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Interactions between the co-located intermediate-level waste/low-level waste and high-level waste/spent fuel components of a geological disposal facility

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ABSTRACT

The 2008 UK government White Paper, published as part of the Managing Radioactive Waste Safety programme, identified benefits to disposing of all of the UK's higher activity wastes at the same site. That is, a single geological disposal facility (GDF) could be constructed that consists of a module for low- and intermediate-level waste, and a module for high-level waste and spent fuel.

A safety case for a co-located GDF will have to consider the extent to which evolving thermo-hydro-mechanical-chemical and gas (THMCG) conditions in and around one module may affect conditions in the other module, including the extent to which barrier performance and radionuclide migration behaviour could be altered. Several research projects have been undertaken on behalf of Radioactive Waste Management Directorate aimed at understanding and evaluating the THMCG interactions that might occur during the disposal facility operational and post-closure phases.

This paper describes research on THMCG interactions between disposal modules based on illustrative GDF designs for different host rock environments. Interactions were evaluated using simple analytical solutions and detailed three-dimensional models. The analyses demonstrated that interactions can be controlled by design constraints.

KEYWORDS: disposal facility, radioactive waste.

Introduction

THE Radioactive Waste Management Directorate (RWMD) of the Nuclear Decommissioning Authority (NDA) is responsible for implementing UK Government policy for long-term management of higher activity radioactive wastes. Government policy is for geological disposal of radioactive waste preceded by safe and secure interim storage, as set out in the *Managing Radioactive Waste Safely* (MRWS) White Paper (Department for Environment Fisheries and Rural Affairs *et al*., 2008). The currently preferred disposal option is for all of the wastes to be co-located in a single geological disposal facility (GDF) in England or Wales. This policy is consistent with the White Paper, which states that "In principle the UK Government sees no case for having separate facilities if one facility can be developed to provide suitable, safe containment for the Baseline Inventory." Construction of a single facility could lead to major cost savings and reduce environmental impacts because, for example, surface facilities and access tunnels would be shared (Department for Environment Fisheries and Rural Affairs *et al*., 2008).

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The wastes intended for disposal in a GDF include vitrified high-level waste (HLW), intermediate-level waste (ILW), and low-level waste (LLW) unsuitable for near-surface disposal. The RWMD also considers other nuclear materials, namely spent nuclear fuel (SF), separated plutonium and uranium, that have not been declared as wastes by their owners, but which might be declared as wastes in the future if it were decided they had no further use (Nuclear Decommissioning Authority, 2010*a*). This paper focusses on the geological disposal of ILW, LLW, HLW and SF. Different disposal concepts will be implemented for these different waste materials, but the concepts are broadly grouped in distinct and separate ILW/LLW and HLW/SF disposal modules that are co-located in that they share surface facilities and access tunnels.

Evolving thermo-hydro-mechanical-chemical-gas (THMCG) conditions in one disposal module during the construction, operational and post-closure phases could influence conditions in the other disposal module. This paper is concerned with the analysis of potential THMCG interactions between disposal modules and presents results from a study undertaken on behalf of the RWMD by Watson *et al.* (2009). The approach to identifying THMCG interactions and an overview of results was presented by Towler *et al.* (2009).

Geological disposal concepts

At the present stage in the process of implementing geological disposal in the UK, no disposal sites have been identified. Therefore, the RWMD's programme considers disposal of higher activity wastes in different geological environments in order to provide a basis for planning and assessment. The RWMD has defined three generic geological environments, which are designed to capture and illustrate the range of behaviour and issues that may need to be addressed when evaluating candidate sites (Nuclear Decommissioning Authority, 2010*a*). The host rock types correspond to three distinct general rock types that occur in the UK and that are considered potentially suitable to host a GDF for higher activity radioactive wastes, based on studies carried out in the UK and overseas. The three host rock types are as follows:

(1) Higher strength rocks, typically crystalline igneous and metamorphic rocks or geologically older sedimentary rocks.

(2) Lower strength sedimentary rocks, typically geologically younger sedimentary rocks.

(3) Evaporites, typically containing anhydrite, halite and other minerals that have been formed by the evaporation of surface water bodies in the geological past.

