NAnet Project

WORK PACKAGE 2

Analogues for the far-field of a repository

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CONTENTS

1 INTRODUCTION

The fundamental objective of the geological disposal concept is to isolate radioactive wastes from the human environment for as long as is possible, allowing for radioactive decay to reduce the hazard posed by the waste. The designs of most repositories adopt the 'multi-barrier' principle, with the isolation capacity provided by a series of engineered barriers in the near-field and the host rock in the far-field (geosphere).

The key requirement of the host rock is that it should be relatively stable so as to protect the engineered barriers and its behaviour should be adequately predictable. In this regard, geological stability relates not only to the physical features of a site but also to the geochemical and hydrochemical aspects. The rocks usually considered as potential host rocks include:

- crystalline basement rocks;
- extrusive volcanic rocks (e.g. lavas and pyroclastics);
- low-permeability sedimentary sequences; and
- thick or diapiric evaporite (salt) deposits.

The far-field is usually defined as the rock mass that remains largely undisturbed by the presence of the repository excavations and the evolution of the repository over time. Thus the engineered damaged zone (EDZ) and the chemically disturbed zone (CDZ) are considered to be part of the near-field rather than the far-field.

In safety assessment models, the performance of the far-field can, in broad detail, be evaluated by calculating the rate of migration through the geosphere of those radionuclides that are released from the near-field and, ultimately, the concentration of those radionuclides that reach the biosphere (surface environment). As part of an repository safety assessment, consideration also needs to be given to those processes that could affect the stability of the far-field and, therefore, the rate at which radionuclides may migrate through it.

These migration processes operate today, and have done in the past, in many natural systems without a repository being present. The main difference is that only naturally-occurring chemical species (such as natural uranium) are affected by them. It is the migration of naturally occurring radioelements in geological environments similar to those anticipated to host a repository that first attracted natural analogue researchers as a means of 'predicting' far-field performance. Many tens of individual analogue studies have been performed in the last few decades on natural radionuclide migration systems, usually in the vicinity of uranium orebodies, with the aim of 'measuring' transport and retardation processes. Some of these studies have provided quantitative information (e.g. on matrix diffusion depths) but the majority have provided only qualitative information that has, nonetheless, proved useful for conceptual model development and testing.

Work Package 2 of the NAnet project had the objectives of reviewing and assessing these analogue studies. The scope of the work package included all of the likely repository host rocks and geological environments, and priority was given to analogue studies which have considered:

- radionuclide transport, including diffusion and fracture and porous media controlled advection;
- radionuclide retardation, including chemical (sorption, precipitation/co-precipitation, immobilisation) and physical (filtration and ion-exclusion) processes etc;
- geostability and tectonic processes, including uplift and subsidence, volcanism and seismic activity; and
- palaeohydrogeology and palaeohydrogeochemistry.

For thoroughness and completeness some consideration was given to the possibility of periodic high temperature repository conditions occurring which will require analogues of hydrothermal and geothermal conditions and their influence on radionuclide transport and retardation processes in the far-field. In addition, the high pH conditions expected for cementitious ILW and LLW repositories and their impact on radionuclide behaviour have been addressed also. The repository processes for which far-field analogue data were thus sought included:

- Disruption to the geosphere
  - mechanical
  - chemical
- Radionuclide migration at low temperature (<100ºC)
  - hydrogeological
- Radionuclide migration at high temperature (>100ºC)
  - hydrothermal
  - geothermal
- Radionuclide retardation at low temperature (<100ºC)
  - physical
  - chemical
- Radionuclide retardation at high temperature (>100ºC)
  - physical
  - chemical
- High pH-plume

The following summary and discussion focusses on these main processes.

In general the quality of the information derived from the various natural analogue studies has long been an area of uncertainty because of the inherent complexity of natural geological systems. Consequently, analogue data often are referred to as qualitative (or soft, or indirect) and quantitative (or hard, or direct), the former normally providing support and confirmation of FEPs, i.e. the building blocks to construct scenarios which form the basis of repository safety analysis, and the latter as direct input into safety assessment calculations. Qualitative data by far comprise the main input of natural analogue studies to the safety case and constitute, with some notable exceptions (e.g. matrix diffusion), almost all of the data input derived from far-field studies. However, by interfacing natural analogue studies with laboratory and/or in situ experiments from the same site, good progress has been made, for example in the testing and further development of far-field models used in (or supporting) repository performance assessments.

When investigating an analogue of far-field processes, ideally the geological and geochemical environment in which it is located, and the elements migrating, need to be similar to the repository situation. So, for example, to investigate the sorption of uranium on fractured rock surfaces, it is important that the pH, Eh and salinity of the groundwater replicate the conditions to be found in a repository host rock. It is recognised, however, that there will never be an exact similarity between the analogue and repository systems and, therefore, it is the extent of the differences as well as the similarities which limits the value of the analogue study and of the information derived from it.

1.1 Approach

Overall, the NAnet project reviewed more than 70 separate analogue studies. As part of these reviews, those analogues that were considered to be relevant to the far-field were identified and assessed to determine whether they provide qualitative or quantitative information on specific far-field processes. The quality of the data selected to best represent the analogue in question has been an important objective of the natural analogue reviews and an attempt to highlight such data is described and discussed below.

In Work Package 4, it was recognised that there are many different potential audiences for such analogue information. One primary audience is the safety assessment community because it has been widely recognised that they have made only limited use of analogue information in recent safety assessments. One explanation for this is that they simply are unaware of the extent of analogue information that exists and of its relevance. This may be because it is hard to find the information that meets their needs from the large body of technical reports and papers that have been published.

As a result of this conclusion from Work Package 4, it was decided that one of the most useful outcomes from this work package would be a simple referencing system that would enable safety assessors rapidly to find all those analogues that relate to specific far-field rock types and processes, so that they could apply this information to the development and validation of safety assessment models.

The referencing system that was devised is based on a simple matrix of rock-process couples, and this matrix is presented in Section 3.

2 SUMMARY OF ANALOGUE INFORMATION ON FAR-FIELD PROCESSES

The following sections provide a summary of the available analogue information with respect to the main far-field processes derived from the reviews undertaken in the this work package.

2.1 Disruption to the geosphere

2.1.1 Tectonics

Instability of the geosphere hosting repositories for radioactive wastes often derives from tectonic processes including uplift and subsidence, volcanism and seismic activity, cold climate change etc. Because of its geographic location, positioned at the margins of interacting plate boundaries, tectonic activity is a critical issue in Japan and the Tono uranium deposit analogue study is pertinent in this respect. Tono is characterised by one deeply penetrating fault that cuts through the 10 Ma old ore body and other large faults occur close by. However there is no evidence that significant uranium transport has occurred along these faults over geologic timescales. This suggests that, provided the chemical environment in a repository near-field remains stable and reducing, long term tectonic activity involving uplift and faulting will not necessarily cause uranium release from the wasteform.

