A UK view of the management of high-level waste

by W. Marshall*

In recent years a great deal of public attention has focused on nuclear wastes, especially the most radioactive or "high-level" wastes. These wastes have gripped public imagination as something unique, no doubt because people have been told that they contain elements whose radioactivity will take hundreds of thousands, or even millions of years to decay. Moreover the public are regularly told by opponents of nuclear power that the nuclear industry has failed to find a solution for what to do with these wastes, and indeed they can notice that some twenty years after the first nuclear power stations were built scientists are still arguing about whether to store wastes, whether to dispose of them, whether to dispose of them in this rock or that. People interpret the scientists' calls for further research as a sign that they really do not know what to do with these wastes.

Public confusion about this has been further heightened in the UK by what is seen as a change in Government policy towards the geological drilling programme. This has been aimed at gaining information about conditions that would be encountered in a deep geological repository for high-level wastes. Strong local opposition was raised to the planning applications to drill on particular sites, but scientists replied by arguing the importance of the drilling programme if we were to demonstrate a satisfactory way of ultimately disposing of the wastes. Then it was announced that Government had reviewed the geological programme and that further drilling would no longer be needed. Quite understandably the public are confused.

It is useful in clarifying these issues to start with the major source of high-level waste, which is spent fuel from nuclear power stations. This comprises unburnt uranium and plutonium, both of which are potentially valuable fuel materials, and the fission products and waste actinide elements, all of which are highly radioactive. After a period of storage, which allows this radioactivity to decay to a level that can more readily be handled, the spent fuel is reprocessed. This separates out the useful materials, the uranium and plutonium, from the wastes. These wastes, which emerge from this process as a liquid, are concentrated to reduce their volume and are then stored in the liquid form. Because there is still sufficient radioactivity to generate a considerable amount of heat, the storage tanks have to be kept cooled by water circulation.

Although safe storage in this way is simple in engineering terms, and perfectly acceptable on a short timescale, it is in the longer term easier, safer, and cheaper to store solids than liquids. It was therefore recognized right from the early days of reprocessing that it would be logical to convert the liquid waste into solid blocks for long-term storage. There was however no pressing need to do this. The amount of waste produced was small; for example, the 1000 m^3 or so of high-level waste that is currently stored at Windscale represents almost the entire accumulation from the UK's nuclear programme over the past 30 years. However, since conversion into solid was the logical next step, a great deal of research has been carried out on the science and technology of converting these wastes to a solid form.

The solid chosen for 'fixing' these wastes has to have a number of properties:

good capacity to accept all the elements in the waste;
good resistance to leaching by water;
good resistance to radiation damage;
high thermal conductivity to dissipate heat produced by radioactive decay.

Glass is a most attractive material not only because it has many of the properties required, but also because glass-making technology is well-developed. This has therefore led the UK to decide to build a vitrification plant based on the French AVM process, which is demonstrated and working well at Marcoule in France. Other materials than glass have also been suggested such as ceramic oxides, and Professor Ringwood of Australia has suggested a crystalline material of artificial rock which he calls *Synroc.*

Once the high-level waste has been converted to a solid, it can be stored on the surface for as long as we care to provide the very little supervision it requires. The rate of heat-generation in the glass blocks falls quite rapidly in the first few years of life of the waste. The figure shows the thermal power of a 0.4 t block containing a high loading of waste. Such blocks can be shielded with concrete to attenuate the radiation of energy from nuclear decay, and placed in a simple dry-store cooled with a current of air. A store of this kind would be of modest size and require minimal attention.

