REPOSITORY CONTAINMENT

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ABSTRACT

UK Nirex Limited is concentrating its further investigations at Sellafield in Cumbria to establish the sites suitability as a safe location for a deep disposal facility for intermediate and low level radioactive waste. Good progress has been achieved in the Site Characterization Program. The emerging picture of the geology and hydrogeology continues to suggest that the site holds good promise as a potential repository location. This paper sets out the latest results from site investigations at Sellafield and reviews some possibilities for enhancing waste containment deep underground at the site.

INTRODUCTION

United Kingdom Nirex Limited is responsible for providing and managing a national disposal facility for solid intermediate-level (ILW) and low-level (LLW) radioactive waste. Such wastes have been produced in the UK for over 40 years and come from the nuclear power industry, medical and defence establishments, as well as research and industry. UK Government policy is to dispose of these wastes in a deep underground repository. Similar policies are followed by other countries which produce substantial quantities of long-lived radioactive waste.

Following an extensive site selection exercise, Nirex announced in 1989 that it would investigate, initially, sites at Dounreay in Caithness, and Sellafield in Cumbria, to establish their suitability as safe locations for a deep disposal facility for ILW and LLW. Initial borehole drilling and other geological work subsequently indicated that the geology at both sites had the potential to meet the demanding safety requirements for a deep repository. In July 1991, Nirex announced that it was to concentrate its further investigations at Sellafield. Given that there appeared to be little otherwise to distinguish between the overall suitability of the two sites, transport of waste and the associated costs were major considerations in this decision: an estimated 60 per cent by volume of the radioactive waste destined for the repository arises from British Nuclear Fuels' operations at Sellafield.

This paper briefly describes the latest results from the Nirex Science Program, which is underway to establish the suitability, or otherwise, of the site at Sellafield to host a deep repository and reviews some possibilities for enhancing repository containment.

SITE CHARACTERIZATION PROGRAM

To date, activities carried out within the Site Characterization Program have been surface based. Twelve deep regional boreholes have been completed. These facilitate ongoing testing to generate further valuable data, particularly in respect of the hydrogeology of the site. The borehole investigations have been accompanied by a range of geological, geophysical and hydrogeological surveys. The focus of activities is increasingly on the block of rock within which a repository at Sellafield would be located, the "Potential Repository Zone." In particular, a series of boreholes is being drilled preparatory to construction of an underground 'Rock Characterization Facility' (RCF) which will complement the surface-based program to characterize the geology and hydrogeology of the site.

NIREX SAFETY ASSESSMENT RESEARCH PROGRAM

The Nirex Safety Assessment Research Program (NSARP) commenced in 1982. Its outputs are data and mathematical models for post-closure performance assessments. These may be used either directly in risk calculations or to develop an understanding of parameter relationships to permit simplified models to be developed for direct application.

SCOPE OF GEOLOGICAL INVESTIGATIONS

Regional geophysical surveys commissioned or acquired by Nirex have included seismic reflection and gravity surveys onshore and offshore, as well as airborne magnetic and radiometric surveys. Geological mapping and studies of the near-surface hydrology are still in progress.

Twelve deep regional boreholes have been drilled. The first of a series of deep boreholes preparatory to the Rock Characterization Facility has also been drilled, two more are well advanced. The locations of all the deep boreholes are shown in Fig. 1.

GEOLOGY

The proposed repository host rock at Sellafield comprises volcanic rocks of the Borrowdale Volcanic Group (Fig. 2). These rocks are Ordovician in age - around 460 million years old. Within the Potential Repository Zone, the top surface of the volcanic rocks is at a depth of 400 to 600 metres, occurring beneath an immediately overlying breccia (a rock composed of angular stones cemented by finer material) known as the Brockram. This is of Permian age (around 270 million years old) and is overlain by a younger cover of Triassic sandstones (around 225 million years old). On moving west, towards the coast, the top of the volcanic rocks falls away to greater depth, and an additional sequence of shales, evaporites and limestone of Permian and Carboniferous age occurs between the sandstones and the volcanic rocks.

