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THE DECOMMISSIONING OF COMMERCIAL MAGNOX GAS COOLED REACTOR POWER STATIONS IN THE UNITED KINGDOM

G. HOLT
Magnox Electric plc, Berkeley Centre,
Berkeley, Gloucestershire,
United Kingdom

Abstract

There are nine commercial Magnox gas-cooled reactor power stations in the United Kingdom. Three of these stations have been shutdown and are being decommissioning, and plans have also been prepared for the eventual decommissioning of the remaining operational stations. The preferred strategy for the decommissioning of the Magnox power stations has been identified as 'Safestore' in which the decommissioning activities are carried out in a number of steps separated by quiescent periods of care and maintenance. The final clearance of the site could be deferred for up to 135 years following station shutdown so as to obtain maximum benefit from radioactive decay.

The first step in the decommissioning strategy is to defuel the reactors and transport all spent and new fuel off the site. This work has been completed at all three shutdown stations. Decommissioning work is continuing on the three sites and has involved activities such as dismantling, decontamination, recycling and disposal of some plant and structures, and the preparation of others for retention on the site for a period of care and maintenance. Significant experience has been gained in the practical application of decommissioning, with successful technologies and processes being identified for a wide range of activities. For example, large and small metallic and concrete structures, some with complex geometries, have been successfully decontaminated. Also, the reactors have been prepared for a long period of care and maintenance, with instrumentation and sampling systems having been installed to monitor their continuing integrity. All of this work has been done under careful safety, technical, and financial control.

1. INTRODUCTION

There are nine commercial gas-cooled reactor power stations of the Magnox type in the United Kingdom. These are owned and operated by the recently established (1996), sole remaining public sector electricity utility, Magnox Electric. Each of these stations consists of twin gas-cooled, graphite moderated reactor units which use Magnox clad natural uranium fuel. The stations were commissioned between 1962 and 1971 and six of them are still operational. The other three stations have been shutdown and are in the process of being decommissioned. These decommissioning stations are Berkeley in England which was shutdown in 1989, Hunterston A in Scotland which was shutdown in 1990 and Trawsfynydd in Wales which was shutdown in 1993.

Magnox Electric, and its predecessor companies, have undertaken extensive studies over many years to develop detailed strategies, plans, processes and costings for the decommissioning of all of its stations. These plans are now being implemented at the three shutdown stations and are available for implementation in the future when the other stations reach the end of their operating lives.

2. DECOMMISSIONING STRATEGY

A wide range of decommissioning strategies have been considered for the Magnox stations ranging from dismantling the whole station immediately following station shutdown through to not clearing the site but burying the main radioactive parts such as the reactors in-situ.

Work originally undertaken in the 1980s identified that there were potential technical and economic benefits in deferring the dismantling of parts of the stations, and that this was particularly marked for the reactors. A typical radioactive dose decay curve over time following station shutdown for a Magnox reactor internals is shown in Fig 1. The rate of dose decay is initially dominated by the short half-life radionuclide Cobalt-60 and hence it continues to fall rapidly by orders of magnitude until a level is reached at which the radiation dose becomes dominated by longer lived radionuclides such as Niobium-94 and Silver-108m. The rate of dose decay over time then begins to level off and, after about 135 years following reactor shutdown, there is no further significant reduction in dose rate over time. Although the dose rate within the reactors is too high to allow any internal man-access for some decades following station shutdown, by the time the dose decay curve has levelled off significant man-access is allowable.