2.1.2 Cold climate events

Cold climate events that might impact on the stability of the geosphere include crustal rebound mechanisms following ice melt. In this respect geologically recent neotectonic faulting (thousands to hundreds of thousands of years) have been studied, especially in Fennoscandia where isostatic movement is known to have occurred periodically in response to one or more past glacial events. From repository performance and safety case considerations there is the worry that such tension release faulting may penetrate to repository depths. However large-scale post-glacial faulting investigated at Lansjärv (Sweden), rather than indicating the formation of new faults, was shown to represent reactivation along pre-Quaternary structures. Any new fractures appear to be restricted to within a few metres adjacent to the reactivated fault. This is in general agreement with fracture zones repeatedly ruptured by earthquake activity, where it has been estimated that 95% of the fault rupture replicates itself. In conclusion, tectonic instability caused by glaciation processes seems to be adequately buffered by reactivation along pre-existing ancient fault zones, and any marked downthrow movement (i.e. metres to a few tens of metres) seems to be confined to the upper 50-100 m. Even acute seismic activity appears to be confined to shallow depths as evidenced by observations in deep mines in China and elsewhere where little impact is recorded at depth compared to wide scale destruction at the surface.

Freezing of water in bedrock leads to the segregation of dissolved salts possibly into a separate fluid phase. Formation of salt segregations, brine pockets or a saline front below frozen bedrock has been postulated. Study of these processes in natural conditions was one of the objectives of the Lupin study (Canada). Drilling through the base of permafrost, and related hydrogeological and mineralogical studies did not, however, show any signs of those processes.

Other cold climate effects include the formation of methane hydrates in the upper part of the bedrock with the onset of permafrost, and continue to form at increasing depth during permafrost conditions, although its formation will be restricted to the conductive fracture systems. The permafrost horizon effectively forms an impervious cap which may serve to trap, concentrate and convert into hydrates the upward transport of methane gas either biogenetically-derived from the waste itself or of mantle-derived abiogenic origin. In nature, methane hydrate has been observed in marine sediments and underneath permafrost. The main problem of large quantities of methane hydrate at or close to repository levels is the energy released during its dissociation during increases in temperature and decreases in pressure. In a repository situation there will be two sources of temperature increase: a) from radiogenic heat from the waste and b) from climatic warming from above. What the consequences are for repository safety when dissociation occurs are difficult to foresee since it will depend on the widespread extent and depth of the permafrost horizon. Some fractured surface block masses in Fennoscandia have been interpreted to result from explosive spontaneous methane hydrate dissociation, but any evidence deeper in the bedrock has not yet been recorded.

Another important cold climate event is the potential incursion through the geosphere of highly oxygenated and aggressive dilute water from glacial melt to repository depths, i.e. hydrochemical disruption of the geosphere. Such an event may destabilise the engineered barrier system and lead to mobilisation and transport of waste products to the biosphere. This possibility has been given much attention and the following conclusions have been reached:

– deep penetration to at least 1000 m in fractured crystalline bedrock of glacial melt waters during glacial retreat can be expected;

– although these melt waters initially are oxidising, the natural redox buffering capacity of the bedrock quickly establishes anoxic groundwater conditions even at hydraulic transmissivities expected to characterise a crystalline rock repository environment;

– in fractured crystalline rock, groundwater flushing and replacement in fractures and potentially in the matrix interconnected pore spaces will be confined mainly to the upper 200-300 m;

– at depths greater than 300 m, under repository conditions, hydrochemical stability (particularly reducing groundwater conditions) will be retained during glacial events;

– in argillaceous bedrock, penetration of oxidising glacial melt waters will access fractures or more porous formations but will be quickly reduced and the maximum influence of meltwater infiltration (and successive flushing of recharge waters) appears to be restricted to depths of 200-300 m;

– in addition, since diffusion will be the main groundwater transport mechanism in argillaceous media, estimated diffusion rates indicate that the hydrochemical stability of the pore waters will be maintained during repository timescales despite glacial events;

– in areas of salt formations confined by a sedimentary cover, there are indications that present-day meteoric waters, with some additional waters of cold climate origin (Holocene?), are present to around 250 m suggesting past and present groundwater circulation at least to these depths; and

– glacial sub-erosion channels in unconsolidated sediments have been known to penetrate to maximum depths ~250 m and occasionally to ~350 m but these processes have not been observed to extend their influence to repository depths.

In summary, observations in natural geological systems generally support the view that groundwater at the anticipated depth of a repository (approximately 500 m) will remain reducing throughout the glacial cycle. This conclusion is crucial for the credibility of the geochemical assumptions normally included in the base-case scenarios for safety assessment.

An additional event during ice melt which can influence a salt host rock is sub-erosion. If large amounts of glacial meltwater have infiltrated into the groundwater system a high hydraulic potential will be imposed on the aquifers overlying the salt horizon. When this pressure exceeds the hydrostatic pressure as a result of ice loading, the meltwater is unable to infiltrate and has to be discharged. Discharge at the ice sheet-bedrock interface may be via tunnels and/or erosion channels. These channels may result in sediment erosion to depths of 250 m, but even down to 350 m, i.e. potentially to the underlying salt. It is doubtful, however, that repository depths would be influenced

2.1.3 Diapirism

Uplift movement due to diapirism can potentially influence repository siting in a host rock environment comprising salt rock domes capped by sedimentary strata. Diapirism could crucially affect the barrier properties of the entire repository system since the repository itself could be elevated by this process. Moreover, the barrier comprising the sedimentary overburden, effective for radionuclide retention and retardation, could be reduced in thickness by accelerated erosion. Studies at Gorleben, Germany also identified subrosion of the salt dome itself as an additional repository safety hazard. By subrosion the salt dome is eroded from the present upper salt horizon down to repository depth. After contact of the waste with the downward circulating groundwaters, the radionuclides will become dissolved and transported through the overburden into the biosphere. The time span until the salt barrier is totally dissolved (determined by the subrosion rate) is crucial, since a large amount of radionuclides in the waste decay during this period. However, at Gorleben the elevation of the salt dome within the next million years is estimated to be not more than 20 m, based on an average subrosion rate of 0.04 m/a. The largest uncertainty to be addressed is the high spatial variation of the subrosion because of variations in strata thickness and the different contents of low soluble minerals in the salt rock. Based on these criteria a variation in subrosion rate from 0 m/a to around 0.15 m/a has been determined. In conclusion, from a repository performance and safety viewpoint the estimation of elevation of the salt dome at Gorleben will be not more than 20 m in one million years, i.e. the barrier function of the salt dome will not be affected by diapirism over a time scale of 1 Ma.

2.1.4 Volcanism

In common with tectonic and seismic activity close to interacting plate boundaries, the scenario of cyclic volcanism and related thermal activity also poses a potential threat to repositories in such places as Japan and Taiwan. An understanding of such processes over geological timescales is a critical factor in repository siting and safety assessment. Indirectly such an understanding is also of importance for the USA where the Yucca Mountain repository site (and the closely analogous Peña Blanca study site in Mexico) is geologically related to past volcanic activity and therefore there exist concerns about the potential for renewed volcanism and its possible effects on long-term isolation for a repository.

Magmatic consequences are divided into an eruptive component, which pertains to the possibility of radioactive waste being erupted onto the surface, and a subsurface component, which will occur regardless if there is an accompanying eruption or not. The subsurface component relates to a suite of processes such as hydrothermal activity, changes in the country rock properties, and long-term alteration of the hydrologic flow field which change the waste isolation system. Potential changes may include: a) altering the radionuclide retardation properties of the bedrock, b) sealing or partly sealing fractures thus modifying the hydraulic conductivity of the bedrock, and c) changing the groundwater chemistry.

