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Natural analogues: studies of geological processes relevant to radioactive waste disposal in deep geological repositories

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Abstract The geological disposal of radioactive wastes is generally accepted to be the most practicable approach to handling the waste inventory built up from over 70 years accumulation of power production, research–medical–industrial and military wastes. Here, a brief overview of the approach to geological disposal is presented along with some information on repository design and the assessment of repository post-closure safety. One of the significant challenges for repository safety assessment is how to extrapolate the likely long-term (i.e. ten thousand to a million years) behaviour of the repository from the necessarily short term data from analytical laboratories and underground rock laboratories currently available. One approach, common to all fields of the geosciences, but also in such diverse fields as philosophy, biology, linguistics, law etc., is to utilise the analogue argumentation methodology. For the specific case of radioactive waste management, the term 'natural analogue' has taken on a particular meaning associated with providing supporting arguments for a repository safety assessment. This approach is discussed here with a brief overview of how the study of natural (and, in particular, geological) systems can provide supporting information on the likely long-term evolution of a deep geological waste repository. The overall approach is discussed and some relevant examples are presented, including the use of uranium ore bodies to assess waste form stability, the investigation of native metals to define the longevity of waste containers and how natural clays can provide information on the stability of waste tunnel backfill material.

Keywords Radioactive waste disposal · Evaluation of long-term safety · Repository design · Natural systems

1 Geological disposal of radioactive waste: a short overview

1.1 Background and objectives

The geological disposal of radioactive waste involves attempting to solve what has been claimed, many times, to be an insoluble problem (cf. Blowers and Sundqvist 2008). That the safe disposal of radioactive waste could ever be considered problematic would come as a great surprise to the pioneers of geological disposal who thought that a repository could be quickly constructed by a group of engineers with some "…suitably trained geologists." (USNRC 1957). Now, alas, it is clear that this was a little naïve and that a radioactive waste disposal programme requires not only geologists but also biologists, physicists, transport specialists, chemists, metallurgists, media experts, lawyers etc.—so engineers and geologists can no longer deal with this on their own!

Radioactive waste repositories should generally ensure that radiation doses resulting from releases of radionuclides to the environment comply with the local regulatory requirements. Although these vary slightly from country to country, it is of note that they are generally orders of magnitude below natural radiation background levels (cf. IAEA 2011). Not only are safety requirements high, but

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these have to be assured for hundreds of thousands to more than a million years (e.g. ENSI 2009), periods of time beyond normal human comprehension (human concern about the future is usually considered to be limited to three to four generations). The claim that the disposal facility implementers can meet such performance levels is often met with disbelief by the general public (and most scientists who are non-geologists) as such timespans really are beyond general comprehension. As such, members of the geoscience community have a unique insight to bring to bear on the conundrum that is geological waste disposal: namely geologists have an intimate understanding of timescales that baffle and bemuse our fellow humans and it is arguably our rôle to guide them through the confusion surrounding the appropriateness of the safe, long-term geological disposal of radioactive waste.

The focus of the "Special Theme" in this issue, containing a short collection of papers presented at the 13th Natural Analogue Working Group Meeting, held at the University of Nagoya, Japan, on 13th–16th May, 2013, is on the use of information from nature and natural systems (in particular geological systems) to meet this challenge. Interest is focussed on whether specific repository designs (and this includes the geological formations in which the repository will be built) really can be depended upon to provide sufficient long-term retention of the radioactive material, so that the more toxic, short-lived wastes decay completely and even very long-lived wastes will be released at such low levels as to be harmless. This paper will provide an overview of how information from natural systems (or 'natural analogues' as they are generally referred to in the radioactive waste disposal community and given the acronym 'NA') is collected, interpreted and used to support the demonstration of long-term safety. However, before moving on to the details, it is appropriate here to briefly consider what is classed as radioactive waste, what processes are involved in assessing repository performance and safety, and what are the main components of designs for geological repositories for these wastes. The general principles discussed will be illustrated by examples from national programmes, but there will be no attempt to detail the status of all such programmes. Sources of information from national and international disposal programmes are available from NEA (2014a). For ease of reference, a glossary of terms and acronyms is given at the end of this paper ("Appendix"). An attempt has been made to harmonize the terminology used in all the papers in this Special Theme according to this glossary.

1.2 Waste classification

Fundamentally, radioactive wastes are little different from other types of industrial, research or medical wastes: the key aspect is that they contain, or are contaminated by, "significant quantities" of radionuclides. Most concern is focussed on radioactive wastes arising either within the nuclear fuel cycle or from medicine, industry and research and, of course, some countries also have military wastes. However, as all natural materials are radioactive, many "non-nuclear" industries produce waste containing significant naturally-occurring radioactive material (NORM wastes). Despite the fact that many industries (e.g. oil, gas, electricity, fertiliser production) produce huge quantities of relatively hazardous NORM wastes, these tend to be subject to less stringent regulations than nuclear industry wastes (e.g. both Norway and Scotland have dedicated NORM waste repositories).

The IAEA has produced guidelines on classification of radioactive wastes for several decades and most recently updated their system in 2009 (see Table 1). Most national disposal programmes acknowledge IAEA terminology to some degree, but modifications in response to country-specific boundary conditions are common. In some national radioactive waste programmes, wastes are classified/managed depending on their source, while in others classification is dependent on the characteristics of the waste, e.g. based on amount of heat emitted, radiological hazard, waste form stability, etc. (see, for example, JAEA 2007). In addition to well-defined terminology, it is also important to have an inventory of the wastes being produced in each country. Without a proper understanding of the quantity and nature (namely their chemical, physical and radiological properties) of radioactive wastes, it is not possible to appropriately design a repository, or to assess the safety of any proposed facility for the handling, storage or disposal of these materials (see McGinnes 2007 for a full discussion on waste inventories). Without a reasonable inventory that bounds the waste types that are expected to be disposed of in a planned repository, the situation could arise that some of the waste may not, at the time of disposal, meet the repository waste acceptance criteria and hence have no place in the repository.

