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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

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ABSTRACT

In June 2008 the UK government published a 'White Paper' as part of the "Managing Radioactive Waste Safety" (MRWS) programme to provide a framework for managing higher activity radioactive wastes in the long-term through geological disposal. The White Paper identifies that there are benefits to disposing all of the UK's higher activity wastes (Low and Intermediate Level Waste (LLW and ILW), High Level Waste (HLW), Spent Fuel (SF), Uranium (U) and Plutonium (Pu)) at the same site, and this is currently the preferred option. It also notes that research will be required to support the detailed design and safety assessment in relation to any potentially detrimental interactions between the different modules.

Different disposal system designs and associated Engineered Barrier Systems (EBS) will be required for these different waste types, i.e. ILW/LLW and HLW/SF. If declared as waste U would be disposed as ILW and Pu as HLW/SF. The Geological Disposal Facility (GDF) would therefore comprise two co-located modules (respectively for ILW/LLW and HLW/SF). This paper presents an overview of a study undertaken to assess the implications of co-location by identifying the key Thermo-Hydro-Mechanical-Chemical (THMC) interactions that might occur during both the operational and post-closure phases, and their consequences for GDF design, performance and safety.

The MRWS programme is currently seeking expressions of interest from communities to host a GDF. Therefore, the study was required to consider a wide range of potential GDF host rocks and consistent, conceptual disposal system designs. Two example disposal concepts (i.e. combinations of host rock, GDF design including wasteform and layout, etc.) were carried forward for detailed assessment and a third for qualitative analysis.

Dimensional and 1D analyses were used to identify the key interactions, and 3D models were used to investigate selected interactions in more detail. The results of this study show that it is possible for ILW/LLW and HLW/SF modules to be co-located without compromising key safety functions of different barrier components, and this reflects international precedents, e.g. the Andra and Nagra repository designs. There are two key technical issues that need to be managed in designing the geometry of the co-located GDF: (i) the heat flux from the HLW/SF module interacting with the ILW/LLW module, and (ii) the potential for development of an alkaline plume from the ILW/LLW module interacting with the HLW/SF module; particularly within fractured host rocks.

INTRODUCTION

In June 2008 the Government published a White Paper as part of the Managing Radioactive Waste Safely (MRWS) programme [1]. The White Paper sets out the UK Government's framework for managing higher activity radioactive waste in the long-term through geological disposal coupled with safe and secure interim storage and ongoing research and development to support its optimised implementation. The currently preferred option is for all of the wastes to be disposed in a single 'co-located' Geological Disposal Facility (GDF) in England or Wales.

The Radioactive Waste Management Directorate of the Nuclear Decommissioning Authority (NDA RWMD) is charged with implementing this policy and is developing a Disposal System Safety Case (DSSC) to explain and assess the safety and environmental implications of all aspects of a deep geological disposal system. At the current time (stage 1 of the MRWS programme), expressions of interest in hosting a GDF have been invited from potential host communities, but sites have not yet been selected for desk-based studies (stage 4 of MRWS), and therefore no site-specific investigation, characterisation and assessment is currently ongoing.

NDA RWMD therefore plans to produce a generic DSSC to be published in 2010, the Environmental Safety Case (ESC) component of which will include an updated generic (i.e. not site-specific) post-closure performance assessment (PCPA). The generic DSSC will consider a GDF in which all of the wastes considered in the White Paper are disposed of (i.e. ILW, LLW, High Level Waste (HLW), Spent Fuel (SF), Uranium (U) and Plutonium (Pu); but note that SF, U and Pu are not currently declared as waste). Different disposal concepts will be implemented for the different waste materials (broadly grouped as ILW/LLW and HLW/SF) resulting in two (or more) disposal modules that implement these different concepts and are 'co-located' (i.e. they share surface facilities and access tunnels).

This paper presents an overview of a study undertaken by Watson et al. [2] to support the generic DSSC by examining the Features, Events, and Processes (FEPs) relating to the potential interactions between the various disposal modules of a co-located GDF. It is an initial study that aims to identify the key interactions that might occur for different disposal systems. It is intended to provide initial guidance on which FEPs are likely to be unimportant and which merit further, more detailed, consideration.

Scope

The evolution of a single disposal module in isolation is complex and involves a range of coupled and time-dependent processes. This study considers those interactions that might arise due to co-location, and processes that would occur anyway but which are in some way changed in importance because the ILW/LLW and HLW/SF disposal modules have been co-located. It does not consider the expected evolution of the individual disposal modules in isolation.

A large number of Thermo-Hydro[1]-Mechanical-Chemical-Gas (THMCG) interactions can be envisaged between the various disposal modules that make up a co-located GDF. The magnitude of these interactions will depend on the host rock, the engineering design (wasteform, geometry, materials and design specification) and the operational history, and will be complicated by the co-dependency of coupled processes, e.g. the impact of heat on groundwater flow and vice-versa. The interactions of interest in this study will therefore change with time both during the operational phase, in response to how the GDF is developed, maintained, backfilled and closed, and post-closure as the GDF re-saturates, biogeochemical reactions occur, and engineered materials evolve. In addition to the system-internal FEPs that drive THMCG interactions, there are system-External FEPs (EFEPs) that also affect the system evolution, and potential interactions on very long timescales (for example, the impacts of possible glacial loading and unloading on the background groundwater pressure field).

It is beyond the scope of this initial study to consider all conceivable combinations of geological environment, host rock, natural THMCG conditions, GDF design (including wasteform, geometry, etc), operational strategy, post-closure evolution and impact of EFEPs. Further, many of the interactions are likely to be site and layout specific so it would not be appropriate to carry out a detailed study at a time when neither the disposal site nor the engineered barrier systems (EBSs) has been selected. Instead, this study takes a high level view and aims to identify the types of interactions (thermal, chemical etc) that might be significant for different types of disposal system. The list of potentially important FEPs depends on the disposal system being considered (geological environment plus EBS) so it is intended that the results of this project will provide input to the development of future work programmes once sites have been selected for further study.

EXISTING WORK

The potential interactions between the co-located modules of a GDF have previously been considered in a number of international programmes. This study aims to build on this existing work by systematically considering all relevant interactions, albeit at a high level, and incorporating recent advances in phenomenological understanding.

