

ISSUES ASSOCIATED WITH THE CO-DISPOSAL OF ILW/LLW AND HLW/SF IN THE UNITED KINGDOM

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ABSTRACT

Nirex's remit is to develop and implement a long-term management solution for the United Kingdom's (UK) intermediate-level waste (ILW) and for the small amount of low-level waste (LLW) that is unsuitable for near-surface disposal. Nirex's response to this remit (which largely consists of transuranic waste) has been to develop the Nirex Phased Disposal Concept: a long-term management solution based on phased deep geological disposal within a cementitious repository.

One means of achieving a more integrated approach to waste management is the combined disposal (co-disposal) of high level waste and spent fuel (HLW/SF) with solid ILW/LLW within a single facility. Nirex has therefore undertaken a study to determine the feasibility of co-disposal of HLW/SF (based on a bentonite-lined repository concept) in an adaptation of the Nirex Phased Disposal Concept. In this study co-disposal is taken to mean the disposal of ILW/LLW and HLW/SF in different excavations within the same rock mass using a common access.

Co-disposal offers potential cost savings over the development of separate facilities for different types of waste, and would involve the development and consequential disturbance of a single site, for example; an integrated process for consultation and planning applications, and a single programme of transport, site selection and characterisation. However, a key technical issue that requires consideration is the interaction between the cementitious plume from the ILW/LLW repository and the HLW/SF wasteforms and bentonite backfill (which is typically used in HLW/SF disposal concepts).

This paper will summarise the key issues associated with the co-disposal of ILW/LLW and HLW/SF. These include:

- Implications for site selection;
- Radiological implications of concentrating increased inventory of different wastes in the same facility;
- Interactions between different waste forms and the associated engineered barriers (as a result of transport of heat and of dissolved materials in groundwater);
- Co-disposal facility layout to minimise possible interactions;
- Integrated retrievability concept;
- Cost savings;
- Integrated programme of Research & Development

INTRODUCTION

Reference Material Inventory

In summary this study has investigated the co-disposal of LLW, ILW, HLW and SF:

- LLW are characterised by low radionuclide inventory and a relatively high organic content. A small volume of low level waste has been identified for deep disposal due to the content of alpha emitting radionuclides.
- ILW contain more radioactivity than LLW but have lower levels of activity and heat output than HLW. There are significantly greater volumes of ILW than other

waste types for deep disposal and they contain a broad spectrum of materials, including organics, and radionuclides.

- HLW is a vitrified product from reprocessing spent fuel when most of the uranium and plutonium are removed. In comparison to ILW, key characteristics are a low volume, high specific activity, no organic materials and production of more heat
- SF from Advanced Gas-cooled Reactors (AGR) and Pressurised Water Reactor (PWR). The spent fuel is of low volume and is heat generating. The uranium and plutonium are still present. In the UK spent fuel is designated as a resource not a waste, so this paper is considering a hypothetical change of policy.

All of these radioactive materials contain some transuranic radionuclides.

If a co-disposal programme were initiated in the UK the inventory of wastes to be considered could change. This paper has not included the decommissioning wastes that would arise towards and beyond the end of this century that are currently not included in the Nirex Phased Disposal Concept. It also assumes no new nuclear construction and no further reprocessing beyond current commitments.

Nirex Phased Disposal Concept

Nirex's remit is to develop and implement a long-term management solution for a planning basis volume of 263,000 m³ of waste comprising of 248,000 m³ of ILW and of 15,000 m³ of LLW. The Nirex Phased Disposal Concept is a long-term management solution based on phased deep geological disposal within a cementitious repository (1). This concept includes provision for an extended period of underground storage.

The ILW/LLW would be packaged in steel and concrete containers. In general a cement-based material would be used to grout the ILW within the containers. The packages containing ILW (and LLW) would be placed in the disposal vaults. A cement-based material, the Nirex Reference Vault Backfill (NRVB), would be used at a later stage to fill part of the space surrounding the containers.

The waste containers, the cement grout within the containers, the NRVB around the containers and rock around the repository would all act to minimise transport of radionuclides to the surface. The containers would act to prevent or reduce the groundwater reaching the waste, but would slowly degrade.

Illustrative Co-disposal Concept

The United Kingdom does not currently have a programme for the long-term management of vitrified high-level waste and spent fuel. Current Government policy is to place HLW in interim storage for at least 50 years to allow the initial high heat generation to decrease. However, the Department of Environment, Food and Rural Affairs has recently launched a Consultation on the long-term management of radioactive waste in the UK (2).