1.3 Assessing the safety of the repository

Deep geological disposal has the primary aim of containing and isolating the waste (e.g. NEA 2013). The aim is to keep the radionuclides within the waste matrix and packaging and to isolate the waste and associated hazard from the biosphere. In deep geological disposal, there is no intent for retrieval after closure. There are requirements, depending on the programme, for assuring that retrieval is possible, but this would require special technical solutions. Deep geological repositories aim at providing passive safety functions after closure of the facility. This is of importance, since the very long time scales discussed in relation to repositories do not allow safety to be based on

Table 1 Current IAEA (International Atomic Energy Agency) waste classification system (IAEA 2009)

Waste class	Typical characteristics	Possible disposal options
1. Exempt waste (EW)	Waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes (see also IAEA 2011)	Once such waste has been cleared from regulatory control, it is not considered to be radioactive waste so there are no radiological restrictions—normal land fill
2. Very short lived waste (VSLW)	Waste that can be stored for decay over a limited period of up to a few years and subsequently cleared from regulatory control	Once such waste has been cleared from regulatory control, it is not considered to be radioactive waste so there are no radiological restrictions—normal land fill
3. Very low level waste (VLLW)	Waste that does not necessarily meet the criteria of Exempt Waste, but which does not need a high level of containment and isolation	Suitable for disposal in near surface landfill type facilities with limited regulatory control
4. Low level waste (LLW)	Waste that is above clearance levels, but with limited amounts of long lived radionuclides	Requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities
5. Intermediate level waste (ILW)	Waste that, because of its content of long lived radionuclides, requires a greater degree of containment and isolation than that provided by near surface disposal	Waste in this class requires disposal at greater depths, in the order of tens of metres to a few hundred metres
6. High level waste (HLW)	Waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long lived radionuclides that need to be considered in the design of a disposal facility for such waste	Disposal in deep, stable geological formations usually several hundred metres or more below the surface
Not included in the current IAEA classification: SF or SNF	Spent (i.e. used) nuclear fuel from a nuclear power plant, generally still in their enclosing material (metal) which is disposed of without any handling other than a long period of cooling. Not addressed by the IAEA as SF is deemed a resource in some national programmes as it can be reprocessed and the plutonium and uranium used again as fuel	Disposal in deep, stable geological formations usually several hundred metres or more below the surface

institutional controls or active maintenance. For repositories, operational safety (including radiological safety) is usually treated as for any nuclear facility, but the topic of long-term safety for humans and other biota, is a unique requirement for radioactive waste disposal. Assuring long-term safety regarding potential radiological hazard arising from the radioactive waste is the focus of the approach often referred to as a "safety case". This is a structured argument, supported by evidence, intended to justify that a system is acceptably safe. It is a "collection of scientific, technical, administrative and managerial arguments and evidence in support of the safety of a disposal facility, covering the suitability of the site and the design, construction and operation of the facility, the assessment of radiation risks and assurance of the adequacy and quality of all of the safety related work associated with the disposal facility" (IAEA 2012).

The two most integral parts of a safety case are the assessment basis and the actual safety assessment. The former is essentially a description of a repository system (including the rock formation hosting the repository) and FEPs (*f*eatures, *e*vents and *p*rocesses) that are of relevance for the long-term evolution of a specific repository. Requirements are also set for various components of the repository system (see Sect. 1.4) in order to be able to show that the system works as planned. For example, for the bentonite buffer, a certain density range can be required to attain the necessary function in a given design.

The safety assessment focusses on showing that the system should function in an expected way in the future; this means, for example, that the climate is assumed to develop in a certain way, which imposes certain changes in the repository host rock (e.g. in relation groundwater chemistry) and in the engineered barrier system (EBS; e.g. changes in porewater chemistry of the bentonite). For example, in the case of Sweden and Finland, defining expected evolution of the site means obtaining an understanding of past glacial cycles and what is expected in the future: here, current understanding implies repeated cycles during the next million years. Figure 1 presents an example of a climate evolution used in the Swedish safety assessment (SKB 2011). This expected line of evolution of a given repository is termed the 'Base Case' scenario and is used for the basic design of the repository system (including the EBS and host rock choice). However, there will always be uncertainties about the likely future evolution of the repository (for example, different timing of the next glaciation), so a safety assessment also includes additional possible futures, usually calling them 'Alternative Cases'. Thus uncertainties related to the site evolution (and,