The RWMD has identified illustrative disposal concept examples based on concepts being developed for these host rock types worldwide. The disposal concepts are designed as multiple barrier systems with the functions of isolating the waste from the accessible environment and containing the radionuclides associated with the waste. The concept examples are as follows:

(1) In the higher strength rock example for ILW/LLW it is assumed that the waste packages are stacked in vaults and a cementitious backfill [Nirex reference vault backfill (NRVB)] which is placed in the space between the waste packages as part of the closure engineering. The backfill is designed to condition the groundwater and provide a long-term chemical barrier that reduces radionuclide release. The HLW/SF disposal module is based on the Swedish KBS-3V disposal concept for SF disposal. In this concept, canisters containing HLW or SF are placed in bentonite-lined vertical deposition holes drilled from horizontal tunnels. The tunnels are backfilled with bentonite soon after disposal to provide sufficient confining pressure to allow the bentonite buffer to function correctly (i.e. to allow required swelling pressures to be achieved in the saturated buffer).

(2) The engineered barrier system (EBS) for the lower strength sedimentary rock example is based on the design developed by Nagra in Switzerland. The ILW disposal packages are stacked in arrays in disposal vaults, which are backfilled and sealed using a cementitious grout. The HLW/SF disposal canisters are placed in horizontal disposal tunnels on top of bentonite blocks and the tunnels are backfilled with bentonite pellets.

(3)The evaporite rock example for ILW/LLW disposal is based on the US Waste Isolation Pilot Plant (WIPP) concept for the disposal of transuranic wastes. It is assumed that the ILW/LLW packages are stacked in disposal rooms and chemical buffering is achieved by placing bags of magnesium oxide on top of each stack. The MgO is intended to absorb CO_2 and water and buffer pH to alkaline values. The illustrative design for the HLW/SF disposal area in an evaporite rock is based on the drift emplacement design developed by DBE in

Germany. It is assumed that HLW/SF disposal canisters are placed on a tunnel floor and the area around the disposal canisters is filled with crushed rock salt.

It is important to evaluate and understand the extent and effects of THMCG interactions between disposal modules for these illustrative disposal concept examples in order to determine minimum module separation distances for which barrier safety functions are not adversely affected; barrier safety functions are described fully by Nuclear Decommissioning Authority (2010*a*). A reference respect distance of 500 m was assumed in earlier work reported by King and Poole (2002). This paper considers the effects of potential THMCG interactions in each disposal concept for different module separation distances.

Thermal interactions

For each concept, heat will be generated in both disposal modules, primarily as a result of radioactive decay. The thermal output of HLW/SF, although relatively short-lived, is significantly greater than that of ILW/LLW, however the peak temperatures on the container surfaces are expected to be similar (no more than 100ºC for HLW/SF and up to 85ºC for ILW/LLW). Heat will also be generated by exothermic reactions, mostly from cement hydration reactions following backfilling in the ILW/LLW disposal modules of the higher strength and lower strength sedimentary rock examples. Heat may be transported between disposal modules by conduction and advection. Key factors affected by temperature increases are:

(1) The rate of corrosion and other degradation reactions which have the potential to result in early package failure and generate gas.

(2) The rate of diffusive mass transfer.

(3) The solubility of many of the substances that will be present in the GDF, with the potential to increase the mobility of substances that might otherwise be solubility limited.

(4) Radionuclide sorption.

(5) Groundwater flow and saturation (i.e. buoyancy-driven flow and drying).

(6) Thermal stresses and strains in the rock, EBS materials and wastes.

(7) Barrier functions that are uncertain at elevated temperatures, especially at temperatures approaching and greater than 100ºC; GDF designs typically specify maximum temperatures within the EBS that should not be exceeded. For example, exposure to elevated temperatures may cause mineralogical alteration in a clay-based buffer or backfill, which could reduce swelling potential (Nuclear Decommissioning Authority, 2010*b*).

Heat transfer in a water-saturated rock mass may occur by advection, conduction or a combination of the two. The relative importance of heat transfer processes may be assessed by evaluation of the Péclet number, which represents the ratio of the advection and conduction terms. GDF concepts generally envisage host rocks in which natural groundwater flow rates are small, and Watson *et al*. (2009) determined that the Péclet number is likely to be much less than unity in such rocks. Therefore, heat transfer will be dominated by conduction even in higher strength rocks where groundwater flow may occur in fractures.

Estimates of the effects of heat generated in one disposal module on the temperature in another may be made using analytical solutions to the linear one-dimensional equation for heat transfer in a water-saturated porous medium (Watson *et al*., 2009). Based on typical parameter values for the higher strength and lower strength sedimentary host rocks and assuming a constant heat source, it would take more than 1000 years for heat to be conducted from one disposal module to the other for a disposal module separation distance of 500 m. It is expected that on this timescale the thermal output from the wastes will have reduced significantly and the thermal interaction between disposal modules will be insignificant. However, if the separation distance is as low as 100 m, heat generated from SF may significantly influence temperatures in the ILW/LLW disposal module within a few tens of years after disposal.