An option for the long-term management of radioactive waste in the UK is the combined disposal (co-disposal) of HLW/SF with solid ILW/LLW within a single facility. This is one means of achieving a more integrated approach to waste management, which was a recommendation in a recent report of the House of Lords Select Committee on Science and Technology (3). It is also consistent with the approach planned in most other western European countries with significant radioactive waste disposal programmes.

In order to develop an illustrative design concept the Nirex concept of a repository for ILW/LLW (1) was combined with a co-disposal facility concept in crystalline rock developed as part of a recent European Commission study (4). This illustrative design concept has been developed for the purpose of feasibility studies and is not necessarily a design concept that Nirex would propose.

In this EC concept, disposal canisters for HLW and SF are emplaced horizontally in a system of circular section emplacement drifts (or tunnels) surrounded by bentonite. The emplacement drifts are 500m long and spaced 35m apart. It is worth noting that the spacing of the drifts will depend on the heat output from the wastes and operational requirements.

The waste canisters, the wasteform, the bentonite around the canisters and the rock around the repository all act to limit the transport of radionuclides to the surface. The waste canisters for the HLW/SF repository have a very different design to the containers in the ILW/LLW repository. They have a thick steel wall and are expected to prevent access of groundwater for many thousands of years, although the canisters will very slowly corrode as a result of interactions between the groundwater and the canister.

There are two rows of emplacement drifts separated by 500m. Hence, the repository is 1500m wide and the length is dependent on the number of emplacement drifts required. It is the intention that the ILW/LLW repository and HLW/SF repository share a common access, and possibly other facilities. It is assumed that the two repositories are 500m apart in order to not adversely affect the containment properties of each other. However, the actual separation distance and layout would be site-specific as discussed later.

Based on the assumptions made of the disposal concept, a total of 76 emplacement drifts with an associated HLW/SF repository area of 2.2 km² would result. A reference layout for a co-disposal facility is shown in Figure 1.

The illustrative concept has been used to provide estimates of the number of disposal canisters, length of emplacement drifts and repository volume for the reference material inventory shown in Table I.

Table I: Total number of Emplacement drifts for Reference Case Material Inventory

Waste type	Material Quantities	Number of Disposal Canisters	Number of Emplacement drifts
HLW	1250 (m ³)	4223	49
AGR SF	2900 (te)	2805	20
PWR SF	1200 (te)	562	7

IMPLICATIONS FOR SITE SELECTION

A key issue for site selection would be public acceptance and equity. In addition, the issue of whether co-disposal would reduce the range of acceptable sites in terms of increased repository footprint and availability of suitable host rocks was also considered.

Equity

There is an equity issue if the wastes were disposed of at one site, as one community would be seen as having an entire burden that could technically be shared between many communities. However, it is important to note that public views on siting do not necessarily differentiate between LLW, ILW, HLW and SF, but may be more concerned with the form of the waste management and other issues. It is also worth noting that the source of waste is potentially significant regarding its acceptability (i.e. acceptability of Ministry of Defence Wastes on moral grounds) (5). These concerns will need to be addressed in public consultation.

Public acceptance

It is commonly accepted that in finding a solution for radioactive waste management a key factor in obtaining a location for a site will be public acceptance (6).

Public support will be affected by the decision making process and the ability of public and other stakeholders to be involved in the process and make a contribution. The process must be open, transparent and inclusive. An environmental impact assessment could be used as the umbrella process as this would help to ensure stakeholder involvement.

Footprint

For the illustrative concept, the footprint for a co-disposal facility was estimated to be 4.3 km², which is the sum of the separate repository footprints for ILW/LLW (1.4 km²) and HLW/SF (2.2 km²) and the space in between. The reference layout for a co-disposal facility is shown in Figure 1.

The co-disposal facility footprint would not only depend on the facility layout and the volume of waste for disposal, but would be limited by the local geology (structure and lithological variation) and, possibly other factors such as constraints of ownership of land and/or mineral rights.

In earlier studies describing the selection of a site for disposal of 600,000 m³ of ILW and 1.4 million m³ of LLW, for inland sites a target threshold of approximately 4 km² was set (7). However, it also states in this report that:

"This was considered to be the likely land-take covering the underground workings, in any geological environment. This guideline was not applied too rigorously since the land-take would be site specific".