MAIN CONCLUSIONS OF THE CURRENT GEOLOGICAL INTERPRETATION

The main boundaries between the rock formations and the larger faults which intersect them have now been mapped. The BVG has been subdivided vertically into a number of formations which can be correlated between boreholes over distances of several kilometers. A relationship is being established between the hydrogeological properties of the rocks and this stratigraphic subdivision.

Cross-hole seismic tomography has demonstrated that geological structures can be mapped between boreholes. This observation is providing added confidence regarding the

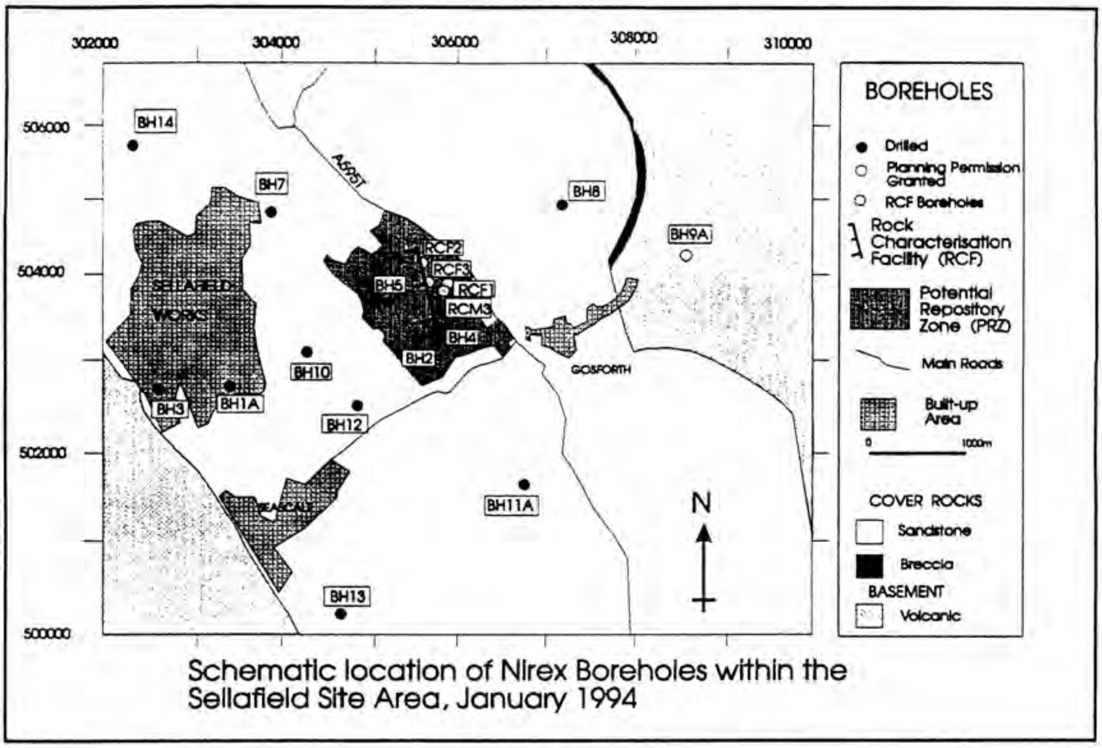

Fig. 1. Borehold locations.