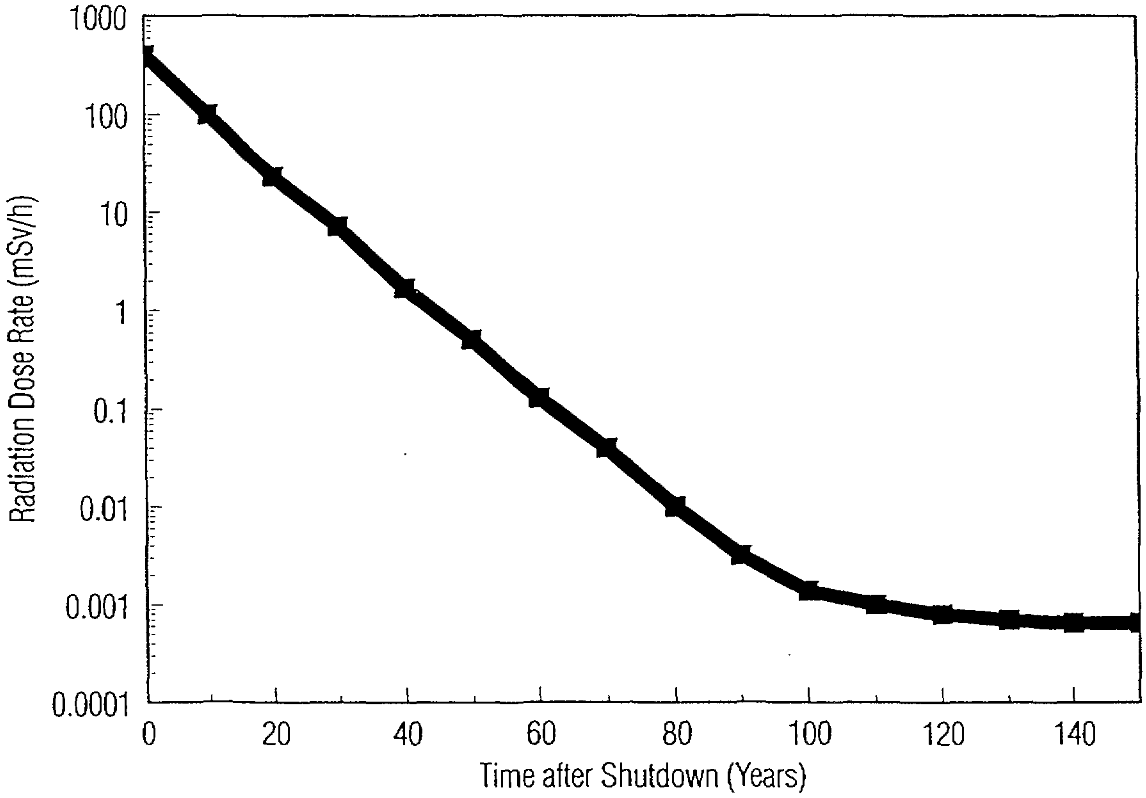

FIG. 1. Reduction in dose rate with time inside a typical Magnox reactor

If reactor dismantling was to be undertaken in the early years following station shutdown it would have to be done fully remotely using sophisticated machinery, and would generate large quantities of radioactive waste and involve the handling of highly radioactive materials. Deferring the dismantling of the reactors by up to 135 years to allow the substantial radioactive decay to occur would mean that 'manual' dismantling using simple technology would be possible. Also, radioactive waste quantities would be much lower as would be the radiation dose rates on the materials needing to be handled.

The shape of the dose decay curve is typical for all reactor types but, for the Magnox gas-cooled graphite moderated reactors, the dose rate at which the curve levels off is much lower than for water reactors for which it is 2 to 3 orders of magnitude higher. This means that there are not the same benefits in deferring the dismantling of water reactors as there clearly are for the Magnox reactors. This may not be a significant disadvantage for water reactors because of their small size and ease of dismantling but the benefits that accrue for the Magnox reactors are particularly marked because of the large size and complexity of the reactor structures. Magnox steel reactor pressure vessels are typically spherical of 20m diameter and weigh 5,000te.

Extensive studies have been performed to determine the most appropriate strategy for the decommissioning of the Magnox reactor power stations. These have taken account of the benefits associated with radioactivity decay, as indicated above, as well as a wide range of other technical, safety, environmental and economic factors. Various strategy options have been considered and compared in a rigorous and systematic way using multi-attribute decision analysis techniques. These studies concluded in 1990 that the 'Safestore' strategy was the preferred option for the decommissioning of the UK's commercial gas cooled reactors, including the Magnox reactor power stations (Ref 1). The final study leading to this decision was independently reviewed, confirming the outcome, and in 1995 a UK Government policy review identified Safestore as a potentially feasible and acceptable strategy for decommissioning nuclear power stations (Ref 2).

The Safestore strategy can be described as follows in terms of the three standard stages of decommissioning:-

Stage 1: Defuelling
Care & Maintenance Preparations
Care & Maintenance 1

Stage 2: Safestore Construction
Care & Maintenance 2

Stage 3: Site Clearance

The Safestore strategy has not been rigorously defined in detail but is flexible in application so that it can accommodate changes in circumstances or reflect specific situations at individual stations. A key feature of the Safestore strategy is to defer the dismantling of radioactive plant and structures where there are demonstrable overall benefits in doing this, subject of course to the essential requirement that the safety of the workforce and public is maintained at all times. This strategy enables the hazards associated with the station to be systematically and progressively reduced.

The first step in the Safestore strategy is to defuel the reactors and transport the fuel off-site for reprocessing, which removes about 99.9% of the radioactivity from the site. This is followed by a period of preparatory work during which the majority of the inactive and some of the radioactive plant and buildings will be removed, and the remaining materials, plant and buildings prepared for a period of care and maintenance. After this period, which could typically last until 35 years following station shutdown, it is assumed that it will be necessary to upgrade the buildings on the site to enable them to remain in a safe, secure and weatherproof condition until final site clearance which could beneficially be deferred until up to about 135 years after station shutdown. It is therefore proposed, as the first step in Stage 2, to convert the buildings into what has been termed 'safestore structures', eg by recladding them in very durable materials. The second period of care and maintenance will then eventually lead to the final site clearance stage when the site will be returned to a 'green-field' status.

The Safestore strategy as described above indicates that there will be two periods of care and maintenance prior to final site clearance and this is how it is presently being applied at Berkeley and Hunterston A. However, the built-in flexibility means that if circumstances are appropriate it is possible to move directly from defuelling through to the Stage 2 activities and only implement the second period of care & maintenance. This version of the Safestore strategy is being applied to Trawsfynydd.

3. ARRANGEMENTS FOR DECOMMISSIONING

All activities on a UK nuclear power station are subject to the Conditions stated in the Nuclear Site Licence and are subject to monitoring and scrutiny by independent regulators). These Conditions are standard for all nuclear sites and apply equally to operational and decommissioning. There is therefore no requirement for a re-licensing stage when a station ceases operation and starts decommissioning. However, the change in status of the site does involve new activities, procedures and arrangements and this does necessitate the preparation, submission, approval and demonstration of various aspects of these changes. All of these processes are subject to the Company's own internal scrutiny and approval arrangements but the more significant aspects require submission to and acceptance by the regulators. These include changes to the overall site safety case, eg for defuelling, and to the site management arrangements. All decommissioning activities are subject to an appropriate level of safety assessment.

Berkeley was the first full scale commercial nuclear power station to be shutdown in the UK and therefore this was the test-bed for developing in detail, applying and demonstrating suitable arrangements for progressing decommissioning and satisfying the regulatory requirements. The lessons learnt from this period have been applied to the decommissioning of Hunterston A and Trawsfynydd Power Stations which closed at a later date. These arrangements are sufficiently flexible to take account of the changing nature of the site, the reducing staffing levels and the associated safety issues as decommissioning progresses. The arrangements and regulatory considerations need to recognise the significantly reduced safety issues and hazards associated with a decommissioning station as compared to an operating station. This reduction occurs after shutdown when the reactor is held firmly sub-critical and not at temperature or pressure, and is most marked following the completion of defuelling and the removal of all fuel from the site.