Alternative layouts

No attempt has been made to optimise the co-disposal facility or repository layouts shown in Figure 1. However, for specific sites, creative layouts that work with features of those sites may reduce the repository footprint, and may allow consideration of an increased number of sites than might be inferred from simple comparison with the reference layout.

Co-disposal implies access from a single surface site, but the underground host environments need not be the same. While most repository concepts use layouts where all disposal vaults and tunnels are in one horizontal plane, there is no fundamental reason why HLW/SF and ILW/LLW should not be disposed of at different depths. Indeed, for some sites, it may be possible to emplace the facilities in two different geological settings. The construction on two levels would provide some of the separation that may be required between the two repositories. Other features of geological settings may also affect the repository footprint required. For example, the magnitude and direction of groundwater flow will affect any required separation between disposal areas. The extent of faults and fracturing may, as for a repository for a single waste type, increase the footprint required, as it may not be possible to excavate all vaults to the ideal length.

Alternative concepts

Disposal concepts developed in other countries were reviewed to determine what implications those designs might have on the size of a co-disposal facility. For designs that differed from the illustrative concept the repository area could be expected to decrease, but for some design concepts a greater volume of rock would require excavation (8).

Alternative Geological Environments

The illustrative design concept adopted for this study is in crystalline rock. In the UK, the principal alternative geological environment is mudrock. Disposal in mudrock would require additional considerations, such as gas migration for ILW/LLW and shorter timescales for retrievability. Mudrocks also contain multiple minor pathways which are inherently difficult to characterise and the groundwater flow is affected by several coupled processes due to chemical and thermal gradients.

Evaporites are of less of interest (but not dismissed) than other geological settings in the UK because:

- evaporites in the UK are frequently associated with the past and present mining activities (e.g. the bedded salts in the Cheshire Basin) and hydrocarbon reserves (e.g. salt domes in the North Sea); and
- the ductile behaviour of evaporites (which allows them to self-seal) means that it would be difficult to maintain excavations for extended periods of time as demanded from a retrievability perspective.

RADIOLOGICAL IMPLICATIONS OF CO-DISPOSAL

A scoping study was performed to evaluate the post-closure impacts on man of a co-disposal facility, that considered the groundwater, gas and human intrusion pathways. The work is based on data and models which have been developed for use in the 'Generic Performance Assessment' (GPA) for the disposal of ILW/LLW (9); these models have been extended to consider a generic concept for the disposal of HLW/SF. This involved using a modified source term model and data to represent the evolution of the near-field of a HLW/SF repository due to the different containment concept as compared with the Nirex Phased Disposal Concept for ILW/LLW.

The approach that has been adopted in the GPA utilises a base case model as a basis for packaging advice (for ILW/LLW) which assumes that the repository is located at a site that:

- would contribute to the long-term performance consistent with meeting the annual individual radiological risk target of 10^{-6} per year for the base case assessment;
- could be achieved in geological settings that may be found in the UK and are considered technically suitable for repository development.

It has been assumed that any releases of radioactive material from a HLW/SF repository or co-disposal facility should be consistent with the 10^{-6} risk per year target as is the regulatory guidance for ILW/LLW (10). However, it is stated in the recent report of the House of Lords Select Committee on Science and Technology (3) that new safety standards would be needed if an integrated strategy for all long-lived wastes is put in place.

In the GPA, the date of closure for the ILW/LLW repository was assumed to be 2080, following a 50 year repository emplacement period. The HLW/SF would be available for disposal over a similar timescale (approximately 2040 to 2085). This assumes 50 years of cooling following vitrification for HLW and removal from the reactor for SF (11). In order to be consistent with the assumptions made in the GPA, the co-disposal post-closure risk calculations were performed using a radionuclide inventory, decayed to the hypothetical year of closure of the ILW/LLW repository of 2080, for both ILW/LLW and HLW/SF.

The ILW/LLW and HLW/SF source terms were modelled separately and do not interact in the base case. To explore what might happen if the source terms were to interact, sensitivity studies were undertaken as discussed in the next section of this paper.

Groundwater pathway

Over the timescale of interest for performance assessment calculations (one million years post repository closure), the calculated radiological risk remains below the 10^{-6} risk target for the assessment of the separate ILW/LLW and HLW/SF repositories. The results for the assessment of the natural groundwater discharge pathway for separate ILW/LLW and HLW/SF repositories show that the key contributing radionuclides to the total calculated risk at various times post-closure include:

- ILW/LLW - chlorine-36, iodine-129, radium-226, thorium-229, thorium-230, uranium-233 and uranium-234.
- HLW/SF - selenium-79, tin-126, iodine-129, caesium-135, radium-226, thorium-230 and uranium-233.