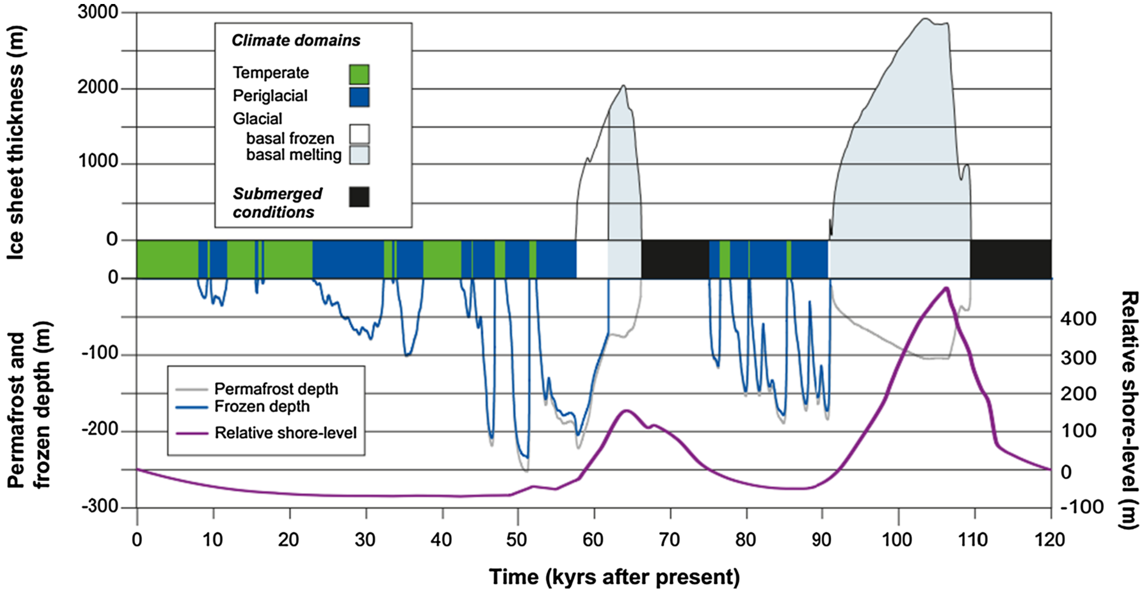


Fig. 1 An example of a model glacial cycle with important climate-related variables (permafrost, sea level changes, climate type) for the Forsmark repository location in SE Sweden (SKB 2011)

consequently, the repository system performance) are covered in the safety assessment by addressing these scenario variants and/or disturbance cases. In all cases (i.e. the Base Case and the Alternative cases), calculations of radiological dose and/or risk are carried out and the results compared to regulatory guidelines (which are generally country specific).

The safety case is an exercise that is meant to be repeated regularly from the start of a given disposal programme in order to allow sufficient iterations with the design to develop a robust repository. “Robustness of the safety case is strengthened by the use of multiple lines of evidence leading to complementary safety arguments that can compensate for shortcomings in any single argument” (NEA 2013). Essentially, this means that, among other lines of evidence, observations from natural systems are used to support development of the Base and Alternative Cases and to verify the modelling and experimental results.

The outcome of a safety case is a presentation of evidence and arguments, handling of uncertainties and ultimately stating the confidence in the system performance. For an overview on the current international status, the reader is directed to the state-of-the-art report on safety cases for deep geological disposal (NEA 2014b).

1.4 Geological disposal concepts

1.4.1 Introduction

Historically, the development of geological waste disposal concepts began in the late 1950s and a good overview of this process is provided in McKinley et al. (2007), and a review of more recent developments is available in NEA (2014a). Many different options for the disposal of radioactive wastes have been proposed in the past and the most commonly discussed alternatives are listed below. Of these, shallow land burial and deep geological disposal are the only options which have developed past the conceptual stage (see Sect. 1.4.1).

- Shallow land burial
- Deep geological disposal
- Storage with institutional control until radioactivity levels decay to below exemption limits
- Disposal into space
- Disposal in the polar icecaps
- Disposal on or beneath the seabed
- Nuclear transmutation

When dealing with radioactive wastes, storage generally refers to a system that requires further management before institutional control over the waste is given up, whereas disposal does not. In this regard, the option “storage with institutional control” is often promoted by individuals and environmental groups opposed in principle to the disposal of radioactive wastes by any means. However, consideration of the very long half-lives of some radionuclides means that institutionally-controlled storage is not a practical option for the longer-lived wastes because control cannot be guaranteed for the required isolation period (thousands to hundreds of thousands of years; see discussion in Alexander and McKinley 2007). In this case, there is currently no proven alternative to deep geological disposal. For comprehensive descriptions of the background to geological disposal of radioactive wastes, see Milnes

(1985), Savage (1995), Witherspoon and Bodvarsson (2006) and Alexander and McKinley (2007).

1.4.2 Repository designs

The first point to consider is just how deep a facility has to be for it to be considered as geological disposal. Currently, repository types may be subdivided into (McKinley et al. 2007):

1. Shallow/near-surface (up to a few tens of metres deep) for the disposal of LLW (see Table 1). These repositories, including Drigg in the UK, Centres de La Manche and de l'Aube in France (Fig. 2) and Rokkasho in Japan, are located at or near the surface because the predominantly low activity and short half-lives of the waste they contain means that the very long isolation times required for other wastes is not necessary. It is, however, notable that many such facilities were developed decades ago, before the potential impacts of processes like anthropogenic climate change were considered. Re-evaluation of associated safety cases is thus now important for many sites, particularly those in coastal locations (see McKinley and Alexander 2009, for details).
2. Intermediate depth disposal (up to a hundred metres or so below surface) is also under consideration or already implemented in some programmes for shorter-lived L/ILW—for example, JNFL's planned L1 repository at Rokkasho, north east Japan and SKB's existing SFR repository and its planned extension in southern Sweden (see Fig. 3). The design for such repositories is generally based on a cementitious EBS, with large masses of concrete used to immobilise the waste in canisters and to backfill the caverns and tunnels in which the canisters will be emplaced (Fig. 4). In these repositories, the design and site characterisation techniques and approach are much more akin to deep geological repositories than shallow land burial and, as such, they can certainly be classified as geological disposal.
3. Deep disposal (several hundred metres or more) is the generally preferred option for longer-lived and higher activity wastes, but may be considered for all types of waste. Such repositories for long-lived ILW are already operational (e.g. WIPP in Carlsbad, New Mexico, USA) or, for HLW/SNF, are in the planning stage, with those in Finland and Sweden being particularly advanced (cf. NEA 2014a).