Financial arrangements for decommissioning is another key issue. The UK practice is to make appropriate financial provision during the operating lifetime of stations for their eventual decommissioning, taking due account of when decommissioning activities are expected to occur by applying cost discounting. Detailed technical and economic studies have been performed to derive decommissioning cost estimates for provisioning purposes, and allowances for uncertainties and risks have been included. To support actual decommissioning work on stations, financial control and monitoring processes have been implemented and these have enabled, for example, actual expenditure to be checked against that predicted thus allowing improvements to be made in future expenditure estimates.

Decommissioning of a nuclear power station is a major project and therefore to manage all the work, including the safety and regulatory issues, requires the application of the full range of project management systems and disciplines. Magnox Electric performs the overall Project Manager role for the decommissioning on the sites and, as appropriate, lets contracts for services or decommissioning activities. The Company, as the holder of the Nuclear Site Licence is responsible for and must remain in control of all safety issues.

4. DEFUELLING

Defuelling of the reactors is the first decommissioning activity that is undertaken and it has been completed at each of the three shutdown stations. Magnox reactors contain typically about 30,000 to 40,000 individual Magnox fuel elements each about 60cm long. Magnox reactors are designed for on-load refuelling and at the standard rate of refuelling it would take about 5 years to defuel the reactors. However it was recognised that this process could be speeded up as there was no longer a requirement to add new fuel alongside fuel removal, and operations could be performed with the reactors depressurised and with an air rather than carbon dioxide atmosphere. These revised fuel removal processes necessitated some modifications to the reactor fuelling machinery.

Defuelling of the reactors requires a new safety case to be prepared that addresses relevant fault conditions and, for example, confirms the acceptability of removing fuel which introduces empty fuel channels and could reduce the cooling flow to the remaining fuel. Fuel was removed systematically, normally starting at the peripheral channels and working towards the centre of the reactor. Prior to the start of defuelling all the control rods were lowered into the reactors and electrical supplies to them isolated so that no more than one rod could be raised at any one time.

The rate at which fuel could be removed from the site was not controlled by how quickly the fuel could be removed from the reactors but by the rate at which fuel transport flasks could be prepared for dispatch. One of the limiting factors in the transport safety case, and hence the number of fuel elements that can be put into a fuel flask, is the residual heat load of the elements. During the defuelling period the heat load reduces sufficiently to allow an increased loading within the flasks by up about 20%. Revised transport safety cases were therefore prepared for irradiated fuel from defuelling which assisted in reducing the overall duration.

Berkeley was the first station to be defuelled and, with the improvements that were identified and introduced in that period, it was completed within 3 years of station shutdown, ahead of the originally predicted programme and about 30% below the identified budget. The experience gained and lessons learnt at Berkeley were applied to later defuelling activities thus enabling, for example, defuelling at Trawsfynydd to be completed in 2 years.

One issue associated with defuelling that was recognised as important prior to the start of defuelling at Berkeley, and which has been borne out by experience, is the need to apply quality control procedures to verify the removal of all fuel from the reactors, and the station. This is particularly relevant to Magnox reactors which contain a large number of fuel channels and fuel elements, each of which are removed and handled separately. Special procedures were adopted and video recordings of fuel handling operations made and reviewed. Human factor assessments were performed to check where errors could occur and to predict their probabilities and significance. Although there was a strong emphasis and regulator interest in verifying complete fuel removal, safety assessments have shown that the consequences of some fuel remaining in the reactors is not significant.

5. PREPARATIONS FOR CARE & MAINTENANCE

Following the completion of defuelling on the three shutdown stations, decommissioning work has continued in preparation for a quiescent period of care and maintenance in accordance with the Safestore strategy. The extent of work undertaken and planned at each site does vary and reflects the time period since station shutdown and individual circumstances at each site. Progress at Berkeley has been the most extensive as can be seen by comparing Fig 2 which shows the station prior to decommissioning and Fig 3 which is a more recent photograph. The work undertaken at Berkeley is more extensive than the minimum level possible under the Safestore strategy but this has been due to a number of reasons. For example, the station layout was unique with external primary circuit ducting and boilers, the commercial climate has been favourable and, as it was the first commercial nuclear power station to be shutdown, there were perceived to be benefits in demonstrating that decommissioning could be progressed without difficulty.

Some of the decommissioning work done at Berkeley is being repeated at Hunterston A and Trawsfynydd although progress is not as advanced. At Trawsfynydd it is intended to moved directly to Stage 2 of the Safestore strategy without applying the intervening Care & Maintenance 1 step. This reflects its unique remote, inland location in a National Park and a local public consultation exercise that was undertaken which highlighted the importance of maintaining local employment and reducing the site's visual impact. It is therefore planned to significantly reduce the height of the reactor buildings, which will involve significant active plant dismantling, and to reclad and improve the appearance of the residual buildings. The extent of work is indicated by comparing Fig 4 which shows the station prior to shutdown and Fig 5 which is an artist's impression of the final safestore structures.

Some of the main post-defuelling decommissioning activities that have been undertaken on the shutdown sites are described below.

5.1 Dismantling

The scale of the Magnox reactor primary circuit components, such as gas ducts and boilers, is large and they are lightly contaminated internally (predominantly by Cobalt-60) although some sections have also been activated by neutron irradiation. At Berkeley the high level top gas ducts had to be removed from their external position where they would have been exposed to weather induced degradation if dismantling had been deferred. This required the ducts to separated from the primary circuit and then lifted and lowered to ground level in large 35m long 100te sections (Fig 6) prior to being cut up into smaller pieces for longer term on-site storage, or decontamination and disposal as inactive scrap metal. For similar reasons it was also found necessary to dismantle the 16 buildings containing the boilers and