Magmatic impact studies have been in progress for some time within the USA's analogue programme focussed on the Yucca Mountain site located in an area characterised by extensional stresses and associated volcanic and seismic activity. The broad tectonic control on these volcanic centres suggests a specific relation between magmatism and tectonism. Work is in progress to understand the details of the tectonic environment and the mafic complexes in relation to their magmatic histories (i.e. time, place, style and volume of shallow intrusive and extrusive activity) which may provide an improved basis for assessing, forecasting and predicting future activity. Some Quaternary basaltic volcanism (i.e. within the last 2 Ma) is known to have occurred in the vicinity of Yucca Mountain, and may even be as late as the Holocene (i.e. less than 10,000 years old).

Attempts are also being made in the Japan and the USA to apply nonlinear dynamics and the chaos theory to magmatic events; for example, theoretical studies indicate that mantle convection may be a chaotic process. If this is the case, then predicting volcanic and seismic events within the life-span of a repository may be somewhat uncertain.

2.1.5 Geothermal/hydrothermal events

Associated with magmatic instability and related thermal events is widespread geothermal and hydrothermal activity which occurs coevally but also continues to influence the bedrock during quiescence periods. The far-field is influenced to the extent that the mineralogy of conducting fracture zones is changed during both progressive and retrogressive alteration thus significantly affecting the porosity and permeability and radionuclide sorption properties of both matrix and fractures resulting in the sealing of former fluid flow paths. The rate of precipitation is often controlled by kinetic processes. Supersaturation can be caused by processes such as boiling, cooling, heating, degassing and mixing of two distinct fluids. Such processes have been documented, for example, from Imperial Valley (USA), Wairakei (New Zealand), Medicine Lake (California, USA) or Otako (Japan). This gives rise to a variety of alteration and precipitation processes as a function of temperature, pressure, solution and rock chemistry and other factors.

Hydrothermal activity may result also in hydrofracturing leading to the opening of new fractures and short-circuiting of existing fractures thus locally changing the groundwater flow network pattern and possibly also the groundwater flow rate. Furthermore, many geothermal systems have reservoir rocks with relatively low matrix permeabilities, but high overall formation permeabilities caused by the presence of a high-permeability fracture. Such system occurs in Dixie Valley (Nevada, USA) where interference and tracer tests were conducted to demonstrate connectivity of wells by a high-permeability fracture network. Similar features were characterised at Silangkitang geothermal field (Indonesia) and Wairakei (New Zealand). Such examples demonstrate the importance of high-permeability fractures for the circulation of fluids. If such faults/fractures are permeable, then they could serve as fast fluid flow path for infiltrating surface waters reaching the repository level, as well as path for dissolved radionuclides transport from the waste packages down to the water table (analogy with Yucca Mountain).

The physico-chemical processes associated with hydrothermal activity also have played an important role in mobilising, transporting and precipitating uranium over distances compatible with the volume of host rock envisaged to surround a repository. For example, the hydrothermally formed uranium deposits represented by the analogue study sites at Marysvale (USA), Oklo/Okélobondo (Gabon) and the Osamu Utsumi mine (Brazil) indicate uranium distribution over shorter distances of metres to several metres, whilst the hydrothermal vein uranium deposits of El Berrocal and Mina Fe in Spain and the massive Cigar Lake hydrothermal deposit in Canada represent tens of metres and more.

2.1.6 Gas overpressure

The build-up of gas pressure within the repository may occur to such an extent as to compromise the integrity of the host rock. Large volumes of gases may be generated from some waste inventories by a number of processes, in particular for the more reactive and heterogeneous ILW. These include the anaerobic corrosion of metals to form hydrogen, the microbial degradation of organic materials to form methane and carbon dioxide, and the radiolysis of water. Gas migration timescales can occur on human timescales (0 – 100 years) but the time when gas migration commences depends on the nature of the wastes and packaging and may extend into historical (100 – 1000 years), archaeological (1000 – 10,000 years) and ultimately geological (hundreds of thousands of years) timescales. A range of natural and anthropogenic analogues are available that relate to processes associated with the migration of gases from a deep repository.

For repository far-field crystalline rock environments, characterised by permeable fracture networks, anthropogenic analogues have been documented from hydroelectric power station air cushion surge chambers (used to damp pressure fluctuations in water flowing to the power station), natural gas storage caverns and borehole injection tests. It appears that gas leakage occurs at pressures less than the hydrostatic water pressure acting on the caverns. This is a valuable observation since it confirms that gas over pressure is unlikely to occur in repositories constructed in fractured crystalline rocks.

In contrast mudrocks are known to be able to limit gas migration and may form the caprocks to natural gas accumulations. Accumulation of gases may therefore result in the build up of an overpressure which could result in mechanical failure of the mudstone. In practice mechanical failure may be expected only when gas pressures exceed 80% of lithostatic pressure. At depths below ~1.5 km such fractures are likely to reseal due to the high lithostatic pressure, so that only at depths less than ~1.5 km is fracturing considered to be an important gas leakage mechanism. In the North Sea the flux of gas at the seabed has been measured in the range 400 – 1000 $l/m^2/y$ and has been taken to represent typical gas fluxes through mudrock caps. As such they provide examples of the gas permeability of thick mudrock sequences relevant to repositories constructed in such rocktypes. However the nature and significance of gas migration may be affected by the presence of localised barriers to gas permeability thus restricting the general use of analogue-derived information on gas flux rates. All potential repository sites are site specific.

2.2 Radionuclide migration (< 100ºC)

2.2.1 Solute transport by advection and diffusion

This section dealing with radionuclide migration at ambient temperatures includes dissolved solute transport in saturated/unsaturated host rocks. Solute migration may be by advective groundwater flow and diffusion (i.e. in fractured crystalline rocks, tuffs, sandstones and limestones) and by diffusion (i.e. in mudrocks and salt rock), continuous in a saturated bedrock or intermittent in an unsaturated bedrock. Diffusion as a transport mechanism takes on importance where transport with flowing water, advection, is small. Such conditions prevail in the pores of the rock matrix where there is no or very little water flow. Solutes transported with water flowing in fractures in the rock may enter these pores through diffusion, a phenomenon known as matrix diffusion (see Section 2.4.3).

There are many analogue examples of advective solute transport under saturated conditions, less so for unsaturated flow. However in the majority of these examples dissolved solute transport is mainly observed at locations where redox conditions are marginally oxidising (i.e. when the redox front lies close to the surface). Where conditions are truly reducing, for example at repository depths, very little dissolved solute transport is observed (e.g. Cigar Lake, Canada). A good example of solute transport under marginally oxidising conditions is at Bangombé (Gabon). Here, evidence of radionuclide mobilisation (i.e. in the form of depleted 234U/238U) from the natural reactor zone was traced to around 50 m downflow; this proved to be much greater than had been predicted by the transport models used at that time.

Redox fronts and solute mobility may not only be restricted to near-surface localities. With respect to HLW disposal, radiolysis is expected to occur when the groundwater eventually comes in contact with the waste itself providing a source of oxidants. This may result in the outward propagation of a redox front accompanied by mobilised radionuclides and actinides. If the host rock is a fractured crystalline rock, this redox front may extend into the far-field. This possibility was tested at Cigar Lake (Canada) where safety assessment models developed to calculate oxidation by water radiolysis were found to be realistic to conservative. Radiolysis was demonstrated to be minimal at Cigar Lake which means that the groundwater conditions could remain reducing; quite simply the produced oxidants are being consumed close to the ore itself. Drawing on an analogy with exposed spent fuel, a similar situation would prevent the build-up of a redox front and probably simplify the chemical processes to be considered for radionuclide release and transport.