The most relevant existing study for UK wastes is that of King and Poole [3], which considered potential interactions between a Nirex Phased Geological Repository Concept (PGRC) ILW/LLW disposal module and an HLW/SF disposal module with a bentonite/carbon steel EBS. They identified the following interactions as potentially significant:

- Degradation of bentonite, most likely a buffer, in the HLW/SF component by an alkaline plume (including cement colloids) emanating from the ILW/LLW component. (Cement will definitely be present in the ILW/LLW component because a significant quantity of ILW has already been immobilised in cementitious grouts).
- Preferential groundwater flow from the ILW/LLW component to the HLW/SF component due to different resaturation rates (i.e. slower resaturation for the HLW/SF component).
- Interaction of HLW/SF with an acidic plume from insufficiently buffered ILW/LLW and organic breakdown products / NAPLs derived from the ILW/LLW component.
- In low-permeability geospheres, advective flow patterns in excavation damaged zones (EDZs) potentially linking the two components, driven by a natural disequilibrium head profile, by the disturbance associated with excavations and operations or as a result of the generation of gas in one or more disposal modules.

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[1] Often referred to as THMC. In this context, Hydro is taken to refer to multi-phase flow including water and Non-Aqueous Phase Liquids (NAPLs) such as 'oils', but gas (G) is considered separately.

- Development of ‘open’ connections between the different components caused by reactions between materials sealing linking tunnels and:
    - the host rock ; and / or
    - materials released from the contained wastes; and / or
    - degradation products of waste containers.
- Impacts of thermally-driven groundwater flow due to the HLW/SF component on the ILW/LLW component, including coupled THMC issues such as thermal stress / strain effects, barrier and wasteform degradation rates, speciation, and solubility.
- Delayed resaturation of the HLW/SF component due to pressurisation by gas migrating from the ILW/LLW component along a poorly sealed connecting tunnel and its EDZ, thereby reducing barrier performance.
- Mechanical effects such as the linking of stacked components due to roof collapse and upwards migration of the collapse zone EDZ.

It is noted that the majority of the potential interactions identified by King and Poole [3] are deleterious impacts on the HLW/SF disposal module as a result of the presence of the ILW/LLW disposal module. This largely reflects the highly alkaline nature of the PGRC porewater, which is conditioned by cementitious backfill to form a chemical barrier to the release of radionuclides.

FEATURES EVENTS AND PROCESSES

Although the various processes, and hence FEPs, that will occur in the GDF are coupled, sometimes strongly, it is generally possible to categorise them according to the dominant type of process. Table 1 summarises the potential interaction FEPs that have been identified, according the headings of thermal (T), hydrogeological (H), mechanical (M), chemical (C) and gas (G). Additional categories are also possible, for example criticality and biological are sometimes included, but in this case these FEPs are considered under one of the other groups.

System External FEPs (EFEPs) may also affect the disposal system during the post-closure period. In the context of the current study the only EFEPs of interest are those that in some way enhance the co-location FEPs already identified in Table 1. These are EFEPs that either significantly change the groundwater flow field or those that result in the creation of new pathways that link the different disposal modules. Examples include glaciation, seismic activity and connecting the co-located modules in a stacked geometry by an intrusive site investigation borehole.

SELECTION OF FEPS FOR FURTHER ANALYSIS

Watson et al. [2] analysed the interaction FEPs summarised in Table 1. They identified that many of the FEPs are coupled, some strongly and also concluded that the importance of particular FEPs will vary with disposal system (i.e. the combination of host rock, EBS designs and operational history).

A number of FEPs were selected to be carried forward within this scoping study. The selected FEPs are those judged to potentially be the most important, taking into consideration that the next stage of the MRWS programme will involve site selection, selection of EBS types and outline design. This study therefore focused on those FEPs that might require major changes in design concept or layout to mitigate their impact should they prove to be significant.

Each of the FEP groups that have been identified can be thought of in terms of a signal (of heat, water, chemistry etc) that must travel from the source (one disposal module) to the location of the interaction (most likely another disposal module) before the co-location interaction can occur. Signals travel fastest when the driving gradients are largest and during the period before the post-closure barriers have attained their long-term properties. Such considerations point to the operational and early post-closure periods as being a crucial timeframe for co-location interactions since:

- The groundwater flow field may be significantly different from the long-term flow field for which the layout has been designed. There is the potential for differential rates of resaturation between disposal modules to cause local reversals of the hydraulic gradients.
- Thermal output is largest at early times. Cements have not yet begun to evolve so pH will be at its highest.
- Some of the engineered barriers may still be evolving to their long term states. For example, bentonite buffers will still be resaturating and long term pH and redox conditions will not be fully established. If the early evolution of these barriers is affected, their long-term efficacy could be detrimentally affected.
- Self-healing of EDZs is unlikely to be complete at this time (for relevant geological environments).
- This is a period during which potentially significant gas generation is expected in the ILW/LLW disposal module (for the UK waste inventory).

The FEPs that have been selected for further study therefore focus on this early timeframe. The analysis has focused on answering three questions about the THMCG signals: can the signal reach the other disposal module?; if it does, is this likely to happen at a time of interest (i.e. before the inventory has decayed or been flushed out)?; and does the signal have sufficient magnitude to lead to a significant interaction? (e.g. is the temperature perturbation significant compared with the uncertainty in thermal evolution of the module when considered in isolation?). The importance of this phase has been recognised in other programmes. For example, Andra [4] give particular consideration to thermal interactions, and hence the operational storage, cooling and disposal sequence for heat generating SF wastes.

DISPOSAL SYSTEMS

At the current stage in the UK development of a GDF, a site has not been selected and the disposal concepts and related EBS types for the ILW/LLW and HLW/SF disposal modules are not fixed. However, in order to carry out any meaningful analysis of the potential significance of the co-location interactions that have been identified it is necessary to make some assumptions about the disposal system.