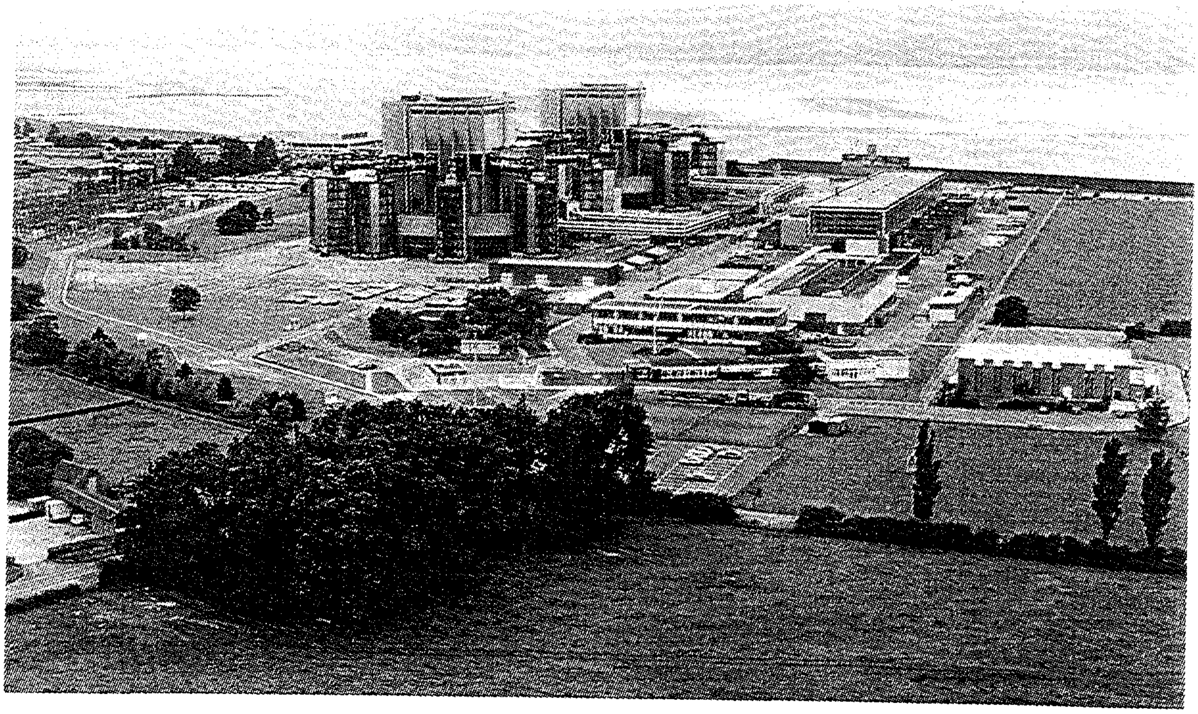

FIG. 2. Berkeley Power Station before the start of decommissioning

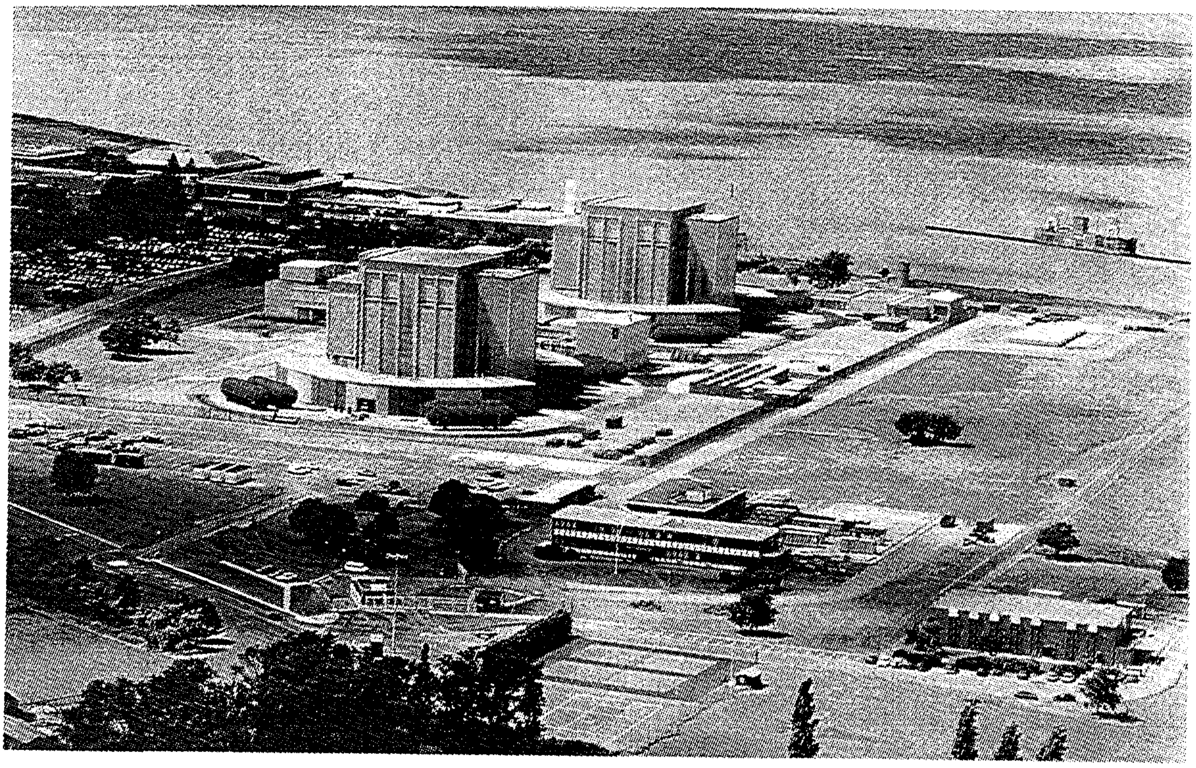

FIG. 3. Berkeley Power Station following decommissioning works (1996)