Evaporite has a thermal conductivity that is a factor of two to three greater than that of the other two host rocks and therefore the thermal interaction will be greater in evaporite. Thermo-mechanical interactions are thus more likely to occur in these rocks than in the other rocks considered for the same disposal module separation distance. However, the response of the evaporite host rock to the thermo-mechanical stresses is likely to be an increase in the creep rate. If this occurs during the post-closure period, it is likely to be beneficial to performance because it will result in earlier healing of fractures in the excavation disturbed zone (EDZ) and permeability reduction (Nuclear Decommissioning

Authority, 2010*b*). However, elevated creep rates might require additional measures to be taken during the operational period.

Hydrological interactions

The groundwater flow field in the geosphere will initially be perturbed by facility excavation and operation. After facility closure the rock around the disposal modules, components of the EBS and other materials will resaturate and the long-term post-closure flow field will be established on a timescale that depends on the hydrological properties of the host rock. This flow field is expected to gradually evolve in response to the changing properties of the waste and EBS as they degrade, as well as in response to the natural evolution of hydrological conditions. Groundwater flow could be focussed through or diverge around the disposal modules depending on the contrast between the host rock hydraulic conductivity and the hydraulic conductivities of materials in the GDF. The presence of one disposal module could influence hydraulic conditions in the other disposal module because of perturbations to the hydraulic head gradient, and access tunnels and shafts (especially the EDZ around them) could provide direct connections for groundwater movement between disposal modules. Key factors affected by changes in groundwater flow are:

(1) Advective transport of solutes, which is likely to be more significant in higher strength rocks where flow may occur in hydraulically conductive features such as fractures or minor faults.

(2) The resaturation process especially in the immediate post-closure period of a disposal module. Depending on facility design and operational history, the possibility exists for head gradients during the resaturation period to be in a different direction to the long-term gradients for which the facility layout was designed, although radionuclides are unlikely to be released from waste packages in this period.

Three-dimensional groundwater flow models have been developed to evaluate interactions between disposal modules for the higher strength rock and lower strength sedimentary rock example GDFs using the *FEFLOW* code (Watson *et al.*, 2009). The modelling was limited to the sub-areas of the GDF in which interactions are most likely to occur (parts of the two disposal modules in closest proximity and the connecting access tunnels). The development of the groundwater flow field was modelled in response to stepwise construction of the GDF, operational dewatering and subsequent resaturation. The natural hydraulic gradient was assumed to be from the HLW/SF module to the ILW/LLW module to investigate whether excavation of the HLW/SF module could alter the flow field sufficiently to draw chemically aggressive ILW/LLW porewaters (e.g. an alkaline plume) towards the HLW/SF module.

Figure 1 shows the evolution of hydraulic heads within different areas of the GDF and up-gradient and down-gradient of the GDF. The impacts of operational dewatering can be seen, as can the sequence in which the different components are constructed based on the time of dewatering. The ILW/LLW vaults are assumed to be kept open and only backfilled on closure of the GDF. The HLW/SF tunnels are backfilled as soon as they have been filled.

The short period of operational dewatering for the HLW/SF tunnels compared with the ILW/LLW vaults, and the smaller pore volume to be resaturated in the HLW/SF tunnels compared with the ILW/LLW vaults, result in the hydraulic gradient driving water from the HLW/SF module towards the ILW/LLW module. Therefore, chemically aggressive ILW/LLW porewaters will not flow towards the HLW/SF module.

The results are similar for the lower strength sedimentary host rock, as shown in Fig. 2. In this example the ILW/LLW disposal tunnels are closed soon after emplacement. However, the hydraulic gradient still drives water from the HLW/SF module to the ILW/LLW module due to the smaller pore volume to be resaturated in the HLW/SF tunnels compared with the ILW/LLW tunnels.

Mechanical interactions

Individual disposal tunnels/vaults within a disposal module will be separated by a sufficient distance to ensure insignificant direct mechanical interaction, and it is expected that there will be a greater separation distance between disposal modules. Therefore, direct mechanical interactions between disposal modules will not be significant. However, mechanical interactions may be significant when combined with other processes, such as temperature increases as described above.