To assess the radiological impact of a co-disposal facility, it was conservatively assumed that plumes from each repository would reach the surface at the same point. The total calculated risk (as the sum of the risks from the combined ILW/LLW and HLW/SF repository) does increase (relative to the risk from ILW/LLW repository) but based on the assumptions made for these scoping studies does not exceed the 10^{-6} risk target.

Whilst the approach taken was conservative from the perspective of maximum risk, it might not be conservative when evaluating other environmental impacts. For example, two separate release plumes would contaminate a wider area.

Gas pathway

A quantitative assessment of the gas pathway has been undertaken for the ILW/LLW repository, as reported in the GPA (9). However, to date such an assessment has not been undertaken for the UK's HLW/SF. A range of gases may be generated within the ILW/LLW and HLW/SF repositories. The key potential hazards are different and the gas generation profile for HLW/SF tunnels will be different to that of ILW/LLW vaults and will also be dependent on the resaturation rate of the bentonite (4). Hydrogen is the principal gas of interest for the assessment of the gas pathway for an HLW/SF repository, generated through anaerobic corrosion of the carbon steel waste containers in the HLW/SF tunnels and, as a small volume in comparison, as a consequence of the radiolysis of water (9). This will affect the rate of overpressurisation in the HLW/SF tunnels. Generation of methane and carbon dioxide will be less significant in HLW/SF tunnels, compared to ILW/LLW vaults, due to the lower amount of organic material and the less significant microbial activity.

Gas generation in HLW/SF tunnels is likely to be of smaller magnitude and occurring at different times to that of ILW/LLW vaults. Hence, it is concluded that interactions between gas source terms are not likely to cause deleterious effects.

Human Intrusion pathway

Nirex has developed a structured approach to the treatment of uncertainty in terms of the human intrusion pathway. The radiological exposure as a result of human intrusion is calculated in terms of dose or risk to a range of potentially exposed groups as a result of a number of potential intrusion scenarios. The type of human intrusion scenarios that might be addressed in a repository performance assessment are illustrated by considering two example scenario representations. These scenario representations are developed from the assumption that exploratory drilling for natural resources penetrates the repository, bringing up radioactively contaminated material up to the surface. The potentially exposed groups of people considered are geotechnical workers who might handle and examine extracted rock core and site occupiers who might use land onto which rock core was discarded.

The radiological risks from human intrusion will depend upon a number of factors. The following factors are considered to be of greatest importance, and whose variation most significantly affects the potential risk from the human intrusion pathway:

- The radionuclide inventory in the repository. It is cautiously assumed for the purpose of modelling that the repository inventory remains in the vaults/tunnels with no radionuclides transported away from the repository (e.g. in groundwater or gas).
- The design of the repository, particularly depth, location and layout (4).
- The frequency for drilling boreholes in the repository location. It is assumed in the GPA the repository host rock is a hard rock, in which the mid-range value for the drilling frequency was taken to be 10^{-10} holes per m^2 per year.

One approach to assessing the risk associated with human intrusion to a co-disposal facility is to assume that the total inventory (*i.e.* the sum of the respective inventories of LLW, ILW, HLW and SF) is homogeneously distributed in a repository that has the same total plan area and volume as the total proposed co-disposal facility. However, this model of 'co-disposal' is not realistic, and provides only an illustration of an 'average' risk for human intrusion.

An alternative approach was therefore undertaken, whereby human intrusion into repository vaults containing one waste type only (*e.g.* HLW) was considered in isolation from intrusion into vaults containing other waste types.

The assessment of the radiological risk from the human intrusion pathway was performed separately for unshielded ILW, LLW and shielded ILW, HLW and SF by the method described in the GPA (9).

The assessment of the overall radiological impact of a co-disposal facility, for a human intrusion pathway is not straight-forward (*i.e.* it is conservative to sum the risks for the separate repositories as performed for the groundwater pathway).

A co-disposal facility constructed in accordance with the illustrative layout shown in Figure 1 would present a larger plan area of waste in disposal than the ILW/LLW repository alone. As the number of intrusion events into a repository for a given intrusion frequency is directly proportional to disposal footprint, the calculated risks will increase for the overall disposal facility as it has a larger footprint. This is largely a regulatory consideration because the true risk, as a result of extraction and examination of rock cores, from disposal of the different wastes in two separate facilities would be the same if the disposal plan areas and the rock-type at the two locations were the same.