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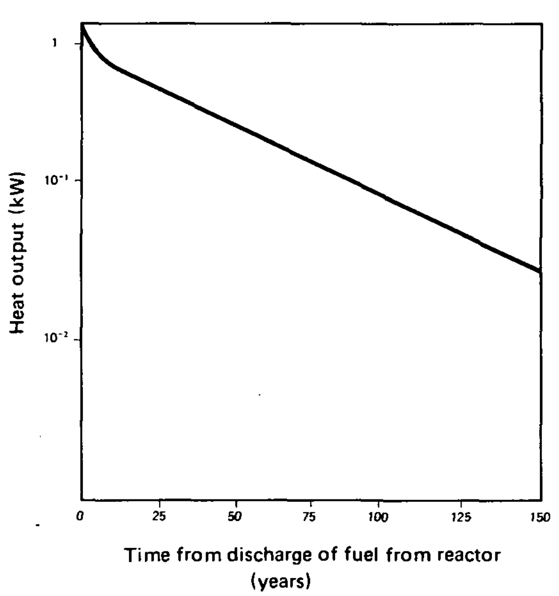
Store waste before burial

Although the surface store presents no technical difficulties, and isolates the high-level waste from the environment as completely as we could wish, there may nevertheless be sound social or political reasons at some future time to prefer disposal to storage. By disposal we mean the placing of the wastes where no retrieval is contemplated and no long-term surveillance is necessary. Various possibilities have been suggested. One that seems particularly attractive, and is the subject of considerable research in the UK and other countries, is the isolation of the solidified wastes in deep geological formations.

Burial of the waste blocks would expose them, over long periods of time, to groundwater; disposal therefore, introduces a potential pathway back to man's environment. Choice of a site with very little groundwater flow, together with the barriers described later, can however reduce any such risk to negligible levels. Another factor to be considered is that burial during the early years in the life of a block could lead to local increase of temperature which might increase the solubility of the waste and the local rate of water movement. If we wanted to dispose of the waste at an early stage, provision would need to be made to ensure that the build-up of heat was not excessive. Either forced cooling could be arranged for a few decades until the radioactive decay reached the point where this was no longer necessary, or the blocks could be made smaller and dispersed widely enough in the rock formations to allow natural conduction to remove the heat.

Heat output from a 0.4t AVM glass block.



Both alternatives would be technically possible but complicated. They also have disadvantages, economic and technical, as compared with leaving the wastes to cool for a longer period on or near the surface before finally disposing of them. There is now general agreement in the UK that we should store the vitrified wastes until their heat output has declined to a level at which they could be recommended for safe disposal. How long this might be is as much an economic as a technical question, but the period is likely to be 50 to 100 years, and possibly considerably longer.