Post-closure nuclear criticality in one disposal module could potentially disrupt the barriers in

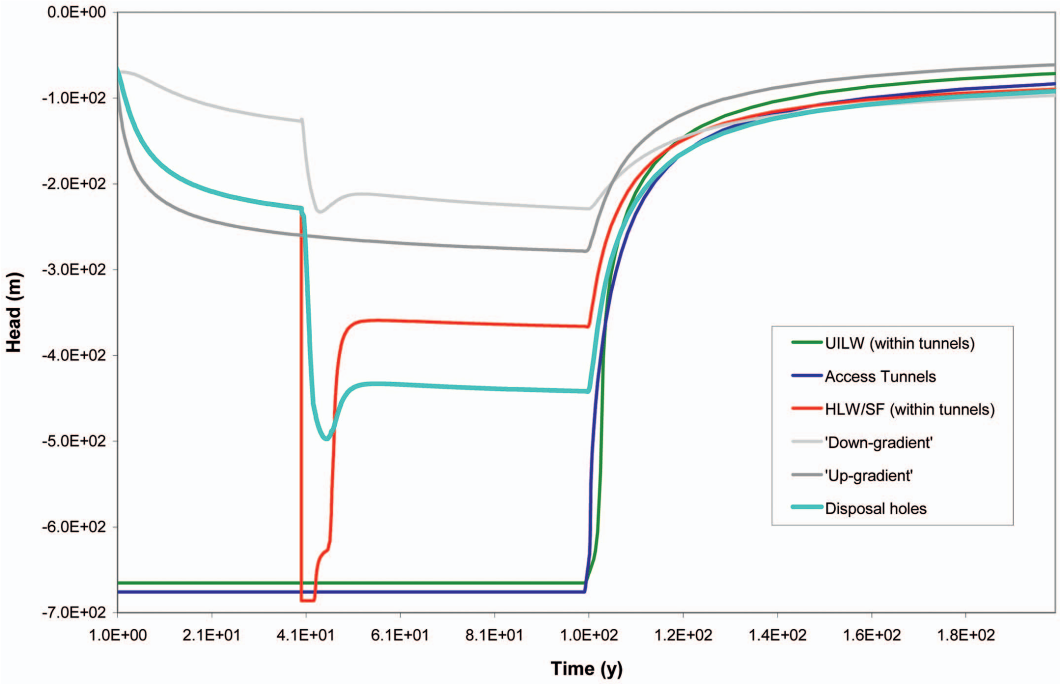

FIG. 1. Evolution of hydraulic head at different locations for the higher strength rock example (Watson *et al*., 2009).

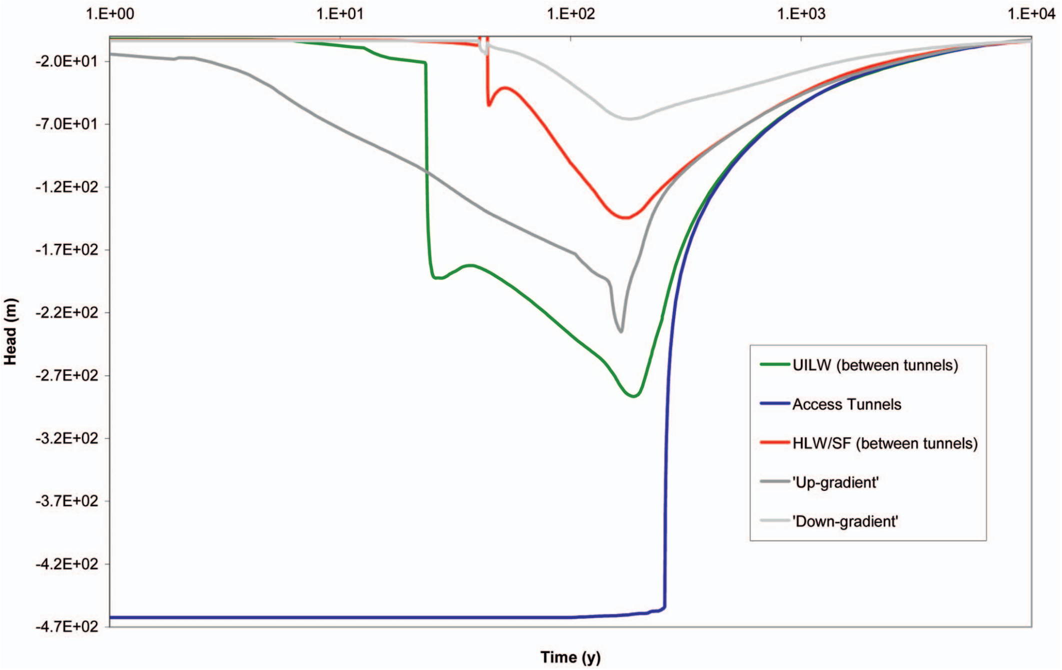

FIG. 2. Evolution of heads for the lower strength sedimentary rock example (Watson *et al*., 2009).