2.2.2 Role of colloids and microbes

Advective transport of solutes may be enhanced by sorption on colloidal or organic particles and microbes carried along by the flowing groundwater. Much attention has been devoted to these processes since they have the potential to bypass normal solute retention/retardation mechanisms such as sorption on fracture mineral surfaces. If the uptake of radionuclides on colloidal particles is reversible, this process will be manifested as a reduction of the Kd value, where the reduction is inversely proportional to the concentration of colloids and the sorption tendency on the colloids. If, on the other hand, the radionuclide should adhere irreversibly, the situation may be different. In this case, the radionuclide will be transported with the particle through the geosphere (e.g. from a corroding waste package to the biosphere) and at worst not be delayed at all by either sorption on fracture walls or by matrix diffusion in the rock. Metal ions with high charge, such as Al^{3+}, Fe^{3+}, Pu^{4+}, Th^{4+} etc. are strongly hydrolysed at pH values prevailing in groundwaters. If present in large concentrations, the hydrolysis products contain several metal ions (polynuclear) and by aggregation they can form colloidal particles. In the case of plutonium, the formation of colloids is practically irreversible.

On-going in situ radionuclide retardation experiments at Grimsel (Switzerland), seem to indicate that actinide(IV) colloids can migrate quite readily with groundwater. Low molecular weight organics such as humic substances can either stabilise radionuclides in solution by complexation, or enhance the mobility of radionuclides by aqueous and/or colloidal complex formation. Moreover, they can also contribute to the radionuclide mobility by coating the active mineral surfaces and blocking potential sorption sites. However, to date no natural analogue study has been able to identify a clear enhancement of the mobilisation of radionuclides due to organic and or colloidal transport.

In a natural environment colloid studies have been addressed in most of the major international analogue studies, for example, Poços de Caldas, Cigar Lake, Oklo and Bangombé, Palmottu and Maqarin where advective flow in fractures is present. In summary, it can be said that radionuclides in the groundwater can occur sorbed on colloids and that the possibility that a small fraction will be bound irreversibly to mobile natural colloidal particles cannot be entirely excluded. However, the overall consequence of this for the safety of the repository is negligible because of the very small amounts of particles that exist in normal groundwater systems at the depths being considered for disposal.

In conclusion, such observations have led to the general conclusion that colloids, from a repository performance viewpoint, are not expected to be a serious concern. However measurements of plutonium (from underground nuclear testing) associated with colloid particles have been reported from the Nevada Test Site in the USA. The sampling locations were 1.3 km from the plutonium source which has caused some unease among the safety assessment community resulting in a reappraisal of the importance of colloids in far-field radionuclide transport. There is, however, some doubt at Nevada as to whether the colloid samples represent transport under natural flow conditions since there is a long history of pumping at the sampling locations prior to sampling.

In common with colloid particles, microbial processes also may significantly alter the mobility of radionuclides in normal groundwater environments. They can accomplish this by either immobilising or mobilising actions, depending on the type of process and the state of the microbes involved. Microbes in biofilms will, with the exception of those which produce complexing agents, be immobilising.

Planktonic cells that biosorb or bioaccumulate radionuclides will have a mobilising effect on radionuclides. If the microbe is unable to move by its own mechanisms, it will transport radionuclides in the same way as a large colloid. Planktonic cells may have the ability to move in a desired direction as a response to various stimuli (e.g. gradients of nutrients, light, oxygen or toxic substances). Doing so, they may override the prevailing groundwater flow direction and also the flow rate, as flow in deep fractures is generally very slow. However, the rate of movement for microorganisms is also very slow at repository depths.

Microbial processes can directly or indirectly affect radionuclide transport in the geosphere. Direct action involves contact between a microbe and the radionuclide, with a resulting change in radionuclide speciation. Indirect action is caused by changes in the environment generated by microbial metabolism, which in turn influences radionuclide behaviour. Finally, all microbial processes except biosorption require an active, energy-driven metabolism. Energy is available at repository depth from mantle derived gases (e.g. methane) or from surface derived biomass, although the supply is limited by the rate of advection and diffusion. The modelling of microbial processes, therefore, must include a proper understanding of microbial energy turnover rates in deep rock aquifers as well as careful consideration of the rates of supply of deeply derived gases.

There are documented analogue studies of microbes from Poços de Caldas, Cigar Lake, Oklo and Bangombé, Palmottu and Maqarin. The microbial populations naturally present in groundwater may affect the redox conditions, and hence, the radionuclide solubility and migration. The results from these two studies and others show no evidence to indicate that microbes have enhanced significantly the transport of radionuclides through the geosphere. In general microbes have the opposite effect, i.e. they tend to stabilise the groundwater physico-chemical environment by lowering the redox potential and therefore immobilising radionuclides.

2.3 Radionuclide migration (> 100ºC)

The majority of the large-scale, international analogue study sites are based on natural uranium deposits originally of high temperature origin (>100ºC) and the subsequent interaction of these deposits with present-day groundwaters at ambient temperatures (<100ºC). These studies are particularly relevant for repository designs that may experience near-field temperatures >100ºC. For example, hydrothermal studies comprised an important part of the analogue programme at the Osamu Utsumi mine, Brazil, where the extent of the high temperature gradients during emplacement of the host uranium ore body was determined and modelled, and linked in with the degree of far-field hydrothermal mobilisation and transport of radionuclides. Unfortunately these hydrothermal studies, at the time relevant to the USA disposal design, are no longer valid as the disposal concept has subsequently changed to a dry host rock. Hydrothermal studies at Marysvale, USA were also focussed on uranium mobilisation and transport in both intrusive and volcanic host rocks. This analogue demonstrated the very restricted advective movement of radionuclides by the hydrothermal fluids at low pH (2-4 units), up to 200ºC and over a period of approximately 10,000 years.

As French and Swiss interests lie in mudrocks as a potential repository host rock, the Oklo/Okélobondo and Bangombé natural reactors in Gabon surrounded by a clay zone and overlain by pelitic strata would appear to be of interest. However, the high temperatures achieved within and around the reactor zone during their formation (>200ºC) are in excess to what is envisaged, although the observed reactions at Gabon may provide a useful means to gauge extreme conditions. Even under such extreme conditions, there is little evidence of significant advective mobilisation and transport of radionuclides outside the near-field scale confines.

2.4 Radionuclide retardation (< 100ºC)

2.4.1 Physical retardation

Analogue evidence points to the efficiency of clays and mudrocks to retard the transport of both colloid particles and microbes. At Morro do Ferro (Brazil) high lateritic weathering has generated iron hydroxides and clay minerals which have formed large concentrations of colloid particles. Groundwater samples collected from the near-surface unsaturated zone to the deep saturated zone along the groundwater flow path showed a marked decrease in the colloid concentration. This was attributed to filtration by the largely clay-rich horizons which form part of the weathering front above and below the water table. The colloid concentrations at depth were < 1 mg/L which differs little from that measured in deep groundwaters from the Fennoscandian Shield environment, for example. Similar filtering of colloidal particles was observed at Cigar Lake (Canada). Here at approximately 400 m depth a systematic decrease of colloid concentrations from a sampled profile along the groundwater flow path from the ore body, clay and out into the surrounding sandstone host rock suggested an efficient filtering of colloidal material by the clay horizon which mostly surrounds the massive uranium deposit. In common with Morro do Ferro the final colloid concentrations in the sandstones were considered too low to have any significant impact on radionuclide migration. Both of these examples have important repercussions on the integrity of the near-field backfill material (e.g. bentonite) to a repository, and those concepts considering a clay-based host rock.