The approach adopted in the GPA to evaluate the impact of intrusion by drilling upon the site-occupier group is necessarily simplified, and excludes potentially important features, events and processes (FEPs) that could affect calculated radiological risk. For example, the modelling approach assumes site occupiers use the same 10,000m² 'resource area' over the whole of the one million years considered in performance assessment, and that this area remains viable for, and is only used for, arable agriculture over this timescale. The approach also assumes that all core removed by drilling over the one million years considered in the performance assessment is discarded onto the same 'resource area'. If applied systematically, treating the co-disposal facility as a single facility, risks should be calculated assuming the accumulation of cores, resulting from drilling into all waste types, on this single 'resource area'. This assumption implies transport over significant distances from the drill site, which is arguably unrealistic. If an alternative assumption were made, whereby extracted core were discarded at the site of drilling, lower radiological risks than those calculated here would result.

The above points, including the treatment of wastefrom heterogeneity issues, emphasise the need to review the current approach used by Nirex in the assessment of the human intrusion pathway. This could usefully be compared with the approach used in other, international programmes for HLW/SF disposal.

The layout of a co-disposal repository could affect risks to the human intrusion pathway.

If repositories were vertical, with vaults containing ILW (say) directly overlying tunnels containing HLW, there would be an increase in the calculated risk in both the geotechnical worker scenario and the site occupier scenario, compared with risks from a co-disposal facility with adjacent ILW vaults and HLW tunnels. This is because, in a stacked geometry, a single drilling operation could penetrate both wasteforms.

It is worth noting that, however, in practice, intrusion scenarios involving drilling are likely to include a number of activities that have the potential to alert the intruders to the hazardous nature of the material and hence could result in a changed course of action and reduced radiological exposure. Additionally, the hazardous nature of contaminated material brought to the surface might be identified, for example, by its unusual appearance or by analysis, and appropriate precautions could be adopted in any further handling of the material.

Given activities such as those described above, it is not clear that if a single drilling operation penetrated the shallower vault type in a stacked co-disposal facility, and drilling would subsequently continue to penetrate the deeper vault type. Therefore, it is difficult to estimate the overall risks to the human intrusion pathway for such a drilling operation.

REPOSITORY INTERACTIONS

Thermal

The Nirex Phased Disposal Concept for ILW/LLW is designed to achieve a long-term temperature target of less than 50°C for all waste packages. Short-term excursions above the 50°C target, for example temperatures of up to 80°C for a period of up to five years, would be tolerable. For the purpose of the scoping calculations it has been assumed that 80°C represents a reasonable short-term upper bound on temperature in the ILW/LLW vaults (12).

Many HLW/SF disposal programmes have adopted disposal concepts with engineered barrier systems similar to the illustrative concept for the HLW/SF repository of the co-disposal facility. Where a bentonite barrier is assumed, these programmes have generally considered that the long-term

performance of the barrier would not be adversely affected by temperature variations, provided the bentonite experienced temperatures no greater than 100°C (4). However, in the presence of chemical interactions between the repositories the allowable maximum temperature in the bentonite would require investigation.

Design options that minimise the repository footprint without exceeding the derived limits on thermal interactions were investigated. Variations in the reference repository design that were explored include reduction of the horizontal separation between the two repositories and stacking the repositories vertically. Thermal interactions can be minimised to a tolerable level for a 100m separation between the repositories (vertically or horizontally) by positioning the hotter AGR and PWR spent fuel furthest from the ILW/LLW.

Conceivably, the temperature limit could be exceeded in the vicinity of an ILW/LLW vault if the vault was backfilled at a time when heat from the HLW/SF tunnels had reached the vault. It is possible to envisage this scenario occurring if delayed backfilling is employed for retrievability purposes. For the case in which the two repositories are stacked with a 100-m vertical separation, heat from the HLW/SF repositories could reach the location of the ILW/LLW vaults after 100 years, because of the dominant vertical component of heat transfer. It may be possible to define alternative stacked disposal arrangements that minimised the thermal interaction between the two repositories by not locating any ILW/LLW vaults above the PWR SF and AGR SF tunnels.

In absence of site specific parameters, provided the combined thermally induced stresses from the two disposal regions are no more than a few MPa greater than would occur in separate repositories, it can be assumed that thermal stresses will have an insignificant impact on fracture behaviour and hydraulic conductivity around the repositories. Hence, the thermal-stress interactions in a co-disposal facility can be considered insignificant for most design options explored.