the other module and the properties of the rock between the two disposal modules. Watson *et al.* (2009) considered the size of cavity that could be generated by a criticality event and concluded that criticality in one disposal module will have little impact on the performance of the other module provided the disposal modules are at least a few hundred metres apart.

Chemical interactions

Different EBS designs will be used for different disposal modules, potentially containing different engineered materials. The materials within each module will degrade with time and react with the host rock groundwater; a co-location interaction could occur if solutes from one disposal module were able either to reach the other disposal module or to interact with a plume of solutes emanating from the other disposal module. Key chemical interactions are:

(1) Precipitation/dissolution reactions between the host rock or sealing materials and fluids derived from a disposal module, which have the potential to modify the hydraulic conductivity of the host rock and any pathways that link the disposal modules.

(2) Interaction of high pH waters that have been influenced by cements (typically in the ILW/LLW disposal module) with clays such as bentonite (typically in the HLW/SF disposal module), which could affect material properties and barrier performance.

(3) The influence of substances, such as colloids or organic complexants, derived from one disposal module on the solubility/sorption in another disposal module.

Watson *et al.* (2009) presented simple analytical calculations of the rate at which solutes might be transported in the higher strength rock and lower strength sedimentary rock examples. It was concluded that for a conservative tracer (i.e. ignoring retardation and decay) there will not be any significant interaction on time scales of 10^6 years in lower strength sedimentary rock (e.g. for a 100 m separation distance, breakthrough of the chemical signal does not occur until around 10^6 years). Similar conclusions can be drawn for evaporite host rocks.

However, for possible regional hydraulic gradients in higher strength rock, solutes could be advected between disposal modules 500 m apart on a timescale of thousands of years (again ignoring retardation and decay). Of particular concern is the interaction of an alkaline plume emanating from the ILW/LLW disposal module with the EBS of the HLW/SF module, which could have a detrimental impact on system performance (e.g. embrittlement of bentonite EBS and increased rates of HLW glass dissolution).

A study by Nirex (2002) on the development of an alkaline disturbed zone (ADZ) around a cementitious disposal module concluded that overall the reactions between high pH waters and silicate rocks will lead to pore blocking or precipitation of minerals in fractures. Pore opening can occur, but such opening will not commonly occur along the entire length of a transport pathway. As the porosity and permeability reduce, flow reduces and the rate of growth of the zones of mineralogical reaction will reduce. This will lead to changes in flow patterns, perhaps with sealing of one region of host rock and flow diversion to a different region, which in turn would seal. Over time the effect will be to seal the host rock and reduce groundwater flow rates around the GDF. Reactivation of sealed fractures could occur and individual fractures would be exposed to groundwaters of varying pH, resulting in the development of a sequence of mineral zones along the margins of the fractures. These arguments suggest that an alkaline plume emanating from an ILW/LW module is likely to be attenuated before it reaches the HLW/SF module, although analyses to support such arguments would need to be undertaken when a disposal site has been identified.

Gas interactions

Gas (H_2, CH_4 and CO_2) is likely to be generated in both disposal modules as a result of corrosion of the various metallic components of the wastes and EBS and the degradation of organic materials. The highest potential gas generation rates could occur in the ILW/LLW disposal module, depending on water availability for corrosion reactions, although the large volume of steel in HLW/SF disposal packages offers the potential for significant gas generation in this module should the chemical conditions permit. With the exception of CO_2, which has the potential to carbonate cements, the gas produced is expected to be relatively unreactive.

Migration of gas from one module to another is not expected to result in any deleterious reactions. However, if gases are generated, interactions between disposal modules could occur as follows:

(1) In a low-permeability host rock, gas pressures could become sufficient to establish, or enhance, hydraulic gradients between modules and could result in forced groundwater flow from one disposal module to another if the pressure rises above hydrostatic.

(2) Gas flow between disposal modules could affect resaturation behaviour.