The size of microbes is considerably greater than colloid particles, which implies that clay filtration may also play an important role. For example, the hydraulic integrity of clay is excellently demonstrated at Dunarobba (Italy), where fossil wood from a 1.5 Ma old forest embedded in a lacustrine clay has been so well preserved that no major decomposition has been observed. In this case, even though the clays are saturated, no oxidised water movement or associated microbial activity has penetrated through the clay to the embedded wood to cause decomposition.

2.4.2 Chemical retardation

Sorption, precipitation/coprecipitation and immobilisation

Solute (e.g. radionuclides, actinides and other trace elements) retention mechanisms which are chemical in nature include adsorption, ion-exchange, precipitation and mineralisation. Adsorption and ion-exchange are often referred to as sorption which is generally considered a reversible process. Precipitation and mineralisation result in structurally fixing or immobilising solutes in new mineral phases. It is often difficult to differentiate between precipitation and sorption, although sorption might be expected to dominate at low concentrations and precipitation or mineralisation at high concentrations. The groundwater chemical environment will play an important role in the process. For example, at relatively low uranium concentrations the mobility of U(VI) in water/rock systems depends on its tendency to form insoluble precipitates or adsorb to solid substrates. Strong aqueous complexes under moderately alkaline conditions (e.g. uranyl carbonate complexes) tend to be weakly adsorbed thus promoting greater U(VI) mobility. Contrastingly, the presence of phosphate (as ternary uranyl phosphates) greatly increases U(VI) adsorption on ferrihydrite (due to the tendency of phosphate to bind to Fe(III) oxyhydroxide surfaces) and possibly on kaolinite in the acidic pH region thus limiting U(VI) mobility. Ultimately, however, in all cases of radionuclide retardation and/or immobilisation a change in solution concentration or in groundwater composition may lead to a release of solutes into solution from dissolution and desorption processes.

There are many examples in the geological literature relating to solute immobilisation at suitable redox and chemical interfaces, the most obvious evidence being the formation of mineral deposits. Large-scale immobilisation of uranium (tens of metres scale) characterises the uranium mineralisation at the Osamu Utsumi mine (Brazil). The formation of redox fronts formed by oxidative weathering of alkaline volcanic rocks (e.g. phonolites) resulted in the precipitation of pitchblende nodules ahead of the propagating redox fronts in the reduced bedrock. In the oxidised bedrock, uranium is closely associated with ferrihydrite formed from the oxidation of pyrite. At Cigar Lake (Canada) the hydrothermal fluids which were responsible for the alteration of the basement and the sandstone host rocks, and producing the uranium mineralisation, were reducing when discharged from the graphite-rich basement metasediments into the sandstone along fracture conduits of regional character. These fluids interacted with downward percolating oxidising uranium-rich meteoric groundwaters in the sandstone, and this resulted in the mass precipitation of uraninite and pitchblende close to the unconformity contact with the Archean basement.

Direct support for solute immobilisation

Examples of radionuclide, actinide and REE immobilisation in mineral phases have been reported from natural reactor studies at Oklo and Bangombé (Gabon), for example, during the coffinitisation and phosphatic coffinitisation of uraninites, and coeval with the formation of apatites (e.g. Cs, I), zircon and chlorite in the reactor zones. Unfortunately these processes have occurred at temperatures much in excess of those expected in most repository concepts (< 100ºC), such that their applicability to low temperature conditions is limited. However it does demonstrate how effective and robust these retention mechanisms can be.

There are, however, many relevant examples of low temperature immobilisation reactions at Oklo relating to shallow, oxic conditions, particularly at the Bangombé reactor mineralisation (~ 12 m depth) where redox processes accompany present-day groundwater recharge (e.g. weathering fronts). Here in the upper weathered zone the abundance of secondary uranyl sulphates and phosphates emphasise the importance of sulphur and phosphate during migration and retention of uranium and REEs. For example a La-florencite (Ce-Al phosphate) was shown to contain around 30% fissiogenic Nd and 70% fissiogenic Sm.

The evolution of uranium behaviour with increasing depth at Bangombé has been well documented. In the upper oxidised zone some 30-50% of the uranium (<20 ppm) in the weathered clays is associated with amorphous phases, some 8-20% as exchangeable and/or on carbonate-bound fractions, and around 25% with co-precipitated crystalline Fe-oxides. At greater depths through the redox front into the black shales the uranium content increases to around 500 ppm and is mostly exchangeable with 50% readsorbed unto chlorite and up to 20% associated with amorphous phases. At still greater depths characterised by Fe-rich brown shales (containing 170-540 ppm U) the Fe(III)/U(VI) system dominates and up to 40% uranium is mainly co-precipitated with goethite and phosphate, up to 30% exchangeable on clays or related carbonates (e.g. calcite, dolomite, siderite) and up to 20% on amorphous phases such as Fe- and Mn-oxyhydroxides. The behaviour of REEs, important since they are useful chemical analogues to trivalent actinides, also show widespread mobilisation (mainly as carbonate complexes) and retention at Bangombé. In the oxidised zone HREEs are preferentially leached and accumulate at greater reducing depths mostly in association with Fe-oxides (some with phosphates). The accumulation and distribution of LREEs seem to be controlled largely by clay minerals.

Indirect support for solute immobilisation

Indirect support for solute immobilisation is indicated from laboratory experiments and modelling exercises in connection with several natural analogue studies. Based on work at Bangombé, integrated field and laboratory studies provide additional evidence of the important role of uranium co-precipitation with Fe(III) oxyhydroxides as potential sinks of radionuclides in the oxidised zone. Furthermore, there has been the successful implementation of surface complexation and thermodynamic models to describe the sorption/precipitation behaviour of U(VI) on the heterogeneous clay material characteristic of Bangombé. Most pertinent for this discussion is the thermodynamic modelling which simulated the behaviour of uranium and U-retention during the alteration of the black shales (pelites) under oxic weathering conditions. This showed that: a) the simulated sorption/precipitation sequence is consistent with field observations, b) adsorption of uranium on clays under acidic weathering conditions are not efficient processes for retention, and c) dissolution/precipitation processes may be more efficient for uranium retention.

The so-called Blind Prediction Modelling (BPM) exercise carried out at Bangombé confirmed field observations that uranyl carbonate complexes dominate the aqueous uranium speciation. In addition, the uranium concentrations measured in more reduced groundwater samples are better explained by assuming equilibrium with U(IV) coffinite and /or uraninite, and that in the more oxidised groundwater samples the uranium concentrations are better explained by assuming the precipitation of secondary U(VI) silicates such as uranophane. This further supports field observations. Other BPM modelling results show that the groundwater redox potential is mainly controlled by the Fe(II)/Fe(III) couple whilst in some localities the Mn(II)/Mn(IV) couple is operative. With respect to the U-Fe system the association of uranium to Fe(III) oxyhydroxides as co-precipitates is able to explain more convincingly the measured aqueous uranium in the oxidised groundwaters. This conclusion is also supported from similar modelling exercises documented from other analogue localities.