For the stacked geometry, with a 100m vertical separation between the repository regions, thermal stresses induced from heat from the HLW/SF tunnels were not estimated to cause major stability problems in the vaults and tunnels, although fracture apertures could change by several microns.

Chemical

A key issue to be considered when assessing the feasibility of co-disposal is the compatibility of the two wasteforms (ILW/LLW and HLW/SF) and the respective engineered barrier systems of cementitious backfill and bentonite. The following interactions of the modified groundwater plume from the ILW/LLW repository with the bentonite and wasteforms in the HLW/SF repository were identified as potentially the most significant adverse effects:

- water with high pH and high calcium and potassium content derived from the ILW/LLW vaults adversely affecting the containment properties of the bentonite buffer in the HLW/SF tunnels;
- high pH waters from the ILW/LLW vaults increasing the rate of dissolution of borosilicate glasses in the HLW/SF tunnels;
- organic material and their degradation products from the ILW/LLW vaults affecting the solubility and speciation of radionuclides arising from the HLW/SF tunnels.

The potential importance of effects (B) and (C) both depend upon the containment properties of the bentonite clay buffer. Degradation of the bentonite performance is, therefore, considered the most important of the three issues. Scoping studies have investigated the extent and impact of chemical interactions on HLW/SF repository performance. In addition, the likelihood of induced criticality in or in the close vicinity of the tunnels for spent fuel, caused by an influx of high pH groundwater from the ILW/LLW vaults, has been assessed.

Scoping calculations were also used to investigate the effect of a high pH plume on the HLW glass wasteform dissolution/precipitation. The calculated radiological risk was insensitive to the rate of glass dissolution, and controlled mainly by diffusion through the bentonite and travel time through the geosphere. The potential for criticality due to preferential precipitation of the uranium/plutonium

leached from spent fuel or dissolution of container filler material could be controlled by design of high integrity containers.

However, if the cementitious plume from the ILW/LLW repository did reach the bentonite in the HLW/SF repository, preliminary scoping calculations suggest the impact on radionuclide release would be small, but a better understanding of the possible processes is required. The extent of interactions will depend on the attenuation of chemical species in the plume, bentonite thickness and bentonite emplacement density.

The key issue in the assessment of the impact of organic materials derived from the ILW/LLW vaults on the chemistry of radionuclides in the HLW/SF tunnels is whether organic species can penetrate the clay buffer to affect solubilities near to the wastes. Here, the clay itself would be a formidable barrier to movement of organic species, which would probably be chemically bonded by the clay (13).

Due to the lack of data on how the relevant organic materials affect radionuclide behaviour at lower pH, the impact of changing the near-field chemistry was investigated by removing the solubility limits and sorption properties of the engineered barrier. Scoping calculations suggest that the flux of radionuclides leaving the repository would be increased; the loss of sorption in the near-field would have the most impact. However, overall we can infer that even if the ILW plume reduced near-field sorption and solubility control in the HLW/SF tunnels, there would be no major impact, but this would depend on the retardation and of solubility in the geosphere.

CO-DISPOSAL FACILITY LAYOUT

In order to minimise the effects of chemical interactions (by dissolved substances in groundwater), the repositories should be planned such that the intervening rock separating the repositories should not be connected by any significant groundwater flow channels (or paths). The details of a repository design are site specific, and in the absence of a site, only general guidelines can be given. However, given a specific site it might be possible, in principle, to design a co-disposal facility layout to ensure that the probability of interactions between the two parts is small.

Limiting interactions between the two repositories mediated by groundwater flow is not primarily a matter of the degree of separation of the repositories, but rather of the orientation of the line joining the repositories relative to the direction of flow. It will also require consideration of the impact of disturbance of host rock due to excavation of repositories and emplacement of wastes and buffer/backfill.

Given a flow field, it would be straightforward to design a co-disposal facility layout such that interactions between the two repositories is negligible. However, the groundwater flow could change as a result of, for example, climate change, particularly glaciation. It would therefore not be possible, in general, to ensure that interactions are negligible for the very long periods of time that need to be considered (hundreds of thousands of years to millions of years).

The aim would therefore be to ensure that the probability of interactions is small. It is suggested that the spacing between the two repositories should, as a minimum, be comparable to the horizontal dimensions of the ILW/LLW the repository (of the order of several hundred metres at least). A larger spacing would, however, be beneficial.