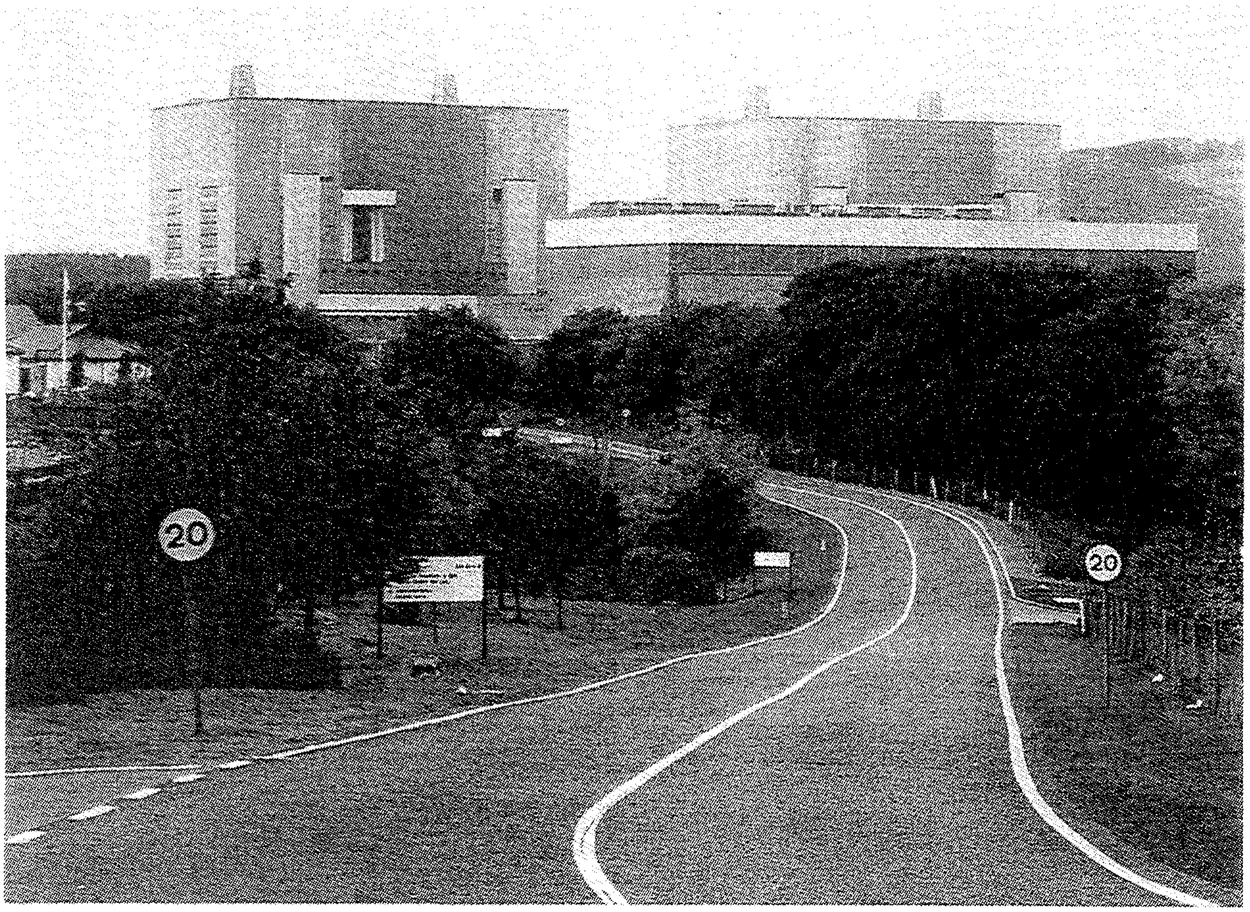

FIG. 4. Trawsfynydd Power Station before the start of decommissioning

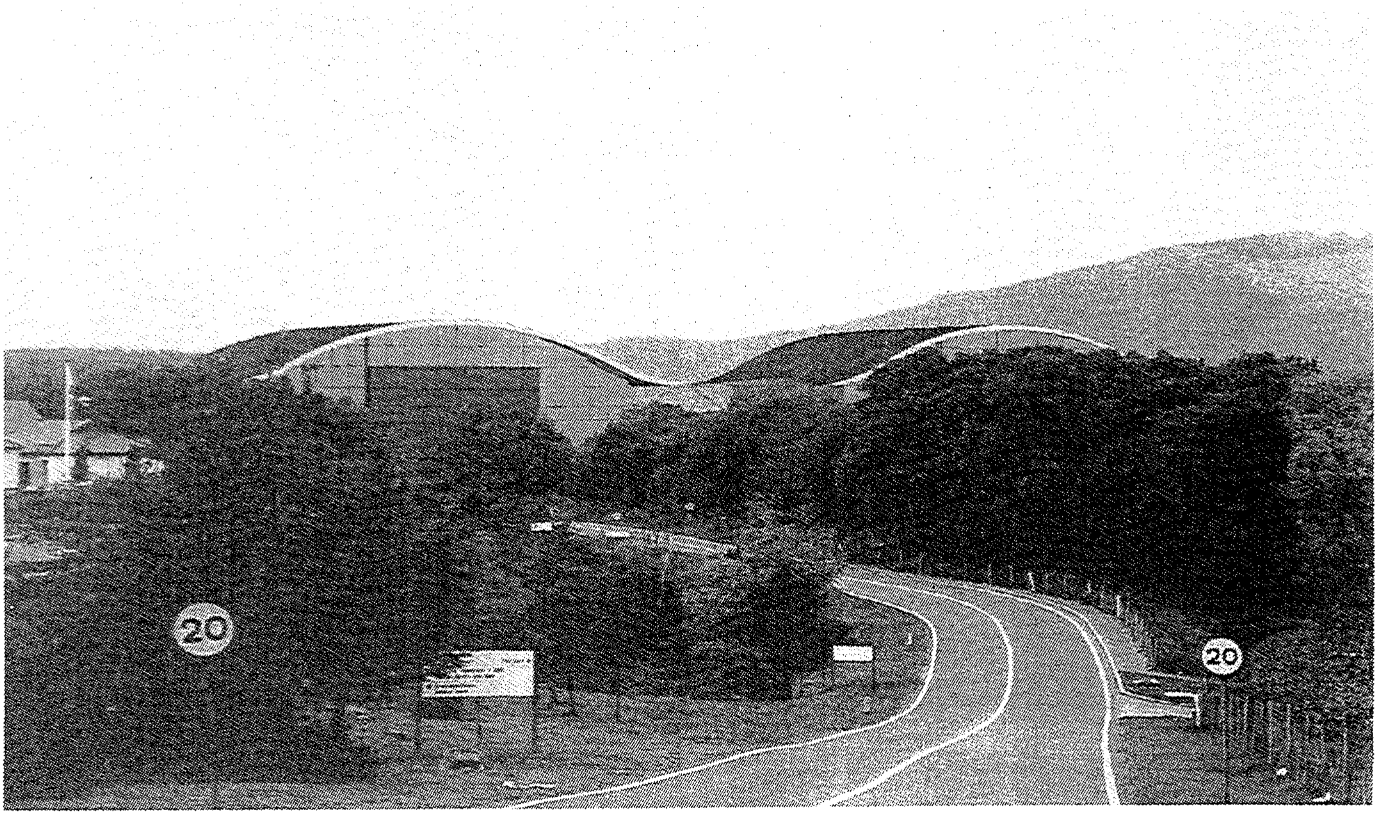

FIG. 5. Trawsfynydd Power Station following safestore construction (artist's impression)