Other analogue evidence

As presented, the Oklo studies underline the importance of radionuclide and REE immobilisation at suitable redox and chemical interfaces, in particular associated with the precipitation of carbonates (e.g. calcite) and Fe/Mn-oxyhydroxides. The importance of these phases is reflected also in several other important analogue studies. For example, there is evidence from studies at El Berrocal (Spain) and Palmottu (Finland) of low temperature calcites and Fe(±Mn)-oxyhydroxides containing uranium and, in some cases, accompanied by REEs and thorium; Fe-oxyhydroxides from Alligator Rivers (Australia), Osamu Utsumi mine (Brazil) and Oklo (Gabon) also show similar associations. At Tono (Japan) significant radionuclide retention has been observed in association with Fe-oxyhydroxides, pyrite and carbonates. These analogue data have been documented also from site characterisation studies at Äspö (Sweden) and further supported by laboratory studies where immobilisation of uranium by calcite has been demonstrated. Here, U(VI) was successfully co-precipitated with calcite using pre-prepared samples, although it was concluded using natural samples that the formation of U(VI)-calcite solid solution is not a major immobilisation mechanism.

Studies at Äspö (Sweden) considered the incorporation of REEs, Sr, Th and U in calcite to be significant, suggesting that the precipitation rate may influence (i.e. increase) the amount of Sr (and other elements) in calcite. In the Palmottu study (Finland) the immobilisation potential of calcite was investigated in the laboratory using natural fracture filling samples. Here, sequential leaching of layered calcite indicated that in addition to calcite, the uranium was associated also with separate U-bearing phases. At Palmottu, therefore, uranium immobilisation in association with calcite was explained by adsorption, co-precipitation, and as occlusions or inclusions; simultaneous co-precipitation as a dominant mechanism was excluded. Laboratory sequential leaching results from El Berrocal (Spain) showed that uranium was mainly precipitated in mineral phases and/or co-precipitated with carbonates, although the main retention mechanism operating in the site was U(VI) co-precipitation with Fe(III) oxyhydroxides as a result of the pyritic quartz vein oxidation.

Additional solute immobilisation issues to be considered in the upper 50-100 metres of bedrock at the oxic/reducing interface include the potential role of microbial and/or colloidal/organic mechanisms. For example, the sulphate in solution at these depths is often reduced to sulphur by sulphate-reducing bacteria (SRB) which facilitate the precipitation of secondary pyrite. Radionuclides may become incorporated in such pyrite as demonstrated with uranium at the Osamu Utsumi mine (Brazil). SRBs can also produce carbonate and subsequently the local formation of calcite that may result in the immobilisation of radionuclides.

2.4.3 Matrix diffusion

Matrix diffusion is an important retention mechanism for solute transport in the geosphere for all types of host rocks that have advective flow. Sorbing radionuclides are not just limited to fracture surfaces, by diffusing through the fracture coatings they have access to a much greater rock matrix volume. Access to these inner surfaces can typically expose the solutes to a 3 to 6 orders of magnitude larger area than the surfaces of the fractures where the water flows. The efficiency of matrix diffusion is dependent thus on the diffusion penetration depths into the rock from water-conducting fracture zones (e.g. dependent on rock porosity and diffusivity), and also the area of fracture surface in contact with the moving groundwater (i.e. flow-wetted surface).

From repository performance and safety considerations the depth of interaction between the rock and groundwater is a crucial factor. Consequently, a considerable number of laboratory and field studies have been carried out during the last 20 years or so to try and quantify diffusion depths, initially in crystalline rocks but now in all rock types. Laboratory and in situ field measurements of matrix diffusion have been performed using non-sorbing as well as sorbing species; ion migration in electric fields has been used to speed up the diffusion process and to cover deeper penetration (e.g. by using thicker samples). Diffusion experiments in rock samples under stresses similar to those at repository depth have been conducted in the laboratory, together with in situ diffusion experiments at suitable depths to closer simulate natural conditions. Natural analogue studies, however, are probably more reliable than laboratory data in most respects by virtue of realistic timescales and that the measured radionuclide profiles (using natural uranium decay series measurements) represent processes which have been occurring under natural groundwater and overburden pressure conditions.

Natural analogue studies of crystalline rock have mostly focussed on radionuclide diffusion penetration depths in a variety of different geological environments, for example Palmottu (Finland), Kråkemåla, Äspö (Sweden), Coles bay (Australia), El Berrocal (Spain), Grimsel (Switzerland), Whiteshell (Canada) and Tono (Japan). These data show that most penetrative depths in crystalline rocks range from 1 to 50 mm (values up to 50 cm have also been observed); 10 mm has been suggested as a suitably conservative value. In some cases simple matrix diffusion has not taken place always, for example the observed profiles at El Berrocal may have resulted from a complex combination of matrix diffusion and chemical interaction within a zone of structural change adjacent to fractures. Other studies have shown that greatest penetration usually correlates with increased palaeohydrothermal alteration (i.e. greater porosity) adjacent to the fractures. Unfortunately little information exists for open, water-conducting fractures unaffected by hydrothermal alteration or microstructural influence. To conclude, it has been accepted for some time that the measured 'diffusion' profiles can be attributed to several mechanisms, of which matrix diffusion within an interconnected pore system may, in some circumstances, be of least importance. The crucial point in assessing repository safety is that radionuclides do penetrate into the rock matrix, where they are efficiently retarded by processes such as sorption and precipitation/coprecipitation etc.

Few analogue data presently exist to derive diffusion coefficients, and those data that are available indicate a confusingly large range of values (10^{-19} to 10^{-9} m^2/s). Taken collectively, these data show that current performance considerations, although laboratory data should also be regarded as non-conservative because of experimental artefacts. With respect to analogue studies many drawbacks still exist, for example there is a bias to select fractures heavily altered by earlier hydrothermal activity etc. and it is difficult also to establish the physico-chemical boundary conditions during diffusion. The greatest potential source of error lies in the nature of the specimens selected, i.e. hydrothermally-altered fracture profiles versus unaltered; destressed samples used in laboratory experiments etc., and subsequently how to interpret the measured data.

Fewer diffusion studies have been documented from sedimentary rocks; those that have been carried out indicate penetration depths of some tens of millimetres in clay (Opalinus Clay, Switzerland) and to depths of 40–70 mm in clay biomicrites (Wellenberg, Switzerland; Maqarin, Jordan).

As a general conclusion, the basic theory of matrix diffusion has been clearly verified from natural analogue studies, at least for fractured crystalline rocks, with connected porosities (and in some cases microfracture networks) extending well into the rock matrix. Furthermore, the combination of observed penetration depths of uranium and estimated timescales are in good agreement with predictions with a simple diffusion model using apparent diffusivities based on laboratory measurements. However, more quantitative field studies (integrated with laboratory experiments) are required to support this statement.