Process	Cause	T	H	M	C	G
T	Radioactive decay, exothermic reactions, criticality.	Conductive heat transfer.	Buoyancy-driven flow.	Thermally-induced stresses/strains and creep alter flow and transport pathways, especially in the EDZ, and EBS integrity.	Temperature-dependent changes in aqueous speciation, solubility, sorption, diffusion, EBS material corrosion and degradation rates, microbial populations, cement curing, and material properties.	Temperature dependence of rate and mechanism of gas-generating material degradation and corrosion processes. Solubility of gas and gas-liquid partitioning.
H	Excavation and operational conditions, resaturation, gas pressurisation, and flow focusing or divergence in the long term.	Advective heat transfer.	Changes in groundwater flow magnitude and direction and resaturation rates.	Changes in effective stress and saturation alter permeability. Changes in saturation alter EBS behaviour (e.g. swelling pressure).	Changes in flow rates affect advective mass transfer, EBS degradation and erosion and wasteform leaching.	Changes in flow rates affect supply of water for corrosion and other gas-generating reactions.
M	Excavation, rock fall, creep, criticality impacts, radiation damage.	No FEPs of significance identified.	Changes in groundwater flow pathways alter flow magnitude and direction.	Stress and strain changes alter flow and transport pathways (e.g. EDZ, fracture reactivation, permeability changes) and damage EBS materials.	No FEPs of significance identified.	Changes in stress impact on gas permeabilities.
C	EBS evolution and degradation results in release and migration of solutes, colloids, complexes.	No FEPs of significance identified.	Changes in groundwater flow pathways alter flow magnitude and direction. Migration of solutes alters fluid properties (e.g. density).	Migration of solutes (e.g. alkaline plume) alters EBS mechanical behaviour (e.g. swelling pressure).	Precipitation and dissolution reactions, colloid filtration, interactions with organics alter permeability and porosity. Solute, complexant, and colloid migration changes groundwater composition, pH, Eh, which affects corrosion and degradation of EBS materials, microbial populations, radionuclide speciation and solubility.	Supplies reactants or catalysts for gas-generating or consuming reactions.
G	Corrosion, microbial degradation of organics, radiolysis	Desaturation changes thermal conductivity.	Gas transfer and gas-driven groundwater flow though geosphere, accessways, EDZ, EBS materials.	Induced stress/strain, fractures, displacements alter flow and transport paths and permeability.	Mass transfer in gas phase; gas (methane) effects on microbial populations in EBS.	Gas generation causes desaturation which affects supply of water for gas generation reactions.

Table 1: Potential THMCG interactions between disposal modules of a co-located GDF. The processes that result in the THMCG FEPs emanating from, or relating to, a particular disposal region are indicated in the 'cause' column and the potential impacts of these FEPs on THMCG conditions in the surrounding geosphere and neighbouring disposal regions are indicated in columns headed T, H, M, C and G.

Three example disposal systems were selected as the main focus of this study: a strong (crystalline) host rock, a lower strength sedimentary host rock (indurated mudrock) and an evaporite host rock. The examples are expected to bound the range of behaviour that might be expected for a GDF developed in England or Wales and are consistent with the examples that will be used to illustrate the generic DSSC. The properties of these environments were based on the UK relevant alternative geological environments described by Watson et al. [5] and Towler et al. [6].

It is also necessary to make some assumptions about the timescales on which the GDF will be operated. Table 2 details the timescales for the strong rock example. These timescales differ between the different disposal system designs considered, in particular in relation to the backfilling strategy and consequently tunnel dewatering. For example, for the lower strength rock examples it was assumed that backfill will be emplaced concurrent with disposals and disposal tunnels would be sealed immediately thereafter.

YEAR	EVENT
2028	Start of construction, initial shaft sinking etc.
2028	Start constructing access drifts.
2032	Start construction of first ILW vault.
2040	First emplacement of ILW. Vaults will be constructed on a just-in-time basis. Each vault expected to be open for 1-2 years for fit-out before waste emplacement starts.
2072	Start construction of first HLW/SF vault/panel.
2075	First emplacement of HLW/SF. Vaults/panels constructed on a just in time basis. Each vault/panel expected to be open for 1-2 years for fit-out before waste emplacement starts. Tunnels assumed to be backfilled and sealed very soon after waste emplacement.
2125	Final ILW emplacement.
2128	Final HLW/SF emplacement.
2128-2138	Backfilling of ILW vaults and sealing of other underground openings.
2138	Final closure of facility.

Table 2: Timescales for Development of the GDF

NDA RWMD is currently developing Outline Design Reports for the GDF for each of the example systems but these reports were not available at the time of this study. An illustrative GDF layout was used for the purposes of this study.

The strong rock example assumes that the Nirex PGRC EBS [7] will be used for the ILW/LLW disposal module and the KBS-3V disposal module will be used for the HLW/SF disposal module [8].

The EBS for the weaker sedimentary host rock layout was based on a hybrid of the Andra / Nagra designs. The GDF layout for lower strength sedimentary rock is illustrated in Figure 1. The illustrative layout shows the ILW/LLW and HLW/SF disposal modules arranged regularly and adjacent to one another, at the same depth. In reality the two disposal modules could be at different depths; stacked (possibly in different host rocks); and irregular in layout, for example to provide a respect distance around fractures, etc. The ILW/LLW disposal module is subdivided into an area for the disposal of Shielded ILW and LLW (SILW in Figure 1) and Unshielded ILW (UILW in Figure 1).

A respect distance of 500 m has been assumed between the disposal modules, consistent with the assumptions made in earlier work [3]. Access tunnels are assumed to be backfilled with crushed rock and low permeability seals are emplaced as required to isolate the disposal modules from each other and to seal the emplacement drift.

Analysis of interactions in the evaporite host rock is treated qualitatively and semi-quantitatively. Therefore it is not necessary to develop an illustrative GDF layout for the evaporite.

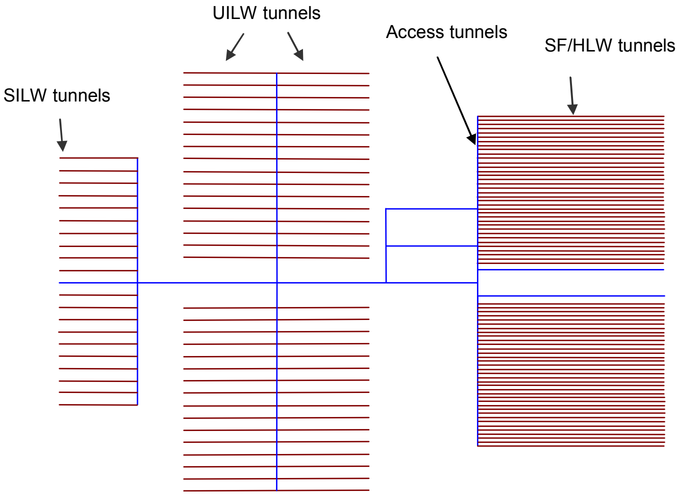

Figure 1: Schematic showing GDF layout for the weaker sedimentary rock example. ILW/LLW disposal tunnels are 300 m long and HLW/SF disposal tunnels are 780 m long and the separation between the two disposal modules is 500 m.