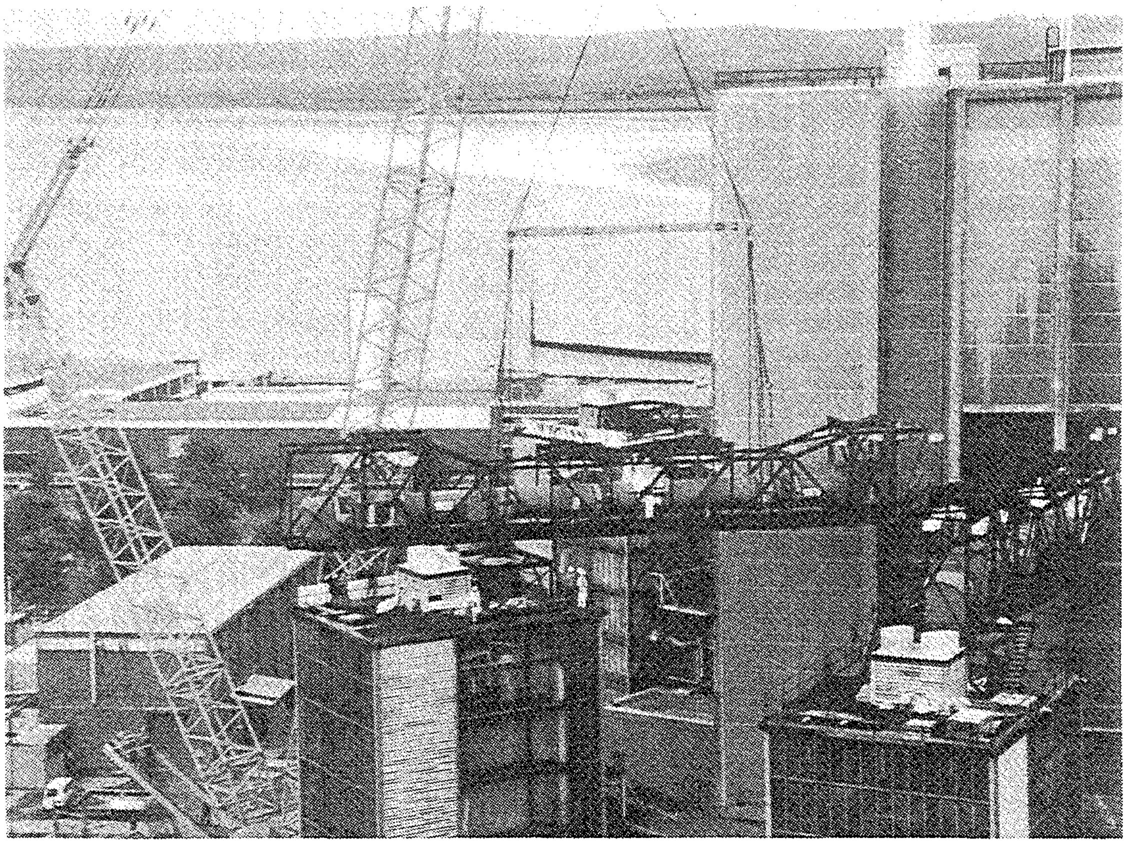

FIG. 6. Berkeley Power Station top gas duct removal

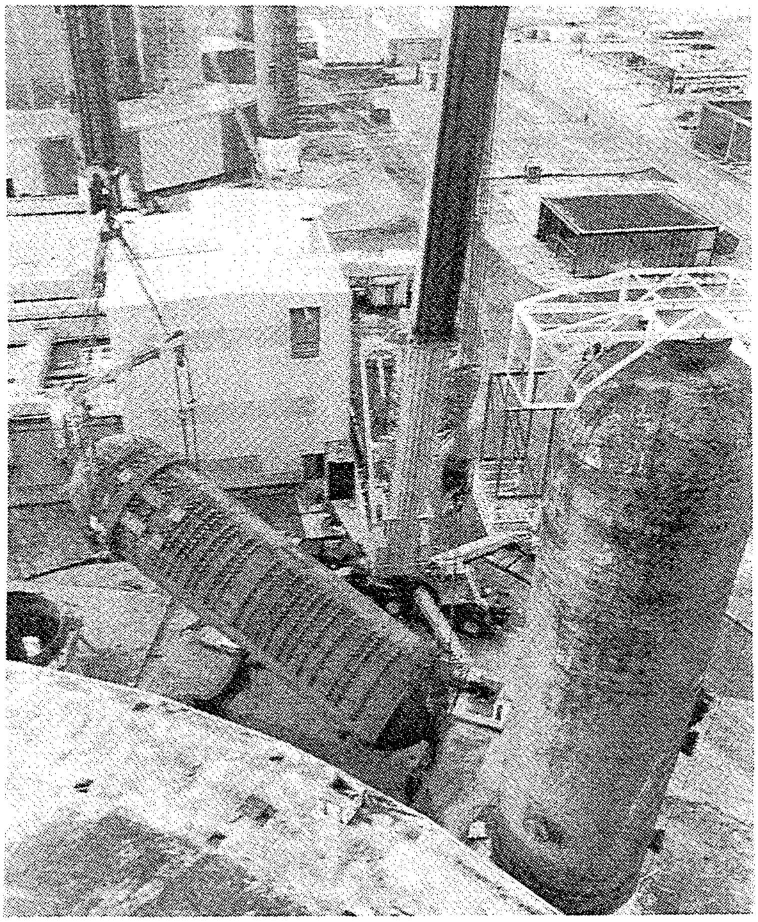

FIG. 7. Berkeley Power Station boiler lowering to the ground

then, to improve the visual appearance of the site, the boilers which weigh about 300te each were lowered to a horizontal position at ground level (Fig 7). Dismantling has therefore involved heavy lifting and handling issues as well as the more usual radioactive aspects.

Other primary circuit related components such as fuelling machinery and reactor gas circulators and plant have been dismantled. This has involved the removal, handling and treatment of some unusual constituents such as bitumen in semi-liquid form and high density polythene chippings that were used for neutron shielding purposes. The gas circulator plant also contains large quantities of oil, typically $50m^3$ per reactor, which is lightly contaminated by tritium. Treatment options being considered are incineration and continued storage to achieve natural decay to inactive levels.

As well as plant associated with reactor gas circuits which are generally contaminated by activation products such as Cobalt-60, there is also plant associated with liquid systems contaminated by fission products such as Caesium-137. Plant associated with the fuel cooling ponds falls into this category. A large proportion of it has been submerged below the pond water level during the station operational period but, when stations are being decommissioned, it is intended that the ponds will be drained and it is therefore necessary to remove such plant. This work has been undertaken at the shutdown stations and has required more extensive contamination control provisions than for the dismantling of the reactor gas circuit plant.

It has been found that the dismantling of radioactive plant that has been done can be performed using standard available industrial techniques and that, apart from the application of normal radiological control provisions, special techniques and technology do not usually need to be developed, ie the 'simple-is-best' approach can be applied.

The majority of the plant, materials and buildings that are to be dismantled in this period are not radioactive. Conventional dismantling techniques can therefore be used but their application needs to be controlled and carefully assessed before implementation to ensure there are no consequent radiological implications, eg as a result of the work being done in a radiation area or because of unexpected radioactive contamination being found. The removal of inactive plant and materials can also involve non-nuclear hazards that need precautions to be taken. For example, a major task on the stations has been to remove thermal insulation materials that have been predominantly asbestos based.

5.2 Decontamination