2.5 Radionuclide retardation (> 100ºC)

2.5.1 Sorption, precipitation/coprecipitation, immobilisation

In many analogue studies of uranium orebodies, uranium has been mobilised and transported from source rocks under oxidising hydrothermal conditions until changes in redox conditions have resulted in large-scale uranium deposition in sedimentary host rocks (e.g. Cigar Lake) or as vein deposits along fracture zones in crystalline host rocks (e.g. El Berrocal). With one exception the dominant uranium phase in these deposits is UO_2, mainly as high temperature crystalline uraninite; El Berrocal is characterised by the lower temperature, less crystalline pitchblende phase (U_3O_8). The presence of graphite at Cigar Lake and Oklo has contributed greatly to immobilising the considerable accumulations of uranium. These two locations also have in common a sandstone host rock which has undergone desilication during hydrothermal activity resulting in a recrystallised residue of clay minerals (chlorite, illite) which has served to concentrate by sorption and coprecipitation considerable amounts of uranium. At Palmottu the main uranium source is magmatic with some derived also from the surrounding metasediments. At El Berrocal uranium is mobilised as uranyl complexes and precipitated as uranium phosphates (autunite), torbernite and uranocircite, and is also adsorbed onto Fe-oxyhydroxides and retained in calcites. Thorium is principally associated with older primary minerals.

2.5.2 Matrix diffusion

Retardation by matrix diffusion was the focus of the Marysvale analogue project in Utah, USA. At this locality there is an abundance of hydrothermally mineralised veins containing uraninite, pyrite and fluorite which cross-cut a series of volcanic rocks. During mineralisation the fluids where acidic (pH 2–4), at around 200ºC and lasted for around 10,000 years. Isotopic and chemical profiles were measured from the veins into the host rock matrix to assess the penetration effects, if any, that could be modelled with respect to coupled advective-diffusive transport. The study indicated the diffusion of several elements, including REEs and uranium, into the rock matrix with penetration depths of 10–20 mm and 50 mm respectively. Up to 5.7×10^5 kg of uranium was calculated to have been mobilised into the bulk rock in the vicinity of the major hydrothermal veins and 6.8×10^2 kg in the vicinity of the minor veins.

2.6 High pH plume

The Maqarin site has been studied as an analogue for the high pH plume expected to form in the far-field around a degrading cementitious ILW repository. At two localities hyperalkaline leachates propagate as high pH plumes extending some 200-400 m through the unmetamorphosed biomicrites to the River Yarmouk. Evolution of these plumes, in terms of hydrochemistry and mineralogy, has been studied in detail. Although the results show that the conceptual model for the evolution of a hyperalkaline plume is largely consistent with cementitious repositories, significant differences in porosity, permeability, hydraulic gradient and lithology with repository sites mean that evidence for the scale of alteration at Maqarin is not directly transferable. However, the information is still of value, not only for fractured, crystalline host rocks, but also in clay-based host rocks where, even though transport is dominated by diffusion, the Maqarin experience shows that it only takes one fracture to allow advection away from the repository. As Maqarin is dominated by fracture controlled advective flow, the site therefore provides important data for model testing and supporting information on the nature of fractures and the potential for their sealing. Data from Maqarin suggest alteration on the 10's to 100's metres scale and evidence shows that fractures containing hyperalkaline groundwater will seal with time by water/rock interaction. When reactivation occurs, flowpath lengths may extend to 0.5 km.

With respect to matrix diffusion, the mineralogical alteration of wallrocks adjacent to fractures at Maqarin gives evidence that, initially at least, the rock matrix is accessible to diffusion. Evidence from 226Ra profiles in the rocks adjacent to fractures suggests that the matrix continues to be accessible to fluids from fractures. This important observation implies that matrix diffusion could continue to act as a retardation mechanism in the altered rock. Mineralogical evidence and porosity studies suggest an opening of porosity in the matrix, but sealing closer to the fracture wall with calcite. The general applicability of these phenomena to other rock types, however, depends on the different rock types and matrix pore waters encountered, leading to different chemical reactions and behaviour. For example, Maqarin has shown that in the absence of HCO_3 pore water, leachates may serve to reduce matrix accessibility by the precipitation of portlandite on the fracture wall.

The Maqarin results have been used in a preliminary safety assessment in Sweden, for example involving the following far-field related conclusions:

- minerals formed in cement paste remain for more than 100,000 years, provided that the hyperalkaline conditions persist;
- hyperalkaline water reacts with the minerals in the rock, secondary minerals are thereby formed, which tend to clog fractures and prevent the flow of water;

- the surfaces on water-bearing fractures react with hyperalkaline water, but the porosity of adjacent rock (cm scale width) is still available for matrix diffusion of solutes;

- repository-relevant thermodynamic databases provide conservative estimates of solubility, despite the fact that representation of the solubility controlling phases is too simplistic;

- the colloid concentrations are low (as in ordinary deep groundwater) and there is little tendency towards production of colloids;

- microbes can grow and be metabolically active under aerobic and anaerobic hyperalkaline in-situ conditions, but growth and activity is low; and

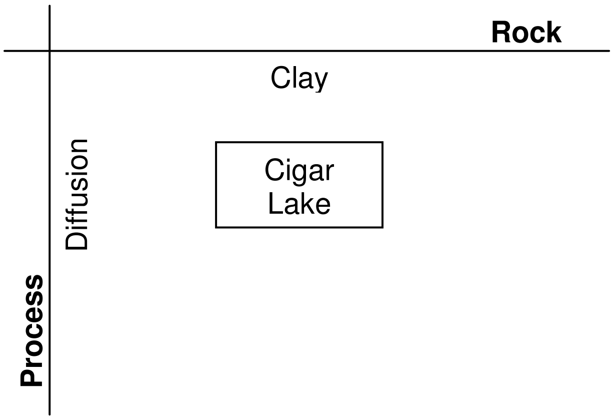
- hydration processes at high pH and low oxygen fugacity appear to trigger redox reactions resulting in a slow oxidation of Cr(III) to Cr(VI). The most probable oxidising agent is manganese Mn(III,IV) often present with the chromium.

3 THE FAR-FIELD ANALOGUE MATRIX

As discussed in the main report, it is evident that the explicit use of analogue information in safety assessments has been quite limited. One reason why this may be the case is that the potential users of analogue information are unaware of what information there is that could be relevant to their work.

It was recognised in Work Package 4 that the potential users of analogue information, particularly the safety assessors and the communications specialists, need easy access to analogue information that is relevant to the issues at hand.

In this work package, it was decided that the simplest way to provide access to analogue information relevant to the far-field was in the form of a matrix that had on one axis the range of host rock types and on the other axis the range of processes that operate in the geosphere. Intersections of the axes identify unique rock-process combinations and analogue studies can be listed at the appropriate intersections. This is illustrated in the figure below which shows that the ‘Cigar Lake’ analogue study is relevant to the understanding of the diffusion in clay.



A generic far-field analogue matrix has been developed (over page) that includes all the analogue studies covered in NAnet that have far-field relevance, based on the outcome of the individual analogue reviews. It should be recognised that this matrix is for general reference use only and does not represent any particular repository design. Indeed, no actual repository geosphere would include all of these different rock types.

It is recommended that repository specific matrices should be developed by analogue researchers and performance assessors to reflect their own particular geosphere and characteristics. These matrices could then be populated to indicate how individual analogue studies have been or could be used to inform the development of their own safety assessment models for the far-field.

The generic analogue matrix for the far-field.