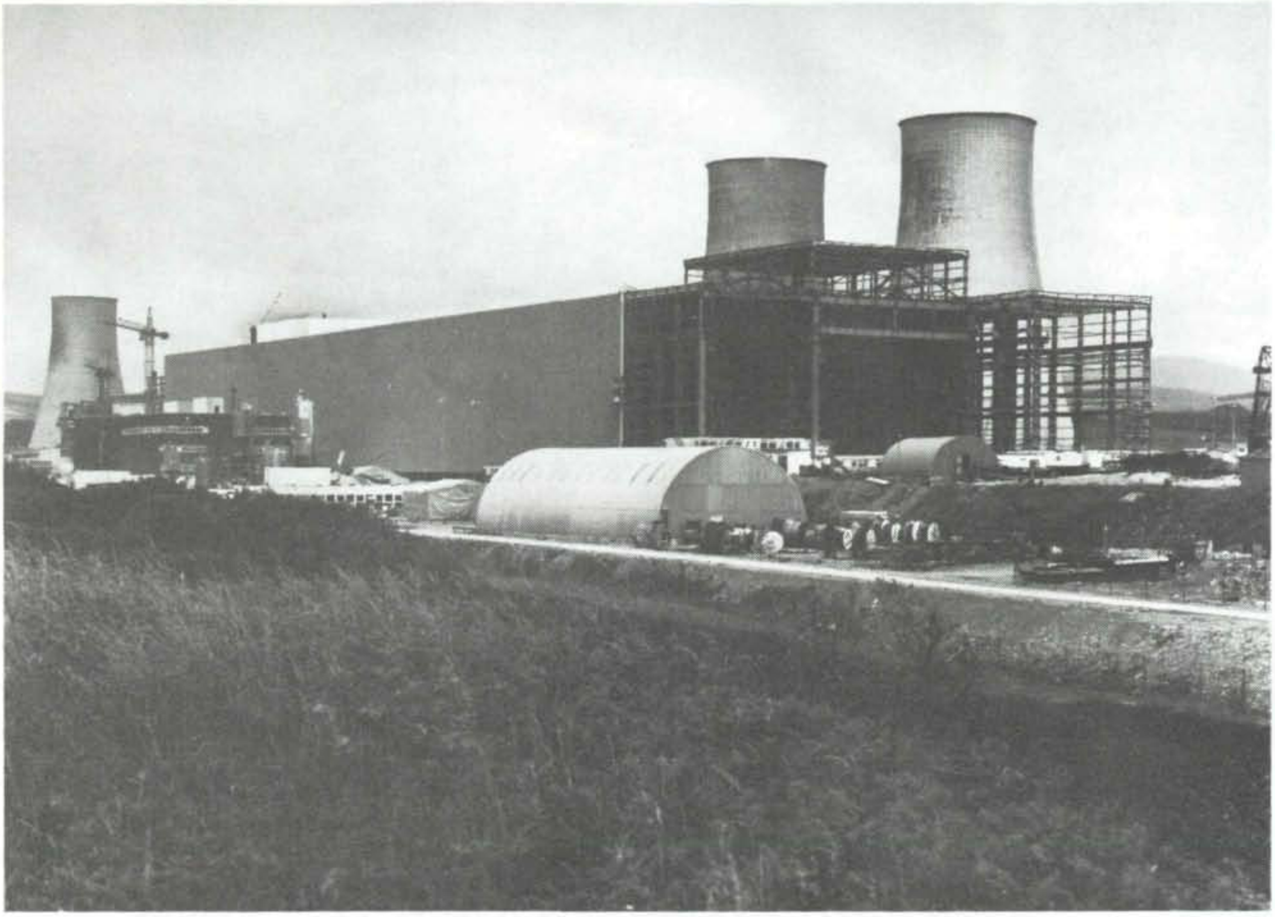
The strategy we are following in the UK for the management of high-level waste is therefore:

- To solidify the waste by turning it into glass blocks;
- To store the glass blocks until they have cooled sufficiently, perhaps 50 to 100 years and maybe more;
- To dispose of the blocks, possibly into deep geological formations, once the heat output has fallen to an acceptable level.

Options other than disposal in deep geological formations include disposal on or disposal under the ocean bed; however, our knowledge of such other options is still at an earlier stage than geological disposal.

Such a strategy is, I believe, entirely sound and sensible. It does, however, face the criticism that the final element – the disposal step – has not been demonstrated. "How", critics will say, "can you have a strategy for the long-term disposal of high-level waste, when you cannot demonstrate that the final disposal method is safe – safe measured against a virtually indefinite time-scale?" This was a point made in the UK in the Sixth Report of the Royal Commission on Environmental Pollution in 1976, which recommended that there should be no commitment to a large programme of nuclear fission power until it had been demonstrated beyond reasonable doubt that a method exists to ensure the safe containment of long-lived highly radioactive waste for the indefinite future. It was to meet this type of criticism that various countries, including the UK, started in the mid-1970s programmes of research on the feasibility of eventual geological disposal methods. The UK programme, which is carried out by the Department of the Environment, forms part of the larger Commission of the European Communities' programme.