In order to reduce the quantities of radioactive waste needing to be disposed, decontamination has been applied where applicable and beneficial overall. One example has been the gas ducts which are generally simple shaped surfaces and are not heavily contaminated. It has proved possible to decontaminate them using simple manually applied cleaning, abrasive or jetting techniques. However, although this removes all surface contamination, it has been found that tritium is dispersed throughout the body of the material which initially prevented the material being free-released. A technique was therefore developed whereby the material is heated in a furnace to drive out the tritium which can then be released to atmosphere. Following the de-tritiation process the material can be released for uncontrolled recycling in the scrap metal market.

Although the boilers contain the same contaminants as the gas ducts they have much more complex geometries, eg finned tubes, and hence simple manual decontamination techniques cannot be used. To check the feasibility of boiler decontamination, and to compare it with the alternative options of longer term storage to allow natural radioactive decay or disposal as active waste, a trial decontamination of one boiler at Berkeley is being progressed. This is using chemical techniques and is now achieving decontamination to a degree which, following de-tritiation, will allow free release of the material as inactive.

The other main area where decontamination is being applied is to contaminated building surfaces, and most notably the walls and floors of the fuel cooling ponds. The ponds are simple, single-contained painted concrete structures and fission product contamination from the spent fuel elements has penetrated the surfaces to a depth of some centimetres. To prevent the spread of contamination and airborne release once the ponds are drained it has been necessary to apply surface removal decontamination techniques. The bulk of the contamination is in a surface layer and ultra-high pressure water jetting techniques have been used successfully to remove this. Once this layer is removed, which significantly reduces background radiation levels, it is possible to perform more detailed and accurate surveys to determine the residual depth of contamination that requires removal. Final decontamination of these surfaces is being achieved by techniques such as concrete planing.

5.3 Disposal

The materials resulting from dismantling and decontamination activities need to be released or disposed of appropriately. The options that are available are, in order of preference: re-use, recycling and disposal. A number of plant items such as inactive tanks, transformers and instrumentation have been transferred for re-use at other sites. A large proportion of the dismantled materials is inactive and can be placed in the recycling market. Over 20,000te of such materials have been recycled from Berkeley and this has included ferrous and non-ferrous metals, cables, cast iron and glass. Concrete and building rubble has been used as infill material on the site. It has been necessary to dispose of some materials and, at Berkeley, this has included asbestos which has been sent to a special licensed disposal site and low level radioactive waste, typically 300te per year, which has been sent to the Drigg repository.