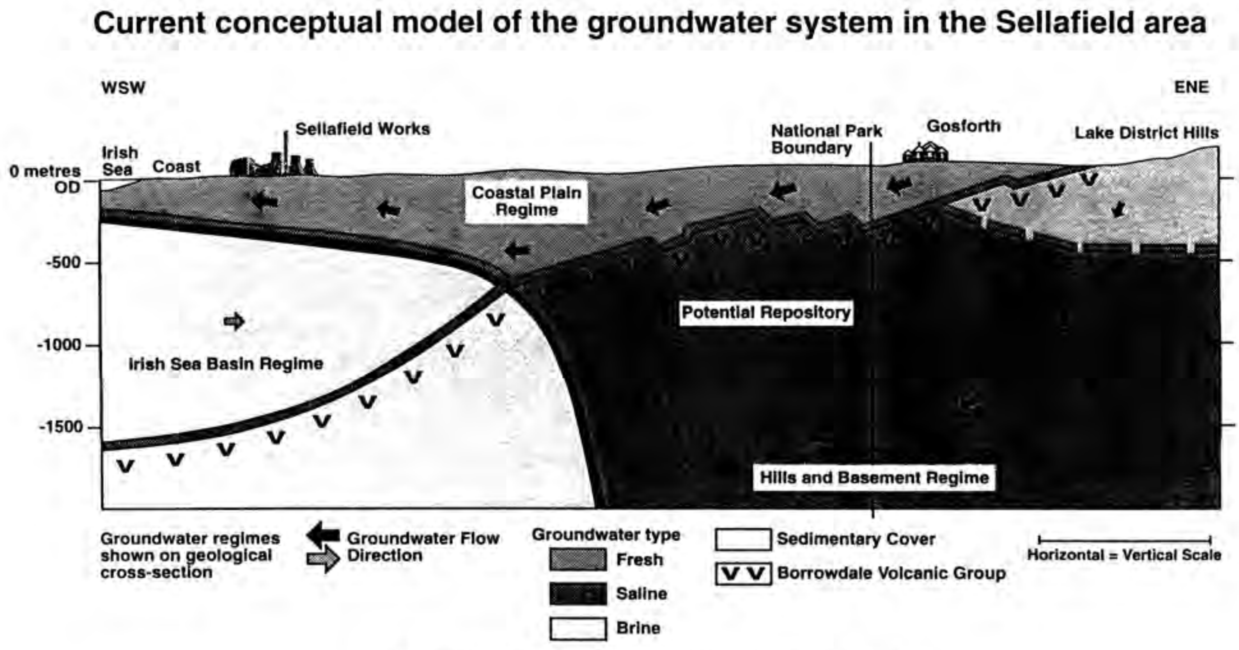

Fig. 2. Geological/hydrogeological cross section.

definition of the geological structure within the BVG and its influence on the hydraulic conductivity of the rock mass.

Hydraulic conductivity has been measured in all the main geological units using borehole and laboratory tests. Based on this testing, preliminary quantitative assessments have been made of the distribution of hydraulic conductivity values in all the major hydrogeological units which occur at the site. Values measured in the BVG are typically low. Half the values measured over 50m lengths in the boreholes, including tests over faulted and fractured zones, are less than 10^{-10} ms^{-1}. By inducing groundwater flow into the boreholes it has been possible to detect a limited number of individual fractures intersected within the BVG along which groundwater flows. These fractures may be interconnected over hundreds of meters. The zones containing interconnected fractures have a somewhat enhanced conductivity compared to the rest of the rock mass. Measured groundwater pressure variations appear in some cases to be associated with such zones.

Geochemical and isotopic analysis of groundwater samples has begun to give some indication of the age and provenance of the groundwater within the BVG. Preliminary results indicate that at depth in the Potential Repository Zone the groundwaters are many thousands of years old and possibly greater than 30,000 years old.

The database of groundwater pressures has been significantly extended, but it has not yet been possible to model fully the distribution of groundwater pressures within the basement rocks. Hydrogeological models based upon discrete flowing fracture networks in the BVG, overlain by low conductivity formations such as the Brockram, come closest to reproducing the measured heads.

Good progress has been achieved in the Site Characterization Program. The emerging picture of the geology and hydrogeology continues to suggest that the site holds good promise as a potential repository location.

RISK CALCULATIONS

Illustrative radiological risk from the ground water pathway output curves from the overall system model for a repository at the Sellafield site are shown in Fig. 3. These show the expectation value of risk calculated from 500 individual system realizations for different climate states. For the purpose of model calculations, each climate state is assumed to persist over the full period evaluated. Future work will examine the impact of transitions between climate states. Values of calculated risks are shown for the period up to 1 million years after repository closure: beyond this period it is considered that quantitative risk calculations have little meaning.