I have no doubts that the disposal of vitrified waste to deep geological formations can be made completely safe, and that the amount of radioactivity that will eventually – after many thousands of years – return to man's environment will be so small as to be negligible. And perhaps I could here emphasize the levels to which the radioactivity will have decayed after a few thousand years: it will than be below the level of the original ore from which the fuel was obtained. But my basic reasons for confidence in the safety of this form of disposal lie in the various barriers that we can place between the waste and their return to our environment. However, it is not enough for me to be convinced: the evidence has



The new receipt and storage facility for spent Magnox fuel (Pond 5) under construction at the British Nuclear Fuels Ltd Sellafield (Windscale) site in Cumbria, England. Spent Magnox fuel will be stored here underwater prior to reprocessing.

to be presented and subjected to critical scientific review and, where there is any reasonable basis for doubt, to experiments. Let us therefore consider these barriers and the further work that might be carried out to establish greater confidence in their effectiveness.

Six barriers

Once the vitrified waste has been placed in its final depository it is isolated from man's environment by six barriers, as shown in the box.

First, the waste is fixed in the glass in a highly stable and insoluble form. Some leaching of the glass and of the radioactive elements in it is, of course, inevitable if in the distant future water comes into contact with the vitrified glass block. We therefore need to know the rate at which such leaching could occur. Radiation, and especially α-decay of the actinides, can affect the leach-rate and we need to understand whether this is significant. Radiation can also lead to the production of free radicals in any water present, which could also increase the leach-rate, and to the production of nitric acid by the irradiation of air or nitrogen in contact with water. Clearly we need fully to understand all such mechanisms.

The second barrier is the corrosion-resistant container which houses the vitrified block. The purpose of this

The six barriers which lie between vitrified waste in a geological repository and man

Man

↑

6 **The environment**
which will tend to dilute any radionuclides reaching the biosphere and reduce their biological effects

↑

5 **Geochemical barriers**
processes such as absorption which will tend to retain radionuclides chemically in the rocks

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4 **Geological isolation**
which minimizes the possibility of radionuclides reaching the biosphere either directly or through water

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3 **The backfilling**
which complements the properties of the geological environment in preventing water ingress and the migration of radionuclides

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2 **The container**
which isolates the glass from water which might cause leaching

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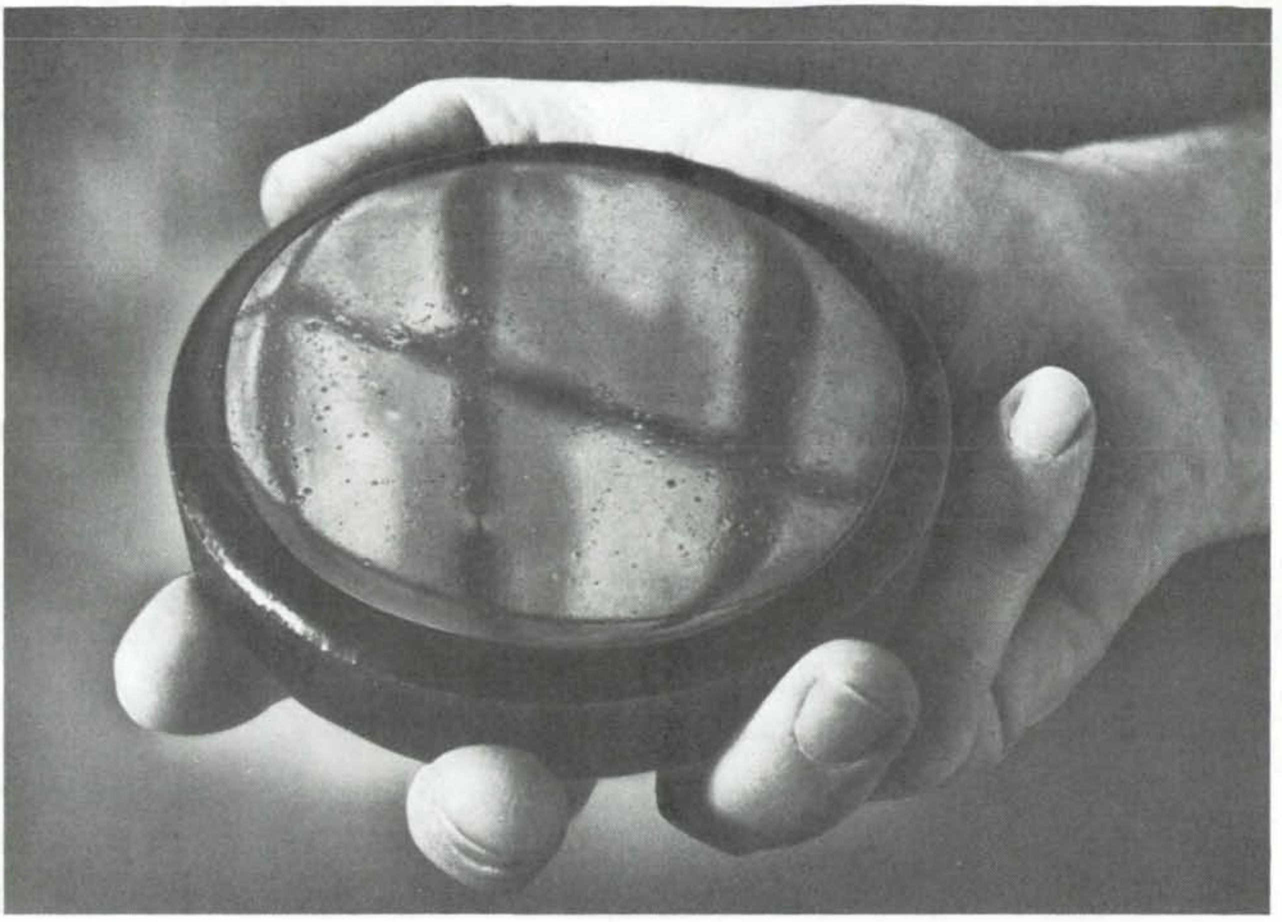
1 **The glass**
and its ability to resist leaching if water is present



