are considered then the maximum benefit from decay is achieved after about 130 years after reactor shutdown. For the Magnox reactors the reactor internal radiation levels at this time are such that fully remotely operated dismantling equipment is no longer required and hence the dismantling process is much less complex.

In order to select a preferred decommissioning strategy it is necessary to consider a wide range of factors and not just focus on one, or a limited number of factors. A rigorous strategy selection process has been performed (Ref. 1) and is kept under regular review. This has assessed a large number of safety, environmental, financial and other factors, considered their relative weightings and addressed sensitivities. This analysis resulted in the conclusion that the ‘Safestore’ decommissioning strategy is the most suitable for UK Magnox reactors. This strategy identifies that reactor dismantling could be deferred for up to 135 years after reactor shutdown. However, it should be recognised that this is a maximum and not a minimum deferral period and, as required to comply with UK Government Policy, the option of undertaking earlier dismantling has not been foreclosed.

3.4. Reactor Graphite Integrity prior to Dismantling

As part of the assessment of the viability of deferring the dismantling of the reactors, work has been performed to check whether there are likely to be any problems with the degradation of the reactor materials or structures during an extended deferral period. Two key requirements are to maintain the containment of the radioactive materials prior to dismantling being performed and to ensure that the ability to perform the eventual dismantling is not compromised.

The radioactivity associated with the reactors results from neutron activation of the materials, rather than contamination, and is therefore the radioactivity is not in a readily mobile form. It is also contained within a very substantial, robust and thick walled reactor vessel which will act as the primary containment barrier. Work to assess and monitor corrosion rates on the steel reactor vessels has demonstrated that they will be very low and hence containment will not be compromised under the planned storage conditions.

With respect to the long term integrity of the reactor graphite, a detailed review has been performed of the extensive body of knowledge on reactor graphite that has been built up over many years. This has considered what the potential degradation mechanisms and implications may be over a deferral period of up to 135 years. This review has considered such issues as Wigner Energy, the oxidation of graphite and carbon deposits, graphite dust explosibility, nitric acid and intercalation compounds, graphite property changes, leaching of materials from graphite, gas-phase activity release and the potential for particulate release. This work concluded that no special precautions are necessary during any deferral period to maintain graphite integrity.

During any period of deferral prior to reactor dismantling the reactors and any other structures remaining on the site will be subject to an effective care and maintenance programme to ensure the continuing safety and integrity of the structures.

3.5. Reactor Graphite Treatment and Disposal

Similar to graphite fuel element debris, the two principal and available options for the treatment of reactor graphite are incineration and packaging in preparation for direct disposal. As mentioned above, incineration is theoretically feasible but not without technical and radiological problems. These radiological concerns are more significant for reactor graphite than for the graphite fuel element debris. This is because of the much larger volumes that are involved and the higher specific activity levels associated with reactor graphite. For example, a study performed under the framework of the European Communities research programme (Ref. 2) identified concerns about the radiological impact resulting from the atmospheric discharge of C14 because of its long half-life (5730 years) and its mobility in the terrestrial environment.

In recognition of the technical and radiological concerns about graphite incineration it is assumed at present that the reactor graphite will not be treated by incineration but will be packaged for direct disposal following reactor dismantling. However, this position will be kept under review and any feasible treatment option that is identified or developed in the future will be given due consideration.

With regards to the disposal of reactor graphite it is presently assumed that it will be necessary to send it to a deep geological repository. No such disposal facility presently exists in the UK and this is another factor supporting the present proposal to defer the dismantling of the reactors for a period of time. A number of alternative disposal options have been considered for radioactive graphite, including shallow land burial, but again concerns have been raised about the potential radiological impact of C14, particularly with respect to the global collective dose into the far future. For example, as a result of this concern, Ref. 3 concluded that wastes with a significant C14 content should be disposed by deep underground disposal. It recognised that even though the collective dose that would be avoided by deep disposal compared to other disposal options would be small in comparison with that arising every year from natural radioactivity, its avoidance would be in line with international guidance.

4. CONCLUSIONS

The major source of radioactive graphite associated with the UK Magnox reactor sites is the core graphite. Detailed studies have been performed to determine the radioactive inventory of this graphite for all the Magnox reactors and to determine the most appropriate strategy for the decommissioning and dismantling of the reactors and the core graphite that they contain. Although it has been shown to be feasible to dismantle the reactors soon after station shutdown it is presently considered that it would be preferable to delay dismantling for a period of time. This would, for example, allow benefits to be gained from radioactivity decay and the associated radiation dose rate reductions and allow time for a deep geological waste repository to become available which could take the resulting waste. The implications of deferring the dismantling of the reactors have been considered in detail and no technical, safety or integrity problems have been identified with this approach. Throughout any deferral period the strategy will be subject to regular review and any alternative strategies or graphite treatment options that are identified will be given due consideration.

In addition to the reactor graphite, two of the Magnox stations also have stored arisings of graphite fuel element debris. The option for treating these wastes have also been considered and a decision made to retrieve and encapsulate the waste in a cementitious grout within waste packages. Work to achieve this is well underway.

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