THERMAL INTERACTIONS

The potential extent of thermal interactions between disposal modules was evaluated using non-dimensional and one-dimensional analyses, as well as the results of three-dimensional modelling. The calculations aimed to answer the questions:

- Can a thermal signal travel from one disposal module to the other?
- If it can, what is the timescale on which this happens?
- If the signal is able to travel from one disposal module to the other, how large might the temperature increase be?

Most disposal system technical specifications define limits on the temperature within the disposal area. In the absence of an EBS design, it is not possible to know what the actual limits would be for the various disposal modules of a UK GDF.

Indeed, if thermal constraints are known early enough in the design process it may be possible to mitigate the impact of higher than ideal temperatures through design measures, and choice of materials. However, the upper temperature limit is unlikely to be significantly above 100°C within the HLW/SF disposal tunnels.

Heat transfer in a water saturated rock mass may occur by advection, diffusion or a combination of the two. If key parameters such as thermal conductivity and groundwater flow velocity, and the length scale of interest, are known, it is simple to calculate which process (advection or diffusion) dominates heat transport in a particular situation. The analyses undertaken by Watson et al. [2] indicate that thermal conduction is likely to dominate heat transport in all of the host rocks of interest.

It is possible to obtain an analytical solution to describe the spatial and temporal variation of temperature, due to conduction, for certain simple sets of boundary conditions. Using typical parameter values for the strong and lower strength sedimentary host rocks and a constant heat source suggests that it would take more than 1000 years for heat to be conducted from one disposal module to the other for a respect distance of 500 m. It is expected that on this timescale the thermal output from the wastes will have reduced significantly and the temperatures in each disposal module will have fallen substantially below their peak values.

Figure 2 shows the evolution of temperature at distances of 100 m, 300 m and 500 m from a fixed heat source for typical strong host rocks. The figures show the dimensionless temperature $(T - T_\infty)/(T_0 - T_\infty)$, where T_0 is the fixed temperature at heat source and T_∞ is the temperature at infinity (i.e. the natural background temperature). This parameter varies between a fixed value of 1 at the heat source and 0 in the far field. It must be noted that this simple analysis over-predicts the increase in temperature compared with the expected situation in the GDF because it assumes a constant heat source whereas in the GDF the rate of heat generation decreases with time.

Within the UK inventory, the Pressurised Water Reactor (PWR) spent fuel has the greatest thermal output. T_0 might be expected to be of the order of 25°C[2] for an area of the HLW/SF disposal module where the waste is dominated by PWR fuel. Thus for a respect distance of 500 m in strong rock a temperature rise of the order of one to two degrees would be expected after 1000 years. For the normal evolution of the ILW/LLW disposal module, this is within the uncertainty that would be expected when predicting the expected evolution of the temperature for a disposal module that is not co-located. For a respect distance of 100 m the temperature rise might be of the order of 17 or 18°C, which is outside the range of uncertainty expected for the predicted temperature of an ILW/LLW disposal module that is not co-located.

The results are very similar for lower strength sedimentary rock. Evaporite has a thermal conductivity that is a factor of two to three greater than that of the other two host rocks. Therefore the thermal interaction will be greater in evaporite. For a respect distance of 500 m and T_0 of 25 °C, a temperature rise of about 5°C would be expected after 1000 years.

For smaller respect distances, for example 100 m, it is valuable to carry out a more sophisticated analysis that considers a more realistic geometry for waste disposal and takes into account the decrease with time in the heat generation.

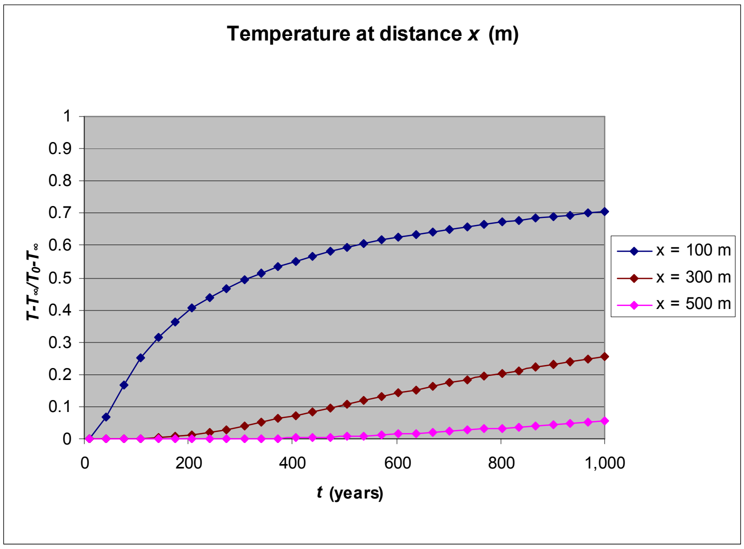

Figure 2: Dimensionless temperature increases in strong rock at different distances from a heat source.

Watson et al. [2] describe some modelling that was undertaken for a disposal system that is similar to the examples considered in this paper using the HOTWASTE code [9]. The modelled system considered a strong fractured host rock and considered a respect distance of 100 m. Two geometries were considered, a GDF developed at a single horizontal level and a stacked arrangement in which the ILW/LLW disposal module directly overlies the HLW/SF disposal module. The wastes were arranged so as to minimise the interactions between the disposal modules with the wastes that generate the most heat (PWR SF) being placed as far from the ILW disposal module as the design permitted and HLW, which generates the less heat than SF, immediately adjacent to the ILW/LLW disposal module. In the stacked layout the ILW/LLW disposal vaults were located above the HLW/SF disposal tunnels as far as was possible.