Three curves are presented, corresponding to Temperate (ie current), Periglacial and Boreal climates. Flow path calculations illustrated in Fig. 2 suggest that the bulk of the discharge for groundwater that has flowed through the repository in a Temperate climate will be to the bed of the sea, and hence a marine discharge case is presented. For Boreal and Periglacial climates, sea-level will fall and the coastline will recede from its present position. This may result in a discharge point to land, and accordingly that case is presented for each of these climate states. (Note that if a terrestrial discharge were considered for a Temperate climate, then the results would be similar to, though slightly higher than, the Boreal case presented but with maximum expectation values still within the risk target).

The predicted risk for marine discharge in the current Temperate climate is, at most, one thousandth of the risk target of 10^{-6}. A peak is observed after only 100 years, corresponding to the rapid transport of the short-lived radionuclides caesium-137 and strontium-90 in a very small fraction of the overall groundwater flow. This reflects the fact that no credit is taken in current assessments for the physical containment of such short-lived radionuclides by waste containers. The containers would, in fact, be expected to have maintained their initial integrity well beyond 100 years, so eliminating this early peak. Such modelling conservatisms are being addressed. This should lead to the development of more representative models which should generally reduce calculated risks.

On the basis of current understanding of global climate patterns, Temperate or warmer conditions are expected to persist at Sellafield for several thousand years. Beyond that time period, colder Boreal or Periglacial conditions need to be considered. Figure 3 indicates that, for these conditions, the highest risks are predicted for terrestrial discharge in Boreal conditions. For this example the expected value of risk reaches maximum values, within the regulatory target of 10^{-6}, after several thousand years and again at a time approaching one million years. These two maxima need to be considered in the context of the discussion above about the likely timing of the onset of Boreal conditions, and with caution in respect of numerical risk predictions at times approaching 1 million years.

In all calculations for discharges to a terrestrial environment, the maximum of the risk curve occurring after several thousand years is attributable almost entirely to two radionuclides: chlorine-36 and iodine-129. These radionuclides constitute a very small fraction of the assumed inventory of radioactivity in the repository. The maximum risk value at about one million years is attributable to the daughter radionuclides generated by the decay of uranium-238. Results

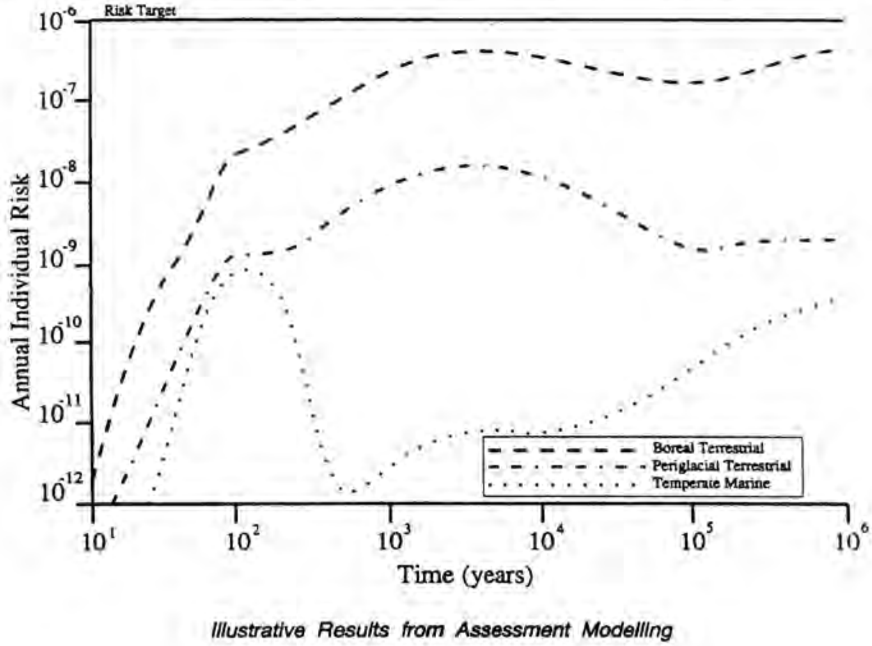

Fig. 3. Risk time curves.