Fig. 2 Photograph of the Centre de l'Aube (France) surface repository for LLW (low-level waste). Waste packages will be placed in the large, open concrete compartments (mid-field) and, after they are full, each will be closed with a concrete roof and the entire site then covered with an earth and clay 'cap'. Image courtesy of Nagra

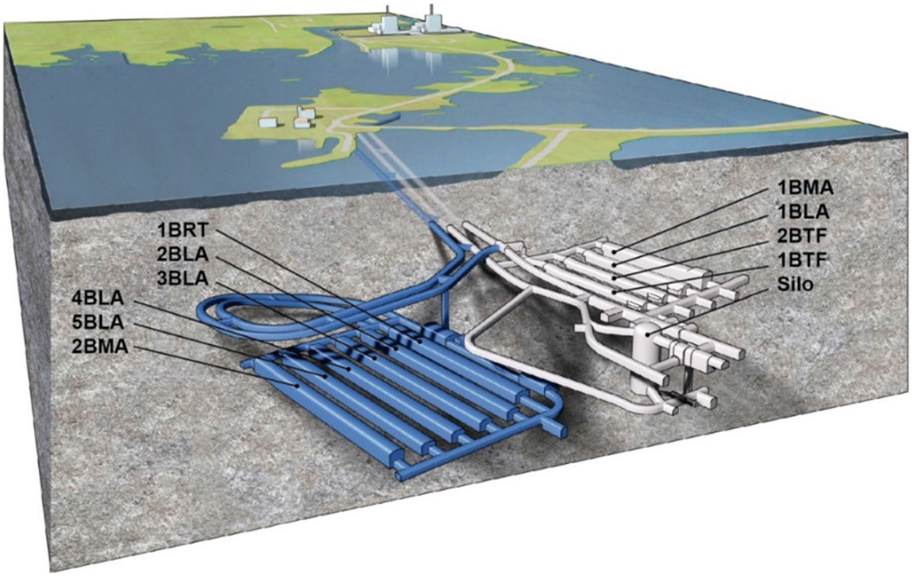
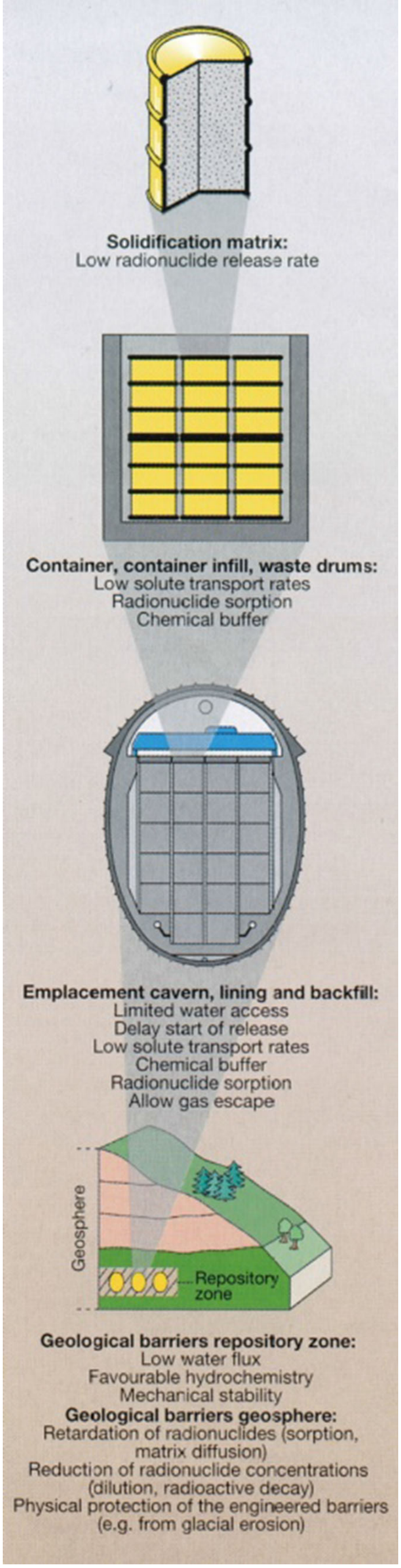


Fig. 3 The existing SFR repository in Sweden is shown in *white* (maximum depth of 60 m below the Baltic Sea) with the proposed extension in *blue* (maximum depth of 120 m) alongside. The details of the different wastes in the various vaults are given in SKB (2014)



◀**Fig. 4** An example of the multi-barrier concept for L/ILW (low- and intermediate-level waste). The wastes are placed in metal drums and immobilised with a filling of cement or bitumen. The drums are placed in larger concrete or steel containers for handling and any voids are usually filled with a cement mortar. The containers are then stacked in the disposal tunnels or caverns and any voids are usually filled with a cement mortar. Image courtesy of Nagra

Here, focussing on deep geological disposal of longer-lived waste (i.e. repository type 3, above), a wide range of concepts has been investigated, with focus on waste emplacement in specially constructed underground tunnels, caverns or vaults. A pre-requisite is geological stability, but many potential host rocks have been identified, including igneous (granite, basalt, tuff), metamorphic (gneiss, schist) and sedimentary (evaporite, clay-rich limestone, argillite). In all cases, a multiple barrier concept which includes both the EBS and the host rock has been adopted (see example in Fig. 5).

As an example, the particular design shown in Fig. 5 minimises radionuclide release from the waste via the intrinsic properties of the simple materials used as barriers. The massive steel canister buffers the Eh of the system by slowly ‘mopping up’ any oxidants present via corrosion (for an example of a copper canister, containing a steel insert, see Raiko 2013). As long as the Eh around the waste remains low, the solubility of most radionuclides will remain low, so automatically limiting releases. The corrosion products (iron oxyhydroxides, green rust, etc.) also retard many radionuclides via sorption and/or incorporation into the structure of the secondary phases. The bentonite clay buffer also ensures low radionuclide solubility by buffering the pH in the alkali zone (Bradbury and Baeyens 2003). In addition, the bentonite is micro-porous, so minimising any advective or colloidal transport of radionuclides away from the waste and into the host rock. As radionuclide migration will be by diffusive transport through the very thick bentonite buffer, many radionuclides will actually decay to (radiological) insignificance during the journey through the bentonite.

More recently, designs have begun to focus on practicality of implementation—a factor almost completely ignored in the early projects which started from the assumption that technology could be developed to implement any specified option in a safe and quality assured manner. Experience gained in underground rock laboratories (e.g. Bossart and Thury 2007; Schaefers and Fahland 2014) has shown that such implementation is not a trivial task—particularly when remote-handling procedures have to be utilised due to the high activity of some of the wastes.