A very important feature in the disposal process is the monitoring of materials to determine and confirm radioactivity levels, particularly where material is to be free-released as non-radioactive. Detailed procedures have been developed, agreed with the appropriate independent regulators, implemented and demonstrated. These include detailed monitoring of individual components and bulk monitoring, and confirmatory checks using gamma spectroscopy equipment and detailed radiochemical analysis.

5.4 Long Term Safe Enclosure

It is proposed, under the Safestore decommissioning strategy, that some buildings and structures could be retained on the site for up to about 135 years after station shutdown. It is therefore necessary to ensure that these facilities can endure this long period in a safe, secure and weatherproof condition. The plant and structures, eg the reactors, that it is intended to retain are of substantial and robust construction and the bulk of the remaining radioactivity is within activated materials and hence physically locked in and not mobile. Therefore the main requirement is to provide conditions that will minimise degradation mechanisms affecting these materials.

A key protective measure is to retain buildings in a weatherproof condition and, ideally, this should result in only minimal maintenance and repair being required throughout the care and maintenance periods. The buildings that are being retained are therefore being refurbish and upgraded, primarily by repairing or replacing roofs and by re-cladding with durable materials. Attention is also being paid to minimising ground-water ingress into buildings and providing appropriate drainage arrangements. Detailed baseline civil surveys have been performed on all retained buildings to identify the present condition of all key structural features, eg the extent and type of any existing concrete degradation. This information is being used to establish repair programmes and long term monitoring requirements.

The main degradation process that needs to be considered for the retained radioactive plant is metallic corrosion, eg of the steel reactor vessels. Detailed studies have been undertaken to determine the potential degree of corrosion, to identify the atmospheric conditions that apply, and to measure and monitor the actual corrosion rates that are being experienced at various positions. A range of corrosion mechanisms or drivers have been considered. For example, there was originally some suggestion that nitric acid may be formed within the vessels as a result of defuelling in an air atmosphere but detailed investigations have now shown that this is not a problem.

Reactor vessels have been placed in their long term storage state which has involved closing or sealing all penetrations other than for a single vent line to the external atmosphere. This provides predictable aerobic conditions within the vessel and the rate of air interchange between the vessels and the external atmosphere is very low. Instrumentation connected to data loggers has been placed within and external to the reactor vessels to measure atmospheric conditions, eg temperature and humidity. Corrosion samples and probes have also been introduced and are inspected routinely. The monitoring that has been done to date indicates that actual corrosion rates are very low, eg $<1\mu m.y^{-1}$.

Studies have also been undertaken on the potential degradation mechanisms that might apply over the long term to the graphite moderator within the reactor vessels. These indicate that there are no significant problems and this is reported in a separate paper (Ref 3).

5.5 Accumulated Operational Wastes

The UK practice has been to store on the power station site, pending the availability of a waste repository, certain intermediate level wastes that have been produced during the operational period of the station. These include sludges and ion exchange materials resulting from the treatment of effluents and fuel pond water, and solid wastes including those materials removed from spent fuel elements prior to transport off site and other miscellaneous contaminated and activated materials. These wastes have been stored in a variety of concrete vaults and metal tanks and part of the decommissioning process is to determine what actions need to be taken on these wastes and to progress the necessary work.

Some of the stored wastes such as activated materials are very stable and held within very robust structures, eg the concrete reactor biological shields. These wastes could therefore be retained on site until the reactors themselves are dismantled. Other wastes are potentially more mobile and some of the storage facilities do not have the same long term integrity. It is therefore necessary to consider each situation on a case-by-case basis to determine the most appropriate management strategy. As a result of such assessments it has been decided that a significant proportion of the total wastes on the three shutdown sites will now be retrieved, treated and solidified, eg in cement, and the resulting packages then stored on the sites until a disposal repository is available. These waste management activities are a major part of the overall work that is being progressed on the sites and will utilise technology and processes that have been developed by Magnox Electric and its predecessors over a number of years.

5.6 Miscellaneous

It has been recognised that decommissioning sites can be a useful source of information that is relevant to those stations that are still operational. For example, one of the key issues relevant to the safety cases for the continued operation of the steel reactor pressure vessel Magnox stations is the effects of neutron irradiation induced embrittlement. The reactor vessels at Trawsfynydd have been identified as a source of representative and highly irradiated material that can be sampled and subjected to detailed analysis to determine the actual rather than just the predicted effects of embrittlement. This has required special remotely operated equipment to be developed that is capable of reaching the base of one of the reactor vessels, which is not readily accessible and is in a high radiation area, and that can then remove and retrieve steel samples for laboratory analysis. This equipment is now being deployed successfully.

6. CONCLUSION

Magnox Electric is progressing the decommissioning of three of its commercial Magnox gas-cooled reactor power stations, and has prepared plans for the eventual decommissioning of its six other stations that are still operational. The decommissioning strategy that is being employed is termed Safestore and involves the deferral of some decommissioning activities, such as reactor dismantling, for potentially up to about 135 years after station shutdown. Under this strategy, substantial decommissioning work is still undertaken in the years following shutdown. This starts with reactor defuelling, which has been completed at all three stations, and is followed by a range of dismantling, decontamination, preservation and waste management activities to prepare the site for a quiescent period of care and maintenance. Significant progress has been made with this work on the three shutdown sites. This has involved the successful development and application of appropriate safety, environmental, technical, financial and project management arrangements and processes. It has also been demonstrated that full scale commercial gas-cooled reactor power stations can be decommissioned using available and simple technologies.

REFERENCES

1. Decommissioning of Nuclear Electric's Gas Cooled Reactors: The Development of a New Strategy, S C Gordelier, OECD/IAEA International Seminar, Paris, October 1991

2. Review of Radioactive Waste Management Policy: Final Conclusions, Cm2919, London HMSO, July 1995

3. Graphite Core Stability During Care and Maintenance and Safestorage, A J Wickham et al, IAEA Technical Committee Meeting, Julich, September 1997