The results indicated that for the case in which the GDF is developed on a single level there is little interaction for the layout considered in the calculations. Although detectable, the increase in temperature in the ILW/LLW disposal module immediately adjacent to the HLW/SF disposal module is just a few degrees Celsius.

In the case in which the ILW/LLW disposal module is located 100 m vertically above the HLW/SF disposal module there is a significant thermal interaction. At times of a few hundred to a thousand years after closure, temperatures in the ILW/LLW disposal vaults were up to 10°C higher than would

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[2] This value is an average for the disposal module. The temperature at the waste package surface might be significantly higher.

be expected were the HLW/SF disposal module not present. Thus, for a vertically stacked layout, where the maximum possible respect distance is likely to be of the order of 100 to 200 m, it is likely that the presence of the HLW/SF disposal module would result in temperatures in the ILW/LLW disposal module that are outside the range that would be expected for a disposal module that is not co-located.

In the case of the stacked arrangement in which the ILW/LLW disposal module overlies the HLW/SF disposal module, the heat generated by the wastes would enhance the natural geothermal gradient. As a result there is the potential for buoyancy driven flow to occur around the HLW/SF disposal module and in the volume between the two disposal modules. Scoping calculations suggest that for a vertical head gradient of the order of 10^{-2} or less, and if the host rock is sufficiently permeable (conditions potentially satisfied in the strong rock example), buoyancy driven flow has the potential to increase heat transport between disposal modules during the first thousand years or so after closure.

It is concluded that the thermal signal is able to travel from one disposal module to the other on timescales that are relevant to the post-closure safety case and that for some disposal systems the magnitude of the temperature increase might result in a significant interaction. Whether or not this perturbation is significant in terms of the evolution of the disposal module depends on whether it results in temperatures that are outside the design specification for the disposal module and on the underlying reasons for those temperature constraints.

HYDROGEOLOGICAL (AND GAS) INTERACTIONS

The groundwater flow field around a co-located disposal module will be different to that which would be expected for the same disposal module were it not co-located. It is expected to be possible to design a GDF layout that will minimise the groundwater flow mediated interactions on long time-scales, once the perturbations associated with construction and operations have dissipated. The layout would also be designed to be robust against expected long-term changes to the groundwater flow field resulting from the evolution of the geosphere.

During the period immediately following closure when the system is resaturating the flow field will be very different to that expected in the long term. The work described in this section explores the potential for significant H and G group interactions to occur during this early phase for designs/layouts of the type that might be appropriate to minimise interactions during the main part of the post-closure period.

3D groundwater flow models were developed for the strong rock and lower strength sedimentary rock example systems using the FEFLOW code [10]. The models were used to undertake transient analyses of the development of the groundwater flow field in response to step-wise construction of the GDF, operational dewatering and subsequent resaturation, accounting for changes in physical properties with time.

The calculations aim to answer the questions:

- Can groundwater flow from one disposal module to the other, in particular from the ILW/LLW disposal module to the HLW/SF disposal module?
- If it can, for how long does this flow field persist?
- What is the flow velocity and is it possible to transport a non-sorbing tracer by advection from one disposal module to the other?

The example systems were described as grids of 75 m by 75 m blocks, each subdivided into several finite elements, with upscaled hydraulic parameters calculated for each block. Figure 3 shows the layout for the strong host rock. In the FEFLOW models only a sub-area of the GDF in which interactions are most likely to occur was modelled (the portion shown in the box in Figure 3). The natural hydraulic gradient was assumed to be from the HLW/SF component to the ILW/LLW component, thereby maximising the potential for interaction to occur. In practice, the GDF layout would not be designed like this.

Figure 4 shows the evolution of hydraulic heads within different areas of the GDF and ‘up-gradient’ and ‘down-gradient’ of the GDF, i.e. with reference to the natural groundwater flow field, for strong host rock. The impacts of operational dewatering can clearly be seen, as can the sequence in which the different components are constructed based on the time of dewatering. The ILW/LLW tunnels are assumed to be held open and only backfilled on closure of the GDF. The HLW/SF tunnels are backfilled as soon as they have been filled.

The relatively short period of operational dewatering for the HLW/SF tunnels compared with the ILW/LLW tunnels, and the smaller pore volume to be resaturated in the HLW/SF tunnels compared with the ILW/LLW tunnels, result in the hydraulic gradient always being 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. In this example the ILW/LLW waste packages are emplaced in pre-backfilled disposal boxes and the tunnels are closed soon after emplacement. However, the hydraulic gradient is still 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.

Migration of gas from one module to another is not expected to result in any deleterious reactions. It is the impact of gas on pressure and groundwater flows between the modules that is considered to be most significant. Significant gas pressurisation is not expected to occur in the strong host rock [11]. However, gas cannot escape easily in the lower strength sedimentary rock and significant pressurisation may occur. The potential exists for gas pressure to drive water out of the ILW/LLW disposal module.