It is noticeable, however, that the relative weighting of the EBS and the geological barriers (geosphere) varies

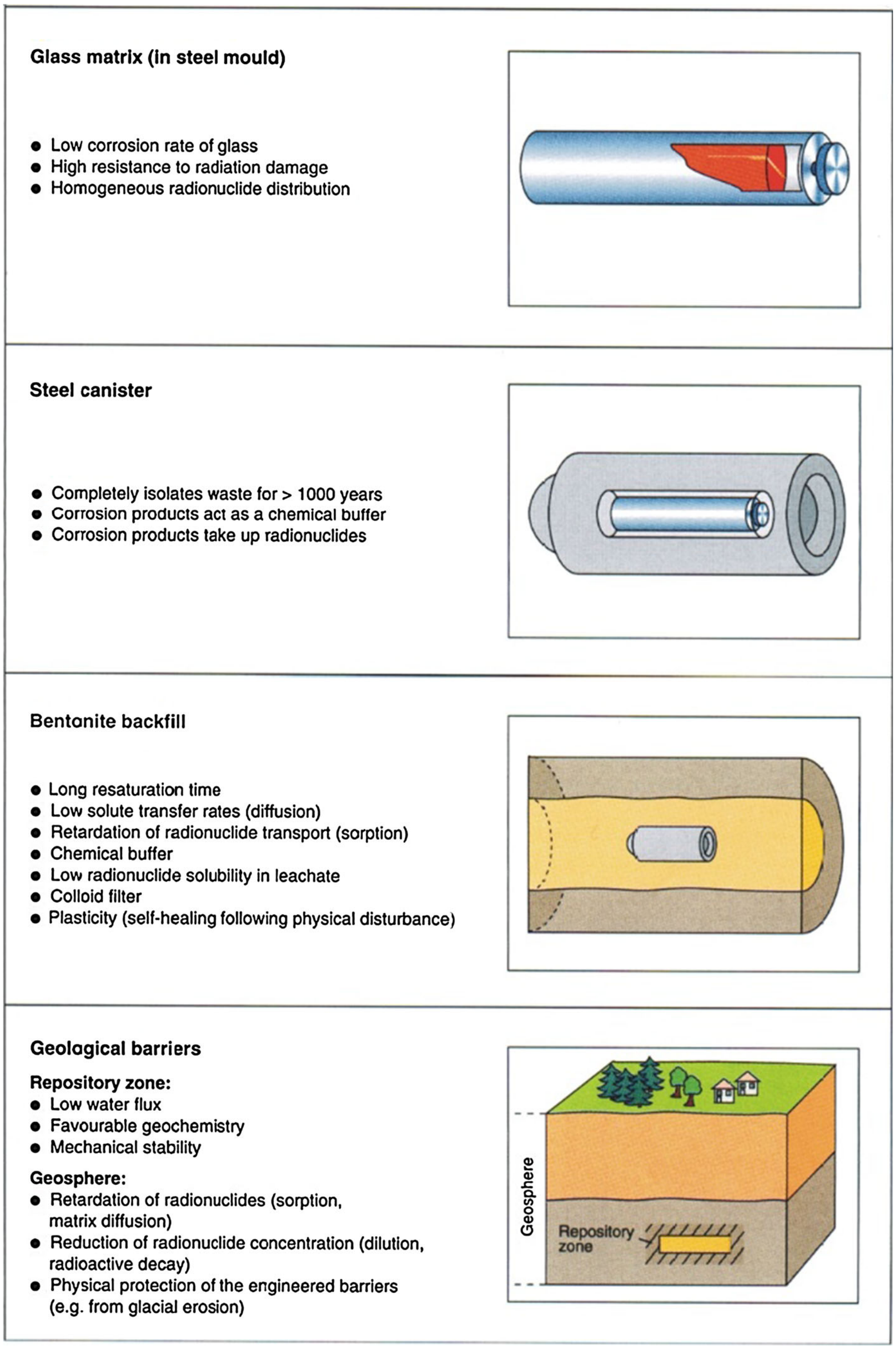


Fig. 5 An example of the multi-barrier concept for vitrified HLW (high-level waste) developed in Switzerland and Japan (e.g. JAEA 2000). The vitrified waste is poured into a steel fabrication container which is in turn placed in a thick metal canister (typically carbon-steel but, in some designs, the container is copper) and emplaced axially in a tunnel which is backfilled with compacted bentonite clay. The EBS (engineered barrier system) is protected by a stable host rock, which also acts to retard any radionuclides which are released by the EBS. Image courtesy of Nagra

considerably between national programmes (see Table 2). Generally, these differences reflect obvious features, such as the physico-chemical properties of a particular host rock, or are a consequence of the national regulatory requirements (see, for example, Savage 1995). Many alternative designs exist and a wide cross section of examples is presented in Umeki (2007) and Chapman et al. (2009).

2 Natural analogues

2.1 Introduction

Argumentation by use of analogy is well established in many fields including philosophy, biology, linguistics and law (Petit 1992), and most earth scientists are familiar with this approach and will have used it at some point in their

Table 2 The weighting of particular contributions to safety for some international vitrified HLW (high-level waste)/SNF (spent nuclear fuel) disposal concepts (after Alexander and McKinley 1999)

Key contribution	Country
Geosphere	
Dry (salt)	Germany, The Netherlands, USA
Low water flow (argillaceous host rock)	Belgium, Canada, France, The Netherlands, Switzerland
EBS: (crystalline host rock)	
Canister longevity (copper)	Canada, Finland, Sweden
Chemistry	Japan, Switzerland

career. For example, in the oil industry, accessible (surface) analogues of the geological conditions expected in physically inaccessible deep oil and gas reservoirs are often studied. Reservoir models of the fields lying deep beneath the North Sea, for example, were built almost exclusively on the results of study of the faulted sandstones of the Sinai Desert and Utah, USA. Similarly, the lead author of this paper spent his youth studying glaciology in the hills and fields of southern Scotland, building analogues of the inaccessible (to him, due to cost and time constraints) glaciers of Greenland and the European Alps on the basis of what he could observe directly only a bus ride from his home.