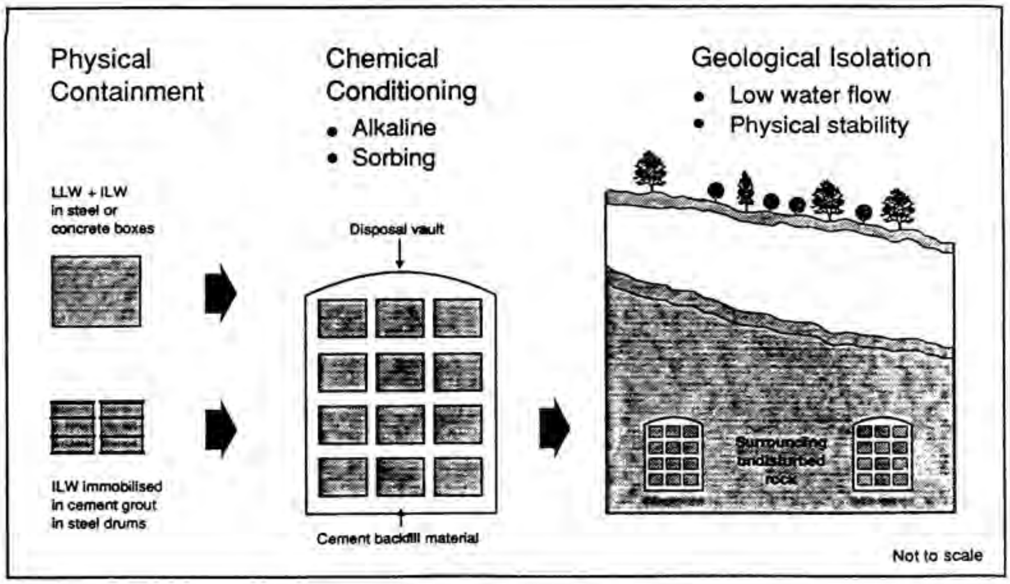

Fig. 4. Multi-barrier concept.

presented in Fig. 3, suggest that the repository concept is working particularly well for other radionuclides.

In carrying out assessments, it is currently assumed that the transport of chlorine-36 and iodine-129 dissolved in groundwater is not retarded by the process of sorption on repository material on rocks in the Geosphere. Given the dominance of these radionuclides in calculations of risk for times up to 100,000 years this conservative assumption is being examined in more detail.

ENHANCEMENT OF REPOSITORY CONTAINMENT

Against the background of Nirex's current best view of the Sellafield deep repository site Safety Assessment, a work program has been set in place to examine how repository containment could be enhanced through optimization of specifications for repository design, waste forms, etc.

The following sections review some of the possibilities and explain work in hand to develop these in more detail.

MULTIBARRIER CONTAINMENT - THE PRESENT POSITION

Nirex has developed a concept of deep geological disposal for radioactive waste which uses a multi-barrier containment system. The concept is illustrated schematically in Fig. 4. It is founded upon a simple and robust specification of the engineered system. In this, containment is not dependent upon the integrity over long time periods of engineered barriers, rather the required containment properties are demonstrated to be available after long-term physical and chemical *degradation* of these barriers towards equilibrium conditions. This is consistent with the broad approach followed internationally.

Considering only ILW, for the purposes of this paper, long-term containment properties of the engineered system stem from the establishment of uniform chemical conditions and high sorption capacity across the repository. This is achieved by surrounding waste packages with the required amount of a cement based backfill material which has been carefully specified to fulfil a number of requirements:

- long-term maintenance of alkaline pore water chemistry in order to suppress dissolved levels of key radionuclides under the conditions of groundwater flow and geochemistry;
- long-term maintenance of a highly surface-active area for sorption of key radionuclides; and,
- relatively high permeability and porosity to ensure that localized concentrations of materials in wastes do not exhaust the desired chemical conditioning and thereby reduce containment performance on a localized basis.

With this concept a "source term" representing the emplaced wastes is modelled through into the biosphere in a conservative manner not making claims that are dependent upon anything more complicated than dissolution and sorption involving well-characterized materials.