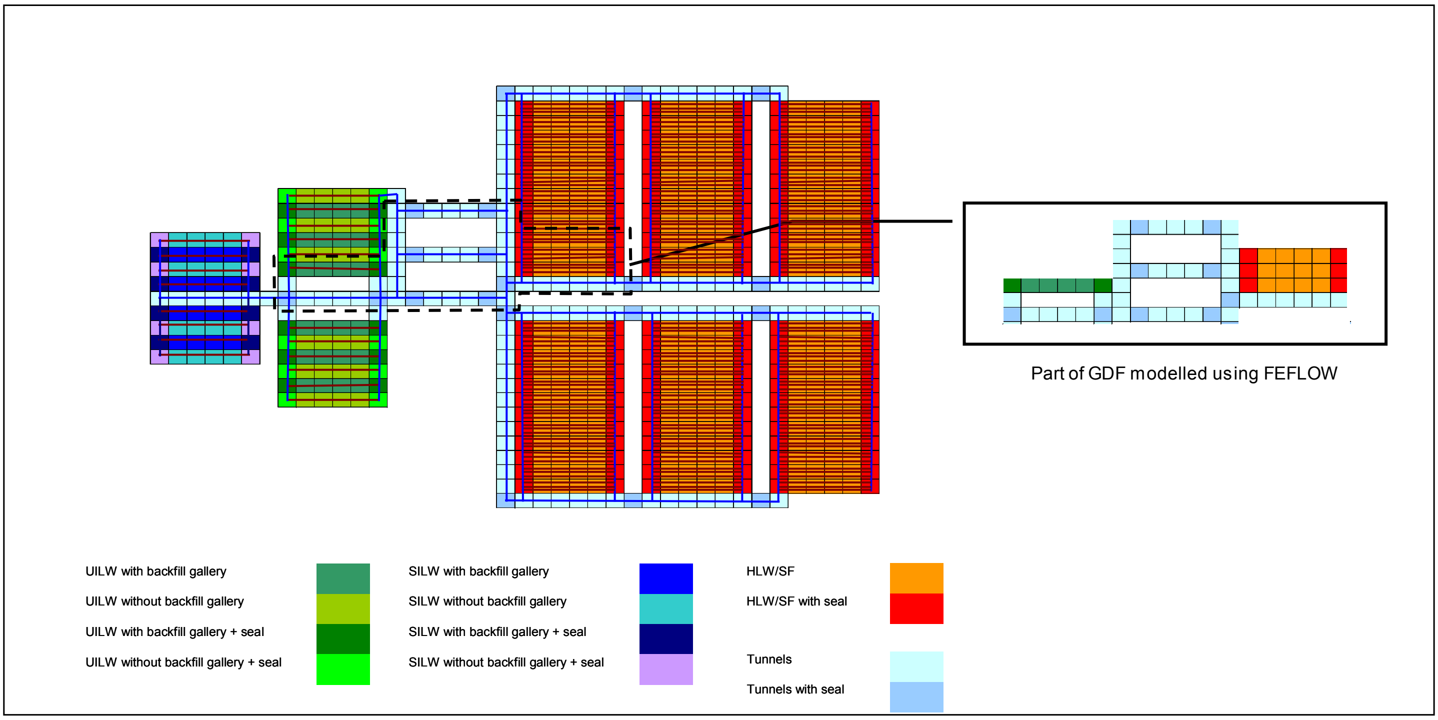

Figure 3: Horizontal layout of the GDF for strong fractured rock, with the segment of the system represented in the FEFLOW calculations indicated separately. Effective properties were calculated for each 75 m x 75 m block, which includes host rock, engineered features and an EDZ.

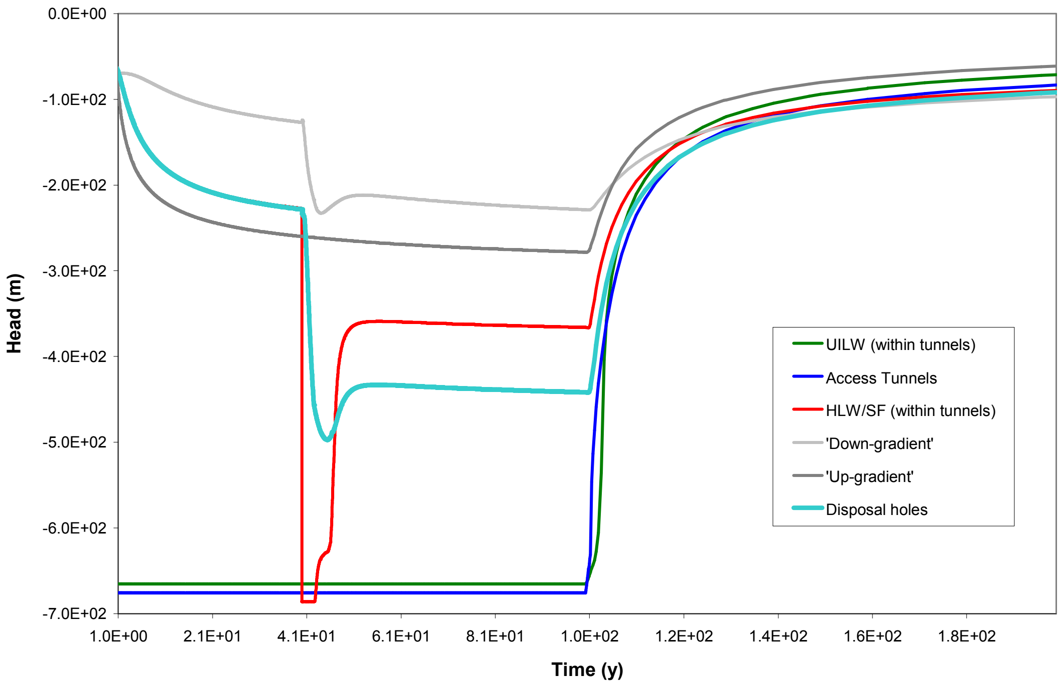

Figure 4: Evolution of hydraulic head at different locations for strong fractured rock example.

The FEFLOW code is unable to model the impacts of gas generation on repository pressures, resaturation and the development / evolution of hydraulic gradients between the two co-located modules. Therefore, a fully coupled 3D gas generation and multi-phase flow model of the weaker sedimentary rock example was developed using the QPAC code [12]. This is described briefly below, and in more detail in the supporting ICEM 09 paper by Bond et al. [13].

The whole of the GDF was represented in the model, with a simplified operational sequence, comprising an average dewatering period of 50 years for each module, and simultaneous operation (dewatering) of the two modules.

A gas generation model was developed that considers 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 calculated pressure curves are shown in Figure 5. There is 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 is from the HLW/SF module towards the ILW/LLW module. Including gas generation and migration in the analyses does not appear alter the overall behaviour seen in the FEFLOW models. Sensitivity analyses examining different host rock permeabilities and capillary curves give similar results.

No calculations were carried out for the evaporite host rock example. However, the extremely low hydraulic conductivity of the evaporite host rock is expected to result in less desaturation of the host rock than is observed for either of the other examples and slower groundwater flow rates. The most likely flow mechanism in the evaporite host rock is the migration of brine pockets under the influence of a thermal gradient.