For the specific case of radioactive waste disposal, the main inaccessible features are:

- the very long time it will take for long lived waste to decay to safe levels—how can anyone know how the materials which are used to contain the wastes will behave over thousands to millions of years?
- the large spatial scales which cannot be directly addressed in a laboratory—how can the migration of radionuclides through several hundred metres of host rock from the repository to the earth's surface be studied and modelled?
- the heterogeneity and structural complexity of the geological environment which will host the repository—how can this ever be approached in a laboratory or modelled on a computer?

Hence the study of natural (predominantly geological) systems has been termed natural analogue research within the radioactive waste disposal community and the term "natural analogue" (NA) has developed a particular meaning associated with providing supporting arguments for a repository safety case (see, for example, Chapman et al. 1984; Côme and Chapman 1986; Miller et al. 1994, 2000; Posiva 2013a; Alexander et al. 2014, for discussion). As noted above, the key factors here are the heterogeneity and complexity of natural systems and, in particular, the very large dimensions and long timescales over which safety must be assured.

Due to the long timescales of concern, the basis of most safety cases is a quantitative evaluation that is based on complex mathematical models and their general lack of transparency only adds to the mistrust of many stakeholders. How then can people be convinced that it is possible to assess the performance (and thus ensure the safety) of a repository over the long timescales of interest? One way is to address the robustness of the safety assessment models, by clearly indicating the form and extent of model testing carried out within the repository safety assessment. Not only can this show that the individual component parts of the complex structure which constitutes most safety assessment models have been checked, but also that the 'mathematical black boxes' (cf. Alexander et al. 2003) constitute an acceptable representation of the repository system.

As noted by Alexander et al. (1998), part of the problem undoubtedly lies in the unusual nature of radioactive waste disposal: in most major engineering projects, such as bridge construction or aerospace engineering, the designs are tested against a range of laboratory experiments backed up by expert judgement based on experience with the same or similar systems. Here repository design deviates from standard engineering practice in that only a few repositories currently exist and testing their compliance to design limits will be impossible due to the timescales involved. In addition, peoples' anxiety about most things radioactive means that they require some greater form of 'proof' that a repository is safe than they are willing to accept for other engineered systems (see discussion in West et al. 2002; West and McKinley 2007). This being the case, significant additional effort has been expended within the radioactive waste disposal community to make it clear that the SA models can adequately predict the long-term behaviour of a repository.

2.2 What is a natural analogue (NA)?

Traditionally, safety assessment modellers have placed much weight on laboratory data for the construction and testing of their safety assessment models and, with only a few exceptions (e.g. Posiva 2013b), have not integrated in their safety assessment reports data from either NAs or in situ experiments in URLs (Underground Rock Laboratories). The over-dependence on laboratory data is understandable in that the information is produced under well understood, fully controlled conditions and thus the modellers feel they can place a high degree of confidence in the results obtained. Unfortunately, the full complexity of a repository cannot be re-created in a laboratory and it is necessary to address processes which are influenced by natural heterogeneities, which include large degrees of uncertainty and which operate over very long timescales. In this case, it is necessary to supplement laboratory data with information from in situ URL experiments and NAs. The potential evolution of geological repositories can be simulated by the use of mathematical models, but the extent to which such models can be validated by conventional approaches is inherently limited. Here natural (along with archaeological and anthropogenic) analogues—systems which have similar properties to components of repositories—have a unique role to play. Arguably, the extent to which natural system evolution in the past can be understood and modelled with existing tools and data, also gives an indication of the ability to determine the future development of a repository.

In its basic form, a NA study can be any form of investigation of any relevant natural system, as long as it provides quantitative or qualitative information which can be used to support (and build confidence in) geological disposal. This may mean that a study provides data which are directly applicable to the safety case or, alternatively, it may provide illustrations of concepts or processes which can demonstrate safety (cf. Posiva 2013a; Reijonen et al. 2015, this issue). Each repository design will require unique information to assist in building and presenting the safety case but, historically, NA studies have tended to focus on only a narrow range of natural systems. They can thus be categorised into a few broad groups which are representative of some major components of a repository system or feature of its evolution, namely:

- natural geological and geochemical systems
- archaeological systems
- sites of anthropogenic contamination

It should be noted, however, that this focus is currently changing and this is reflected in the range of papers presented here. Reijonen et al. (2015, this issue), for example, present an example of a more broad-based approach to the use of NA in supporting the safety case whereas Baik et al. (2015, this issue) and Wolf and Noseck (2015, this issue) look to define specific forms of NA support for repositories in crystalline and evaporite host rocks, respectively. Nevertheless, the objective of the following short discussion is to describe the features of typical NA systems and to discuss some of their limitations.

A range of geological and geochemical systems may be investigated as NAs, provided they are appropriate to the repository system of interest. Historically, the natural systems that attracted the most interest were uranium ore bodies (e.g. Cigar Lake, Canada: Smellie and Karlsson 1996), naturally occurring high-pH systems (e.g. Maqarin, Jordan: Smellie 1998) and naturally occurring metals, glasses and bitumens (e.g. Miller et al. 2000). Taking uranium ore bodies as an example, primary and secondary concentrations of uranium occur in many different geological environments (see, for example, Fig. 6 and Plant et al. 1999). Their principal interest as a NA lies in the mechanisms which have been responsible for their original deposition and any subsequent remobilisation of the uranium. These processes are shown graphically in Fig. 7 and are analogous to those which might be expected to occur in and around a HLW or SNF repository. Secondary deposits and areas of uranium remobilisation adjacent to ore bodies are also of interest because they usually form at temperatures which are representative of conditions in a repository (i.e. <100 °C).