The near-field source term is considered available for transport through the geosphere by many processes, such as advection and diffusion, which control solute transport in groundwater flow systems. Radiological implications of transport out of the near-field are principally dependent upon the volume of groundwater flowing through the repository ("the flux") and periods of time taken for water to travel from the repository to the geosphere.

Geosphere Characteristics

The Nirex deep repository concept is highly sensitive to the flux of groundwater that is available to carry contaminated pore water into the geosphere. This flux will be determined by the effective hydraulic conductivity of the repository host rock (the Borrowdale Volcanic Group at Sellafield). In a fractured basement rock such as the BVG, the effective hydraulic conductivity is dominated by the characteristics of the secondary permeability and in particular the spacing, interconnection and length of transmissive features comprising faults and/or fractures.

It is important to note that current representations of the hydrogeological system are derived from relatively few field observations. More developed modelling of solute flow mechanisms for key radionuclides may imply uncomfortably high peak doses, with the implications discussed below.

WASTE INVENTORY AND SAFETY ASSESSMENT MODELLING

Key Radionuclides

Safety assessment modelling reveals the radionuclides most likely to dominate radiological impact. Generally speaking these will be soluble species which are poorly sorbed within the near-field and the geosphere. In the relatively short term strontium-90 and caesium-137, having half-lives of approximately 30 years, will fall into this category. However it would be possible to engineer containment for 300 years, about 10 half-lives for these short-lived species, by carefully conditioning and packaging wastes. After several thousand years risk from discharging to the terrestrial environment is attributable almost entirely to two radionuclides; chlorine-36 and iodine-129. On the other hand Uranium-238, with a half-life of 4,500 million years yielding the daughter products radium-226 and thorium-230, will dominate risk at 1 million years post-closure and thereafter. Whilst it is unlikely that much can be done to mitigate risk from such long lived species by the provision of more durable engineered packages, lines of attack being followed are described in the following.

Radionuclide Data

Sometimes key radionuclides, likely to dominate the radiological impact, will be contained in a small number of waste streams but often such radionuclides will be distributed across a number of high volume waste streams. Either way there will inevitably be uncertainty with waste inventory data, particularly when estimating future arisings. What is important is to regularly review waste inventory data to establish the accuracy of estimated accumulations and future arisings and to focus particularly on those radionuclides most likely to have an effect on the radiological impact of radioactive waste disposal.

Assessment Models

An integral part of the safety assessment process is to review data needs and models. It is vitally important at each stage in the process to ensure that data values and critical assumptions are realistic. Initially modelling approaches to uncertainty will include conservatisms, which later work will render inappropriate. Regular reviews of critical information and elicited coefficient values underlying nearfield, geosphere and biosphere models are therefore vital.

SEGREGATION OF PROBLEM WASTE

Where key radionuclides are concentrated in relatively few waste streams, a number of repository design approaches could be followed to reduce the impact of these. Possibilities, based upon potentially feasible segregation, include provision of a tailored, more sorbing, encapsulant for wastes rich in problem radionuclides; and, disposal of some wastes at greater depth than others. Specification of a stepped disposal system, with disposal units at various depths, including very deep disposal of problem radionuclides requires a good understanding of site hydrogeology. Generally it might be expected that ground water fluxes would decrease and travel times increase as a function of increasing depth. In hard rock, as depth increases, rock joints tighten, become cemented more easily and ground water flow is reduced as a result. Work on this approach is in hand in the UK. It involves obtaining a better understanding of the Sellafield site's hydrogeology before an assessment can be made of any benefits stemming from increasing the depth of disposal and increased difficulties that would result from higher overburden pressure and temperature.

ENGINEERING BETTER CONTAINMENT

Several engineering approaches have been suggested to improve retention of key radionuclides in the near and farfield (Fig. 5).

Enhancement of engineered barriers is a topic that has been widely researched. A literature search on this topic revealed approaches proposed for use in repository projects overseas. However, a key consideration is whether or not implementation of any one, or combination, of these would affect post-closure safety by a significant margin given the long half-lives of some of the radionuclides involved. Work on this approach would need to be undertaken in parallel with other approaches reported in preceding sections of this paper.