In summary, the modelling results suggest that provided that the seals remain intact (an assumption made for all of the examples) it is unlikely that groundwater will flow from the HLW/SF disposal module to the ILW/LLW disposal module during the resaturation period. The smaller pore volume to be resaturated in the HLW/SF disposal module means that this module always resaturates first. Even if the seals fail the pressure gradients are such as to prevent water flowing from the ILW/LLW disposal module into the HLW/SF disposal module. However, the resaturation behaviour of the central access tunnels and their seals is very important in this case. Including the effects of pressurisation by GDF-generated gas modified the results but did not alter this overall conclusion. Water may flow at a slow rate towards the ILW/LLW disposal module so it may be necessary to build confidence that porewater that has interacted with EBS materials in the HLW/SF disposal module cannot damage the EBS in the ILW/LLW disposal module.

MECHANICAL INTERACTIONS

It has been assumed for the purposes of this study that the design of the disposal modules, which takes into account interactions between the individual tunnels/vaults within the module, means that there will be no significant direct mechanical interactions between disposal modules.

Two important sources of M Group FEPs are the stresses associated with temperature changes and FEPs associated with the EDZ and its evolution. Both of these are likely to be particularly important during the resaturation period.

The M Group FEPs that are described below are therefore very strongly coupled to other FEP groups, notably the T group and the H and G groups. The potential significance of thermo-mechanical interactions depends on whether the thermal signal is able to travel from one disposal module to the other, and the potential significance of EDZ evolution is intimately linked to the pressure gradients (i.e. are the additional flow pathways significant?)

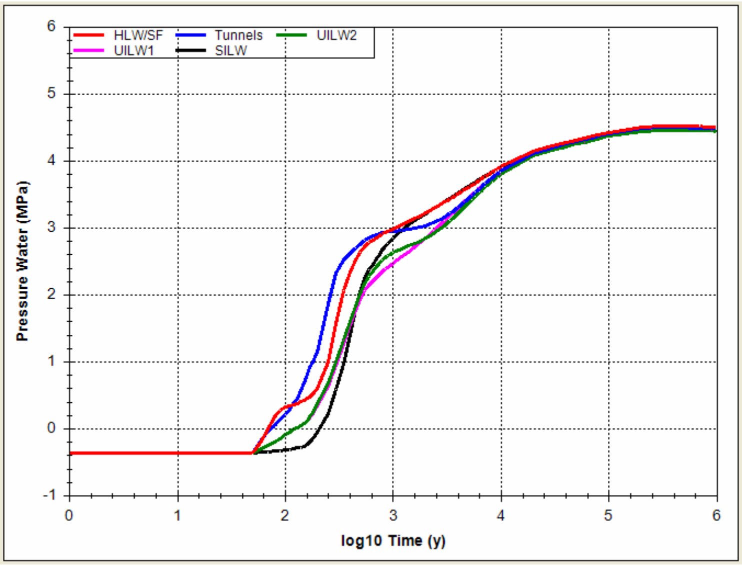

Figure 5: Evolution of Water Pressure in the GDF (UILW1 refers to the UILW panel closest to the SILW and UILW2 refers to the UILW panel closest to the HLW/SF in Figure 1).

Compressive thermal stresses and strains will be induced within a heated rock, resulting in changes in fracture properties and effective rock permeability. Thermal expansion of the heated rock volumes will be resisted by surrounding cooler rock. This will induce tensile stresses and strains in the cooler rock normal to the direction of expansion of the heated region, potentially leading to fracture opening or shear slip on fractures around the heated region. Thus, temperature increases in the vicinity of the HLW/SF disposal module could induce mechanical changes in the engineered barriers of the ILW/LLW disposal module if a sufficiently large thermal signal is able to travel from one disposal module to the other.

Watson et al. [2] describe calculations that were undertaken using the HOTWASTE code to estimate the thermally induced stresses that might result in a disposal system that is similar to the examples considered in this paper. Again, two geometries were studied: a GDF developed at a single level and a stacked arrangement in which the ILW/LLW disposal module was directly above the HLW/SF disposal module. Only the latter geometry resulted in a potentially significant thermal interaction. Similarly, only this geometry resulted in a potentially significant thermo-mechanical interaction.

In the stacked layout with a 100 m respect distance, temperatures in the ILW/LLW disposal module were of the order of 10°C higher than would be expected were the HLW/SF disposal module not present. The resulting vertical and horizontal compressive thermal stresses were up to 6 MPa. These translate into displacements of the order of one to two centimetres, which could be significant for EBS integrity, although it is unlikely that all of this displacement would be taken up on a single discontinuity.

The relatively high thermal conductivity of evaporates means the thermo-mechanical interactions are more likely to occur in these rocks than in the other examples because thermal interactions are more likely to occur. However, the response of the evaporate 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. However, elevated creep rates might require additional measures to be taken during the operational period.

Watson et al. [2] reviewed the latest information (e.g. [14,15]) regarding the development, extent, connectivity, properties, and self-healing of the EDZ for the three host rocks under consideration. The review indicated that the properties of the EDZ are often site specific. For example, self-healing may occur in mudstones and evaporates but not strong crystalline rocks; and continuous and discontinuous EDZs have been reported in strong crystalline host rock.

The significance of the EDZ in terms of providing a pathway for the transport of water, solutes or gas depends on the hydraulic conductivity of the EDZ, the degree to which it is interrupted by seals and the pressure gradients within the GDF. The results previously suggest that even if the EDZ does provide such a pathway, the prevailing pressure gradients will not result in flows that lead to detrimental interactions.

The extent to which the EDZ develops depends on factors such as the length of time for which the excavation is held open and the degree of engineering support. Thus if co-location results in the excavations being held open for longer it may result in increased development of the EDZ.

Self healing of the EDZ in mudstones is linked to water saturation in the EDZ, and hence how the gas pressure affects resaturation. The properties of the EDZ are therefore coupled to the resaturation behaviour.

It is concluded that the M group FEPs are strongly coupled to the other groups. It seems unlikely that a direct M group interaction would occur between disposal modules but the M group FEPs may be significant when combined with other FEPs. It is likely that thermo-mechanical interactions will be insignificant for any GDF design that is satisfactory from the point of view of thermal interactions.

CHEMICAL INTERACTIONS

C group interactions differ from the T, H, M and G group interactions because they cannot occur in isolation. In order for an interaction to occur, either the solutes must be transported from one disposal module to the other (H or G groups) or the physical conditions must be changed so that the chemical change becomes favoured (e.g. increased temperature increase reaction rates or changes in stress results in dissolution/precipitation). Thus if the analysis suggests that there are no significant THM or G groups interactions, there will not be any C group interactions.