One limitation of ore bodies is that many are at relatively shallow depths (e.g. Oklo, Gabon: Gauthier-Lafayer et al. 1996; Louvat et al. 1998), where high fluxes of groundwaters, especially oxygenated groundwaters, will dominate both the current and recent transport processes. This means that extrapolation to the low-flux, chemically reducing conditions expected in a repository requires very careful characterisation of the site palaeohydrochemistry. This can be difficult as significant extrapolation from measured data is required (cf. Milodowski et al. 2005) and depends on estimation of often unknown boundary conditions (such as the initiation of recent groundwater flow through the ore). In addition, ore bodies which have been actively mined (e.g. Poços de Caldas, Brazil: Chapman et al. 1992) may be so perturbed that it becomes difficult to define the original natural boundary conditions.

Overall, then, the main features of uranium ore bodies of potential relevance as a NA are as follows (Miller et al. 2000):

- the composition, long-term stability and corrosion/dissolution behaviour of uraninite as an analogue to spent fuel
- the role of redox processes in mobilising and retarding radionuclides, including redox fronts and other geochemical discontinuities, as an analogue of the conditions around a steel waste container
- the speciation and solubility controls of radionuclides in groundwaters (including colloid formation) as an analogue of the behaviour of radionuclides in the EBS and host rock
- the downstream retardation processes affecting remobilised radionuclides, including sorption phenomena on various surfaces and diffusion into the rock matrix porosity as an analogue of the behaviour of radionuclides in the repository host rock
- the ability to use natural decay series disequilibria to estimate the longevity of various mobilisation and deposition processes as an analogue of the processes expected in the EBS and repository host rock

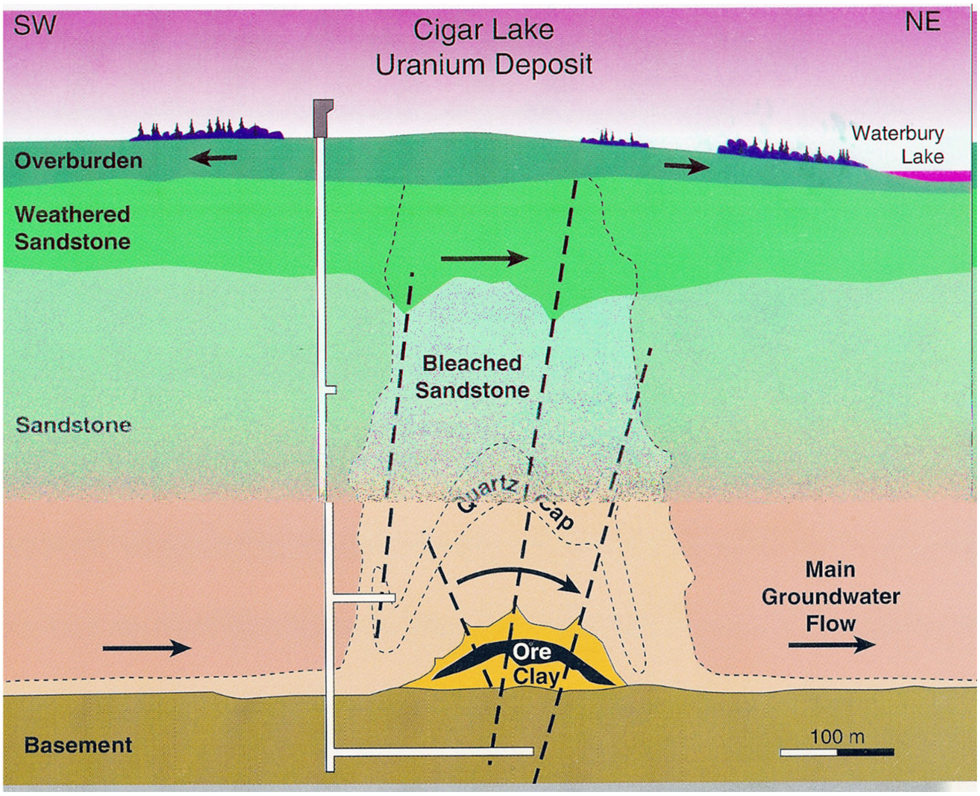


Fig. 6 Schematic cross section through the world's richest uranium deposit at Cigar Lake in Canada. This shows the extent of the primary ore body, major lithological types, the extent of a hydrothermal halo which induced some secondary uranium mobilisation and groundwater flow pathways (after Cramer and Smellie 1994)

2.3 Short overview of some completed/ongoing NA studies

To provide an overview of the types of natural systems studied to date and to examine the type of information provided to various safety cases, a short overview of a few selected NA studies are presented below, to be complemented by the accompanying selection of Special Theme papers.