Increasing Retention in the Nearfield

High integrity containers cannot be guaranteed to retain the longest-lived radionuclides until they have decayed away. Similarly, hindering groundwater flow through disposal vaults by surrounding them with impermeable bentonite could not be relied upon over such timescales. This also applies to the other engineered features such as diverting groundwater through drainage systems or injecting grout curtains around disposal vaults to seal water pathways in disturbed rock. There is little realistic prospect of improving retention of very long-lived radionuclides by such means.

Further work on this aspect is unlikely to be fruitful, and none is proposed. However, it should be noted that the effects of the alkaline plume from the repository on surrounding rock are being investigated as part of the Nirex research program. One result could be expansive mineralization reactions which could self-seal existing and new features.

Increasing Retention in the Farfield

There seems little doubt that repository concepts and designs could be developed which would allow waste to be emplaced, either in part or in total, at greater depth. Compared to the Company's currently preferred design, adopting such concepts is likely to increase costs and the benefit of doing so will be subject to careful assessment.

CONCLUSIONS

It is concluded that whilst engineered barriers have a role to play in short-term containment, they are less likely to affect post-closure safety by any significant margin in the long-term. On the other hand, use of sorbing encapsulants and optimizing the location of underground disposal vaults within a given geological environment could significantly enhance long-term containment. Finally, the importance of knowing the concentrations of key radionuclides in waste streams cannot be overemphasized.

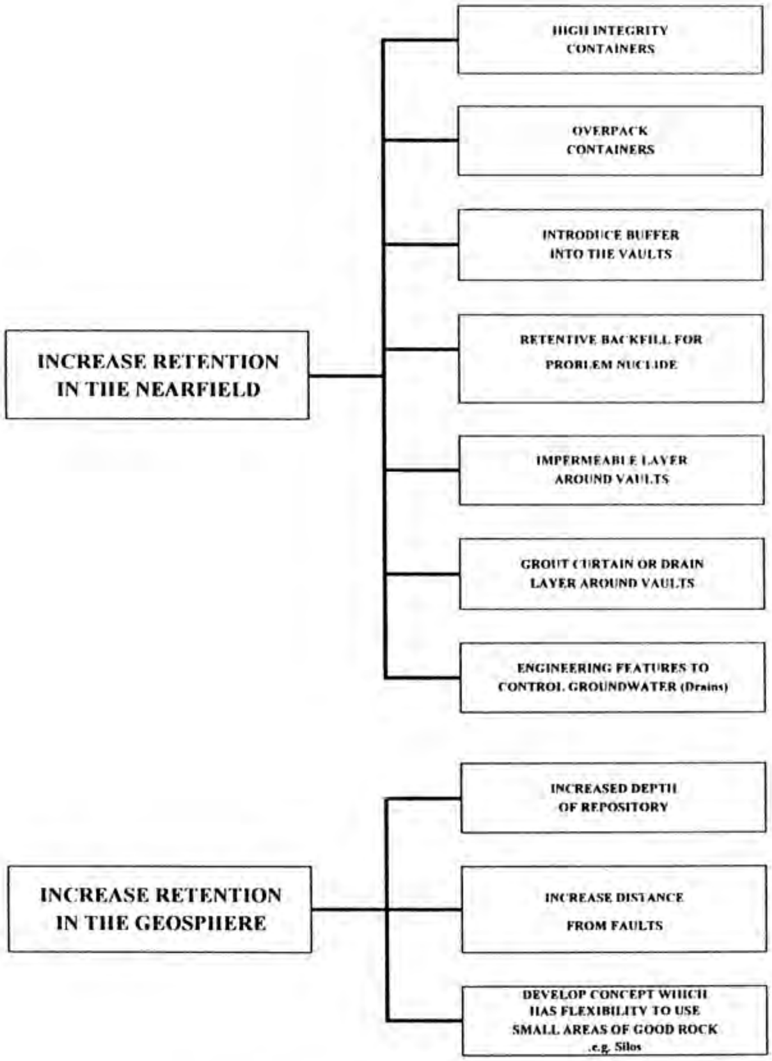

Fig. 5. Engineering better containment.