Features, Events and Processes (FEPs)	Mudrocks e.g. Clays, Shales, Slates	Crystalline e.g. Granites, Metamorphics	Salts	Sandstones	Limestones (including marls)	Tuffs (including ashes)
Disruption to Geosphere						
Mechanical/Chemical						
Tectonics	Tono	Tono		Tono		
Neotectonics		Lansjärv; Pärve; Scotland			Maqarin	
Seismicity		Tono; China mines				
Volcanism						Peña Blanca
Diapirism	Gorleben; Morsleben		Gorleben; Morsleben	Gorleben; Morsleben	Gorleben; Morsleben	
Hydro-/Geothermal	Oklo; Bangombé	Marysvale; Osamu Utsumi; Palmottu; Mina Fe; El Berrocal		Cigar Lake; Oklo		
Cold Climate Events	Gorleben; Morsleben; Mt. Terri; Boom Clay; Opalinus Clay	Lupin Mine; Palmottu; Äspö, Sellafield; Stripa URL , Whiteshell	Gorleben; Morsleben	Gorleben; Morsleben; Cigar Lake	Gorleben; Morsleben	
Gas overpressure	Gas reservoirs; North Sea sediment analogies	Gas reservoirs				
RN Migration at Low Temperature (<100^{o}C)						
Hydrogeological *Advection (Saturated)*	Cigar Lake; Bangombé; Morro do Ferro; Oklo; Ruprechtov; Osamu Utsumi; Needle's Eye; South Terras; Bangombé; Broubster; Heselbach,	Äspö; Palmottu; Whiteshell; Grimsel; Steenkampskraal; Oklo; Grimsel; Eye-Dashwa Pluton; El Berrocal; Osamu Utsumi; Stripa; Needle's Eye; Coles Bay; Klipperås; Mina Fe; Kråkemåla; Menzenschwand	Wolfcamp	Cigar Lake; Tono; Broubster; Oklo; Boris; Heselbach; Morsleben	Maqarin	Nevada Test Site
Advection (Unsaturated)	Morro do Ferro; Heselbach; Bangombé	El Berrocal; Osamu Utsumi				Peña Blanca; Akrotiri
Diffusion	Cigar Lake; Mt. Terri; Morro do Ferro; Oklo; Loch Lomond; Tono; Boom Clay; Bangombé; Opalinus Clay	Äspö; Palmottu; Whiteshell; El Berrocal; Tono; Grimsel; Kråkemåla; Mina Fe; Osamu Utsumi		Cigar Lake; Oklo; Boris; Tono	Maqarin	
Colloids	Cigar Lake; Boom Clay Morro do Ferro; Tono; Oklo; Bangombé; Broubster; Ruprechtov	Äspö; Palmottu; El Berrocal; Grimsel; Osamu Utsumi; Grimsel; Oklo; Alligator Rivers; Steenkampskraal; Whiteshell; Menzenschwand;		Cigar Lake; Oklo; Boris; Tono	Maqarin	Nevada Test Site; Mortandad Canyon
Microbes	Osamu Utsumi; Boom Clay; Cigar Lake; Ruprechtov; Bangombé; Tono?	Åspö; Palmottu; URL Whiteshell; Mina Fe; Tono?		Cigar Lake; Tono?	Maqarin	
Organics	Osamu Utsumi; Oklo; Boom Clay; Cigar Lake; Ruprechtov; Broubster; Morro do Ferro;	Åspö; Palmottu; URL Whiteshell; Oklo; Stripa; Osamu Utsumi;			Maqarin	

Features, Events and Processes (FEPs)	Mudrocks e.g. Clays, Shales, Slates	Crystalline e.g. Granites, Metamorphics	Salts	Sandstones	Limestones (including marls)	Tuffs (including ashes)
Two-phase Flow	Tono?; Needle's Eye; Bangombé; Heselbach?	Mina Fe; Tono?				
RN Migration at High Temperature (>100°C)						
Hydro-/Geothermal						
Advection	Oklo	Palmottu; Marysvale; Osamu Utsumi	Wolfcamp	Cigar Lake; Oklo		Peña Blanca; Long Valley Caldera; Alamosa River
Diffusion	Oklo	Palmottu; Marysvale				Long Valley Caldera Alamosa River
Vapour Transport						
RN Retardation at Low Temperature (< 100°C)						
Physical						
Pore Space						
- *colloid filtration*	Morro do Ferro; Cigar Lake; Dunarobba	El Berrocal				
- *microbe filtration*						
Chemical *[Sorption Precipitation/Co-precipitation Immobilisation]*	Tono, Cigar Lake; Morro do Ferro; Mina Fe; Alligator Rivers; Oklo; Ruprechtov; Needle's Eye; Broubster; Shinkolobwe; South Terras; Bangombé; Boom Clay; Loch Lomond; Heselbach?	Alligator Rivers; El Berrocal; Äspö; Grimsel; Bangombé; Palmottu; Tono; Eye-Dashwa Pluton; Osamu Utsumi; Stripa; Mina Fe; Klipperås; Coles Bay; Kråkemåla; URL Whiteshell	Wolfcamp	Oklo; Cigar Lake; Boris; Morsleben; Tono	Maqarin; Khushaym Matruk?	Akrotiri; Peña Blanca
Matrix Diffusion	Tono; Cigar Lake; Ruprechtov; Heselbach; Opalinus Clay; Bangombé; Boom Clay	El Berrocal; Äspö; Grimsel; Palmottu; Eye-Dashwa Pluton; Tono; Coles Bay; Kråkemåla; Stripa; Osamu Utsumi; Opalinus Clay; URL Whiteshell	Wolfcamp	Oklo; Cigar Lake; Tono	Maqarin; Khushaym Matruk?	Peña Blanca?
RN Retardation at High Temperature (> 100°C)						
Physical						
Pore Space						
Chemical	Oklo; Bangombé					
Sorption		Marysvale; Osamu Utsumi; Palmottu; Mina Fe; El Berrocal		Oklo; Cigar Lake		
Precipitation/Co-precipitation	Oklo; Bangombé	Marysvale; Osamu Utsumi; Palmottu; Mina Fe; El Berrocal		Oklo; Cigar Lake		
Immobilisation	Oklo; Bangombé	Marysvale; Osamu Utsumi; Palmottu; Mina Fe; El Berrocal		Oklo; Cigar Lake		
Matrix Diffusion	Oklo; Bangombé	Marysvale; Palmottu; Mina Fe; El Berrocal		Oklo; Cigar Lake		
High pH Plume		Semail Ophiolite (Oman)?			Maqarin; Khushaym Matruk	

4 CONCLUSIONS

The NAnet project reviewed more than 70 individual analogue studies. Over half of these were found to be relevant to the processes that may occur in a repository far-field.

These analogue studies have yielded a great deal of qualitative and some quantitative information and, on this basis, confidence in the ability of the geosphere to act as a stable host for the repository and to act as a barrier to radionuclide transport could be said to be increased.

Nonetheless, this analogue derived information has not made its way into many safety assessment reports and, thus, its true potential has not been realised. This situation is largely due to poor communication between the analogue researchers and the safety assessors and communications specialists.

It has been recognised that what is required is a simple method to allow relevant analogue studies to be quickly and easily identified from the large body of published information. This work package has developed a far-field analogue matrix that is intended to provide a generic introduction and reference system to the literature.

It is recommended that repository specific matrices are developed by analogue researchers to reflect the particular site characteristics in their own countries.