A sample of simulated waste-glass. If all the electricity used in one person's lifetime were to be generated by nuclear means, then this quantity of glass would be sufficient to incorporate all the resultant high-level waste.

is to delay the time at which the block might become exposed to water and hence to leaching. The aim is for this barrier to remain intact at least for the several hundreds of years required for the most radioactive fission-products, especially caesium-137 and strontium-90, to decay to an insignificant level. We must therefore ask how long will it be before such a container will corrode – 500 years or maybe 1000 years? What are the best materials to use? What sort of barrier to leaching will the container present even after it has first been penetrated by corrosion?

The third barrier is the backfilling that will be placed around the container to complement the properties of the geological environment in preventing the migration of radionuclides. Materials can be used that will act as a barrier against water intrusion, inhibit corrosion, and react chemically with any radioactive elements that are leached from the glass to limit their dispersal. We need to know which materials to use (different ones may be suitable for different geological conditions), and how effective such materials will be as a barrier.

The fourth barrier is the nature of the geological formation chosen for the repository. Formations are required which have very low permeability to water (both to limit the rate at which leaching can take place and to limit the rate at which leached radionuclides can be transported back to the biosphere). We need to be able to assess the rate of groundwater movement (which may typically be of the order of 0.1–0.2 litres per square meter per year). We need to be able to assess whether this rate could be increased either by natural fissuring of the rock or by fissuring caused by the heat from the waste. In addition we need to be able to assess the likelihood of seismic or other events disturbing this geological barrier.

The fifth barrier is the geochemical nature of the rocks. Many of the radionuclides will interact with the geological media as they are transported through it and will be retained by processes such as ion-exchange, surface absorption, or precipitation. As a result, even if all the other barriers fail, many of the radionuclides will travel along the geological pathway at a much slower rate than the water and may decay before they reach the biosphere. On the other hand certain radionuclides are only poorly retarded by this process. We need to understand and be able to quantify these effects.