Suggestions for geological settings features include:

- It would be beneficial for there to be an extensive low permeability feature between the two repositories, although it would be necessary to establish the existence and properties of this feature with sufficient confidence.
- If a sufficiently thick and extensive near-horizontal formation existed at a site, this would be a good location for both parts of the repository.
- If such a formation does not exist at a chosen site, it would be desirable to locate the two repositories in separate blocks of lower permeability rock between higher permeability features.

In order to minimise interactions it would be desirable:

- For high quality seals to be placed in access tunnels and shafts at suitable locations.
- To grout the rock surrounding the tunnels and shafts in the vicinity of the seals and in the vicinity of locations where the tunnels and shafts intersect high permeability features in the rock (if these locations are not the same).
- To establish with sufficient confidence that the seals and rock grouting function as required over the very long times that need to be considered.

The achievement of the idealised limitations on interactions between the two repositories would have to be balanced against other siting constraints (as mentioned in the paper).

INTEGRATED RETREIVABILITY CONCEPT

The Nirex Phased Disposal Concept includes provision for an extended period of underground storage (1). During such a period, waste packages would be emplaced in vaults but these would remain open. The packages could be retrieved using the existing emplacement equipment in reverse. The aim is to have the capacity of retrieving any targeted package within one week.

Co-disposal will require an integrated retrievability concept in which the objectives can be met by both disposal concepts. Current national disposal concepts for HLW/SF differ little in the design concepts employed. Many have been developed to include features that improve retrievability, but most involve the early emplacement of buffer materials and/or backfill.

The illustrative HLW/SF disposal concept assumed for this study could not be readily modified to provide for a period of open storage similar to that provided in the Nirex Phased Disposal Concept. It was therefore assessed whether alternative emplacement concepts for HLW/SF could provide a similar level of retrievability (14). Nuclear safeguards issues and monitoring will require additional consideration.

Alternative concepts that were considered included those based on emplacement in vertical boreholes or short horizontal tunnels and underground implementation of storage techniques currently operated on the surface. The evaluation of options was carried out on the basis of the following criteria:

- The ability to affect and maintain a groundwater management system to prevent direct contact of groundwater with waste canisters.
- The ability to control the repository environment (e.g. with adequate cooling ventilation), to provide suitable conditions for extended storage and, if necessary, waste retrieval operations.
- The ability to retrieve waste packages without compromising the final emplacement of engineered barriers or adversely affecting the long-term safety.
- The ability to provide monitoring and control during the period of institutional management.

In comparison to the illustrative HLW/SF disposal concept, retrieval of HLW/SF is made easier for engineering designs with vertical boreholes or short horizontal tunnels. However, this type of concept that involves early emplacement of bentonite buffer was considered unlikely to meet the Nirex ILW retrievability target because of the time required and the ease with which a waste canister could be retrieved from a saturated or partially saturated bentonite buffer within borehole. The practicalities of this option are currently being tested by SKB. (Although it is worth noting that an environment other than hard rocks may not use a bentonite buffer).

However, the ability to meet the Nirex ILW retrievability target for retrievability could be increased by designs that potentially avoid the difficulties associated with extraction of the canister from swollen bentonite. These could include:

- The use of a steel liner between the waste canister and bentonite buffer (14). The steel liner serves no long-term safety function but as long as the steel liner and the waste canister are intact and accessible, reversible handling is possible.

- The internal containment of bentonite buffer inside the waste canister, e.g. the Integrated Waste Package (IWP) as suggested by Apted (15). It is claimed that the retrieval option is greatly improved because the saturation and the swelling is delayed to times greater than 100 years. However, the IWP is an unproven and largely untested technology requiring more research as a barrier concept design.

The transfer of proven, surface dry-storage technologies to a deep underground facility could include:

- Construction of a vault-in-cavern underground storage system that could be converted directly to a disposal system.
- Dual-purpose storage/transport casks placed in alcoves in tunnels.

These options would require the solution of a number of technical problems, not least of which would be the management of heat production. Once the packages have cooled sufficiently, the storage facility could be converted into a disposal facility by backfilling without the double handling of packages. The backfill to be employed would depend upon detailed design studies, but will require the consideration of alternatives to bentonite (such as cement) due to the larger excavated volume of those type of disposal facility compared to boreholes.