(3) If the gas pressure is sufficiently high, damage to the EBS and host rock could result in the creation of pathways between the disposal modules.

Significant gas pressurization is not expected to occur in disposal modules in higher-strength host rock because the EBS is expected to be gas permeable. However, gas cannot escape easily in the lower strength sedimentary rock and significant pressurization may occur. Therefore, the potential exists for gas pressure to drive water out of a disposal module in lower strength sedimentary rock.

A fully coupled 3D gas generation and multi-phase flow model of the lower-strength sedimentary rock example was developed using the *QPAC* code (Watson *et al*., 2009). The whole of the GDF was represented in the model. The model included gas generation and water consumption from organics (generation of CO_2 and CH_4) and a range of metals (generation of H_2). Microbial reduction of CO_2 with H_2 to form CH_4 was also considered. The gas generation and multi-phase flow calculations are fully coupled such that gas generation ceases if the rate of water consumption is sufficient for the GDF to become dry.

The calculations showed significantly more gas generation in the ILW/LLW module than in the HLW/SF module due to the presence of reactive metals such as Magnox and aluminium. However, gas generation is limited by the availability of water and the pressure gradient remains from the HLW/SF module towards the ILW/LLW module. Therefore, including gas generation and migration in the analyses does not alter the overall behaviour seen in the *FEFLOW* models and chemically aggressive ILW/LLW porewaters will not flow towards the HLW/SF module (Watson *et al*., 2009).

Conclusions

The analysis of THMCG interactions indicates that it is possible for ILW/LLW and HLW/SF disposal modules to be co-located without compromising key safety functions of different barrier components. Interactions are predicted to occur between the different disposal modules but the scoping calculations suggest that their magnitude will be relatively small or that they can be prevented or at least partially mitigated at the design stage.

Two key issues have emerged from the analysis. The first issue is the potential for thermal interactions. The presence of the HLW/SF disposal module has the potential to lead to unacceptable temperatures in the ILW/LLW disposal module. For the higher strength rock and lower strength sedimentary rock examples, a separation distance between the two disposal modules of one to two hundred metres is required. The higher thermal conductivity of evaporites means that heat travels two to three times more quickly in this host rock and thus the respective distances need to be two to three times as large if the same temperature constraints apply.

The second key issue primarily affects the higher strength rock example. For this example, it is possible for fluids to be advected from one disposal module to the other on timescales that might result in a significant interaction. There is therefore the potential for pore fluids from one disposal module to interact with the other disposal module. The interaction that is of greatest concern is that between high pH fluids from the ILW/LLW disposal module and the EBS materials and wastes in the HLW/SF disposal module, although mineralogical reactions could result in blocking of pores and fractures, which would limit alkaline plume migration. It may be possible to prevent a detrimental interaction by designing the GDF layout to ensure that the HLW/SF disposal module is not directly down hydraulic gradient of the ILW/LLW disposal module on timescales of the order of 100,000 years, over which significant activity remains within the HLW/SF disposal module. However, the effects of natural hydrological changes (e.g. climate change effects) would require consideration on such timescales.

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References

King, S.J. and Poole, M. (2002) *Issues Associated with the Co-disposal of ILW/LLW and HLW/SF in the UK.*

WM'02 Conference, February 24-28, 2002, Tucson, Arizona, USA.

Nuclear Decommissioning Authority (2010*a*) *Geological Disposal: Generic Environmetal Saftey Case*. NDA Report NDA/RWMD/021.

Nuclear Decommissioning Authority (2010*b*) *Geological Disposal: Near-field Evolution Status Report*. NDA Report NDA/RWMD/033.

Nirex (2002) *Research on the Alkaline Disturbed Zone Resulting from Cement-Water-Rock Reactions Around a Cementitious Repository*. Nirex Report N/054.

Towler, G., Hicks, T., Watson, S. and Norris, S. (2009) *Implementation of a Geological Disposal Facility (GDF) in the UK by the NDA Radioactive Waste Management Directorate (RWMD): the Potential for Interaction between the Co-located ILW/LLW and HLW/SF Components of a GDF.* Proceedings of the 12th International Conference on Environmental Remediation and Radioactive Waste Management, ICEM2009 October 11−15, 2009, Liverpool, UK.

Watson, S., Hicks, T., Towler, G., Reedha, D., Paulley, A., Baldwin, T. and Bond, A. (2009) *Post-closure Performance Assessment: Consideration of a Co-located Geological Disposal Facility in the Safety Case*. Quintessa Report QRS-1378P-1.