Finally, there is the environmental barrier. Eventually, because we always take pessimistic and conservative assumptions in order to err on the side of safety, we must assume that all the previous precautions have eventually failed and that in consequence some radioactivity will reach the biosphere. (We are talking here of perhaps tens or hundreds of thousands of years into the future.) What hazard will they present, bearing in mind that radioactivity exists everywhere as a natural phenomenon, and that once in the biosphere any radionuclides from wastes will be subject to extensive dilution? To complete a rigorous assessment of the risks from geological disposal of wastes we need to be able to quantify just how effective this environmental barrier really is.

More effective than expected

Since the major research programme began in this area in the mid-1970s, our knowledge about such questions has greatly increased and we now know that several of these barriers are several orders of magnitude more effective than once thought. Major contributions to our understanding have been made through work in many countries – for example, the Swedish KBS study, research in Canada and the Commission of the European Communities' research programme. Extensive literature has been produced.

In particular, experiments at Harwell in which glass has been doped with $^{238}PuO_2$ have shown that at a radiation dose corresponding to about a million years' life of vitrified waste from the UK's Magnox reactors, the rate of leaching has increased by only a factor of two. This, and similar work on the possible effect of radiation on water that might be present, gives confidence that radiation will not have any significant effect on the ability of glass to contain the waste.

It is now also established that the leach-rates that are likely to be experienced under geological conditions are very low, and indeed are likely to be determined by the availability of groundwater. In all cases this is likely to be very limited due to the hydraulic properties of the host rock and the backfill. We have also learnt that as the glass blocks are exposed to leaching, the depleted surface layer that forms on the surface acts to retain certain elements differentially; in particular there is a remarkable retention of the actinide elements, which are found to have a leach-rate several orders of magnitude less than the bulk leach-rates on which earlier calculations were based.

The Swedish study mentioned earlier was based on extensive experimentation at specific hard-rock sites. This work is still continuing. The study has illustrated that it is perfectly possible to design repositories in hard rock such that the maximum amount of radioactivity that could get back to man will not occur for 100 000 years; and that, even on conservative assumption any resulting radiation dose will be small compared with the natural background.

Future of drilling programme

As a result of the various studies and experimental work in various countries – and in different types of rock – we can demonstrate high confidence in the safety and environmental acceptability of geological disposal as the final step in our strategy for high-level waste management. However, establishing safety is always a continuous process. There are many areas in which we need to improve our knowledge, to refine assumptions that we believe are conservative but for which we have inadequate experimental evidence. It was for this reason, primarily, that the UK was conducting a drilling programme to obtain further generic data about the properties at depth of different types of rock that occur in the UK – about their conductivities, water content and fissuring, and about their geochemical properties. The programme was not aimed at identifying specific sites.

It is a matter of judgement how far it is necessary to take such work at this stage. We already have, I believe, enough information to be satisfied that our general strategy is sound. There is no immediate requirement to dispose of high-level wastes – storage of vitrified waste is, as I have argued, the preferred course of action for the first 50 to 100 years after removal from the reactor. The Department of the Environment – whose responsibility this programme is in the UK – recently reviewed the UK's geological research programme. They concluded that the feasibility of emplacement of wastes deep underground is now established in principle, and that nothing has emerged to indicate it would be unacceptable. They have therefore decided that because of the lack of an immediate need for this work, and the competing calls on limited resources, the drilling programme should not be extended.

Many scientists would like to have seen the work continue, to increase still further our confidence that we fully understand and can predict the behaviour of wastes once they have been consigned to geological dispos; to demonstrate to the public that even the most remote possibilities have been accounted for in framing the safety precautions; and to ensure that when our successors decide to dispose of the wastes (if in the end this is what they want to do), they have available the fullest possible information about the subject. I have some sympathy with this view. Nevertheless, it is my firm opinion that the Government has taken a perfectly defensible position in the light of all the evidence presented to it and its need to reconcile the conflict between desirable research and the total resources that Government can afford.