Overall, an integrated co-disposal strategy incorporating retrievability for HLW/SF compatible with the Nirex target for ILW/LLW appears feasible. However, if a strategy of co-disposal were to be pursued, the following issues would require further investigation:

- Repository layouts and waste canister spacing required to achieve operation temperatures compatible with retrieval operations.
- Investigation of the feasibility of canister designs based on the use of an Integrated Waste Package.
- Review of the advantages and disadvantages of the cement and clay based materials as buffer/backfill options for the disposal of HLW/SF.

IMPLICATIONS FOR COST

Separate Repository Costs

For the purposes of provisioning advice to its customers Nirex has provided cost estimates for the disposal of 200,000 m³ of ILW/LLW for the "Base Case Programme" of the Nirex Disposal Concept (16). The total lifetime costs are estimated at £5738 million with a Care and Maintenance period at September 1999 values (these do not include any costs associated with risk or uncertainty).

For HLW/SF the total cost of a separate repository with 76 emplacement drifts has been calculated to be of the order of £3900 million. This calculation assumes that the same organisation undertakes the development of both the ILW/LLW and HLW/SF repository concepts.

Co-disposal Cost Savings

In Table II the cost estimates are given for the Base Case inventory for separate repository programmes for ILW/LLW and HLW/SF, and also for a co-disposal facility programme. This also assumes shared costs for the following:

- site characterisation;
- repository operation;
- repository construction;
- repository closure;
- other programme works;
- institutional costs and
- internal costs.

This assumes that the same organisation undertakes the development of both the ILW and HLW/SF repository concepts and that the operational period is not extended as a result of the requirement to dispose of the larger volume of waste. However, it should be stressed that the potential cost saving

benefits can only accrue if decisions on the material to be managed are made prior to any process commencing.

Table II: Co-disposal Summary Programme Costs for the Reference Case Scenario.

	"Base Case" Separate ILW/LLW Repository	Separate HLW/SF Repository	Co-disposal of ILW/LLW and HLW/SF
Programme Cost (£m)	5738	3900	6738
Risk Assessment (£m)	1532*	not estimated	no less than 1532

* At the 75% confidence level.

This base case value for co-disposal does not include a cost associated with risk or uncertainty. It is worth noting that due to the preliminary nature of the work, the certainty in the cost for a HLW/SF repository is less than that for the ILW/LLW repository.

Integrated Programme

An integrated programme of research and site selection for a co-disposal facility is not expected to take significantly longer than for parallel investigations for separate repositories for HLW/SF or ILW/LLW as the key issues and drivers would be the same. The critical path activities would be those relating to consultation and decision-making, as well as those relating to site selection and investigation.

However, if a retrospective decision were made to adopt a co-disposal approach or include other wastes than those planned at the start midway through a programme of site selection, after an outline repository design had been agreed, then this could require a substantial reworking of the programme. This could also undermine public confidence and be perceived as moving the goal posts.

CONCLUSIONS

This paper has focused on the technical issues associated with co-disposal. However, a key factor to be considered for a co-disposal facility will be public acceptance. The decision-making process must be open, transparent and inclusive.

For the illustrative co-disposal concept assumed for this study, a key technical issue that required consideration was the interaction between the cementitious plume from the ILW/LLW repository and the HLW/SF wastefoms and bentonite backfill (that is typically used in HLW/SF disposal concepts). Scoping studies suggest the impact on radionuclide release would be small, but a better understanding of possible processes is required.

In order to minimise the effects of chemical interactions (by dissolved substances in groundwater), the repositories should be planned such that the intervening rock separating the repositories should not be connected by any significant groundwater flow paths. The details of a repository design are very site specific, but given a flow field, it would be straightforward to design a co-disposal facility layout such that interactions between the two repositories mediated by groundwater flow are negligible.

Over long periods of time (over hundreds of thousands of years to millions of years), however, the groundwater flow field could change as a result of, for example, climate change. The aim would therefore be to ensure that the probability of interactions is small.

Co-disposal offers potential cost savings over the development of separate facilities for different types of waste, and would involve the development and consequential disturbance of a single site. For example; an integrated process for consultation and planning applications, and a single programme of transport, site selection and characterisation.

The study reported in this paper has been based on combining existing disposal concepts for different types of waste. If a co-disposal programme were initiated in the UK it will require an integrated

retrievability concept in which the objectives can be met by both disposal concepts. It is possible that a different approach to repository design could be developed for the range of wastes, in which consideration should be given to the possibility of using the same backfilling material for both waste types.

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Figure 1: Illustrative Co-Disposal Concept – Underground Layout