Watson et al. [2] present some simple analytical calculations of the rate at which solutes might be transported in the strong rock and lower strength sedimentary rock examples. Based on reasonable assumptions regarding the hydraulic properties and background hydraulic gradients (e.g. [5]) 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 regulatory interest in lower strength sedimentary rock (e.g. for a 100 m separation distance, breakthrough of the chemical signal does not occur until approaching 1E6 y). Similar conclusions can be drawn for evaporite host rocks.

Interaction is possible on timescales of interest in strong rock. However, this assumes that the co-located modules have not been orientated relative to the background pressure field such as to prevent interaction, or it is not possible to fully achieve this, e.g. due to a complex spatial distribution of pressures in a fracture network.

The chemical interaction that is of most concern and has been the most extensively studied in the literature is the development of an alkaline disturbed zone (ADZ) around a cementitious disposal module. The concern is that the interaction of an alkaline plume with the EBS of the HLW/SF module would have a detrimental impact on system performance, e.g. embrittlement of bentonite EBS, and increased rates of HLW glass dissolution.

Nirex [16] concluded that overall the reactions between high pH waters and silicate rocks will lead to pore blocking; pore opening can occur, but often such opening will not 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. It can be concluded from this that an alkaline plume from the ILW/LLW module may be attenuated before it reaches the HLW/SF module. Therefore, although the chemical signal is potentially able to travel between the disposal modules on a timescale that is of interest the magnitude of the signal may well be too small to result in a significant interaction.

It is also worth noting that the HLW/SF disposal module will contain structural concrete, and the Belgian supercontainer design even uses a cement buffer. It will be necessary for the HLW/SF disposal module to be designed to be tolerant of the pore fluids generated from the interaction of water with the EBS materials used in the module. Thus an alkaline plume might only be expected to result in a detrimental interaction if the pH was higher than that resulting from the cements already included in the HLW/SF module.

It is concluded that C group interactions are strongly coupled to the other FEP groups, generally either requiring a fluid to transport the solutes involved (H or G group coupling) or a change in conditions (T or M group coupling) to result in an interaction. Diffusion, at a rate influenced by sorption (another C group process), is the only transport process that can transport solutes from one disposal module to the other without a T, H, M or G interaction also occurring. Analytical solutions suggest that the timescale on which the diffusion pathway operates is too long to result in interactions on timescales of realistic interest for Performance Assessment.

The modelling of hydraulic interaction in response to operational dewatering described previously suggests that the area where mixing of fluids from the different disposal modules is most likely to occur is the central network of tunnels that connect the disposal modules. The potential impact of chemical interactions on the seals in this area needs to be considered carefully.

It may be necessary to consider the impact of fluids derived from the HLW/SF disposal module on the ILW/LLW disposal module if an associated detrimental interaction is identified. The groundwater flow modelling described previously suggests that such flows might occur during the resaturation period. However, it seems likely that the timescales of solute transport and resaturation are such that this interaction is unlikely to be significant.

If the EDZ were to act as a pathway for hydrogeological interaction, e.g. due to failed seals, then geochemical interactions in the EDZ would affect the chemistry of the migrating fluids. The chemical conditions in the EDZ will be altered during the operational phase. The extent to which chemical changes (for example, oxidation) occur in the EDZ during the operational phase is a function of the length of the operational period. Co-location may extend the length of the operational period and the importance of oxidation, etc reactions that alter the chemistry of the EDZ.

CONCLUSIONS

This scoping study 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.

The disposal system is strongly coupled. For an interaction to occur there must be both a suitable pathway and a driving force to transport heat, water or solutes between the two disposal modules. The occurrence and magnitude of interactions will depend strongly on the disposal system being considered (i.e. the combination of host geological environment and GDF design).

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 strong rock and lower strength sedimentary rock examples, a respect 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 respect distance needs to be two to three times as large if the same temperature constraints apply.

Minimum spacing requirements will have to be considered alongside geometrical constraints when considering the design of the facility. Thermal interactions are most likely to be an issue for a stacked geometry because this geometry will tend to minimise the respect distance. It should be noted that there is potential for reducing the magnitude of thermal interactions through careful placement of wastes so that the hottest wastes (PWR SF) are disposed of in the part of the HLW/SF disposal module that is furthest away from the ILW/LLW disposal module in a planar geometry, or so that the hottest wastes are not disposed of directly below those components of the ILW/LLW inventory whose evolution is particularly temperature sensitive in a stacked geometry.

The second key issue primarily affects the strong 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. A detrimental interaction can be prevented 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.

During the resaturation period, the flow field will be very different to the long-term flow field. The scoping calculations described in this study explored the resaturation behaviour of a co-located GDF. The results indicate that the HLW/SF disposal module is likely to resaturate more quickly than the ILW/LLW disposal module. During the resaturation period flow is likely to be from the HLW/SF disposal module towards the

ILW/LLW disposal module because the ILW/LLW disposal module is always at a lower pressure than the HLW/SF module during the resaturation period. The effect is strong enough to drive the flow against the regional hydraulic gradient. Including the effects of gas generation, which would increase the pressure in the ILW/LLW disposal module, does not change this conclusion.

The central access tunnels that link the two disposal modules appear to be the final part of the example systems to resaturate fully. Towards the end of the resaturation period, water may flow from both disposal modules into this central area. It will be important to ensure that the performance of the closure engineering in these tunnels is not detrimentally affected by these pore fluids and the result of them mixing with each other. The properties of the EDZ in this part of the system may also be important to system performance.

NOMENCLATURE

Co-location: Locating two or more disposal modules containing different wastes and implementing different EBS designs adjacent to one another with common access tunnels and facilities.

EBS: Engineered Barrier System.

EDZ: Engineered Damage Zone.

EFEP: External, Feature, Event, Process. A FEP external to the disposal system, e.g. climate change.

FEP: Feature, Event, Process, relating to the disposal system, e.g. waste, host rock, groundwater flow.

GDF: Geological Disposal Facility.

Module: Part of the GDF designed to take wastes of a specific type with a specific EBS. Co-location of different modules is the focus of this study.

PWR: Pressurised Water Reactor.

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