2.3.1 Spent nuclear fuel (SNF)

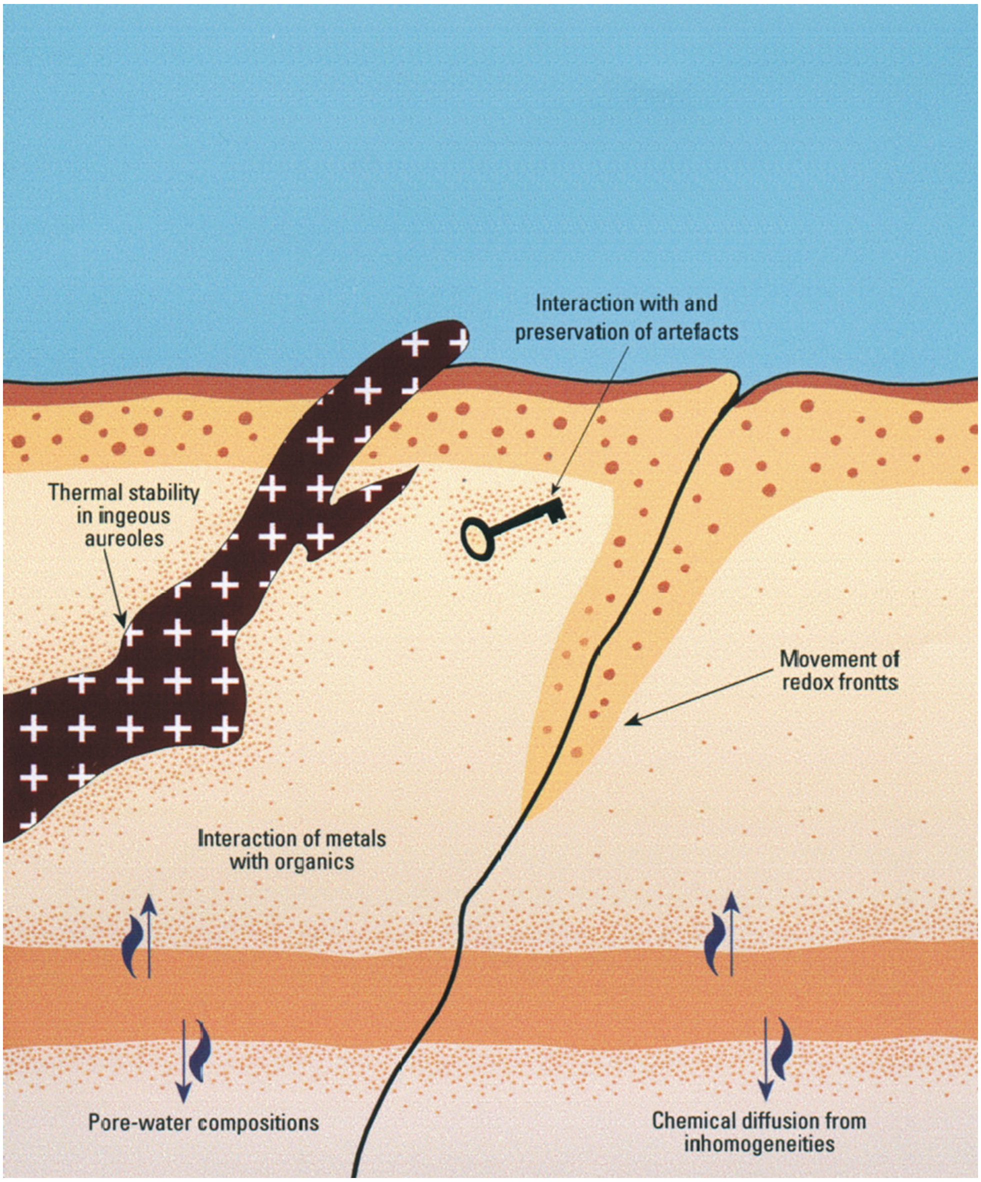
As noted above, many analogue studies have focussed on uranium ores as analogues of directly-disposed SNF and McKinley et al. (2015, this issue) report on SNF analogues for the particular case of the Japanese national programme elsewhere in this issue. SNF has a basic composition of UO_2, and the most appropriate natural analogue for spent UO_2 fuel is the naturally-occurring U mineral uraninite which also has a nominal composition of UO_2 and the same cubic crystallographic structure. There are, however, important differences between uraninite and SNF, the most notable is that, with the exception of the natural reactors at Oklo (Gauthier-Lafayer et al. 1996; Louvat et al. 1998) natural uraninites have never experienced criticality and, thus, do not contain the high concentrations of fission products, actinides and actinide daughters found in spent fuel.

Natural uraninites are relatively widespread in many rock types and are hundreds to thousands of millions of years old, providing illustrative evidence for their longevity and stability in geological environments of relevance to deep geological disposal. Uraninites from several NA study sites have been investigated to understand and quantify these slow UO_2 dissolution and alteration processes (e.g. Amme 2002). For the most part, the resulting information has been only qualitative, but broadly these studies confirm laboratory results which show that, in chemically reducing conditions, uraninite is essentially stable (Finch and Ewing 1991). This has been clearly demonstrated at Cigar Lake (Fig. 6), for example, where uraninites some 1.3 Ga old have experienced only minor dissolution and alteration to coffinite during early hydrothermal conditions (Cramer and Smellie 1994) and no oxidative dissolution under present conditions (Bruno and Casas 1994).

2.3.2 Vitrified HLW

Natural volcanic glasses have similar SiO_2 concentrations to the borosilicate glass of vitrified high-level waste (HLW) but they lack the high boron or radionuclide contents. NA studies show that natural and borosilicate glasses

Fig. 7 Processes in and around an uranium ore body of potential relevance to a radioactive waste repository safety case (from Miller et al. 2000)



corrode by similar mechanisms and devitrification (solid state recrystallisation) has been shown to be very slow in nature and is therefore not considered a significant problem for the waste (e.g. Havlova et al. 2007). In nature, glass dissolution and hydration results in layers of secondary alteration products which slow further alteration and which may also incorporate radionuclides released from the glass (Crovisier et al. 2003). To date, no reliable quantitative analogue glass corrosion rates have been used in safety assessment, but natural glasses up to 40 Ma old have been reported (cf. Ewing 1979), suggesting that glass is a reasonably stable wasteform. However, limitations of the analogy include differences in thermal and radiation doses between natural and waste glasses and that volcanic glasses are usually collected from near-surface or submarine oxidising environments so are clearly only approximates to waste borosilicate glasses (IAEA 2005).

Some archaeological glasses are coloured with metal oxides, including uranium compounds (around 5 wt% uranium in some glasses). These could provide useful information on uranium leaching and incorporation in secondary alteration products, but no such quantitative analogue studies are known to have been undertaken to date.

One possible archaeological analogue which has not yet received much attention is that of glass slabs, such as the one from Bet She’arim in Israel (Fig. 8). This massive slab weighs some 8 tonnes (Freestone 2005) and was fabricated around 1100 BP. Although it is unlikely that this particular example could be sampled for analysis, it was customary to

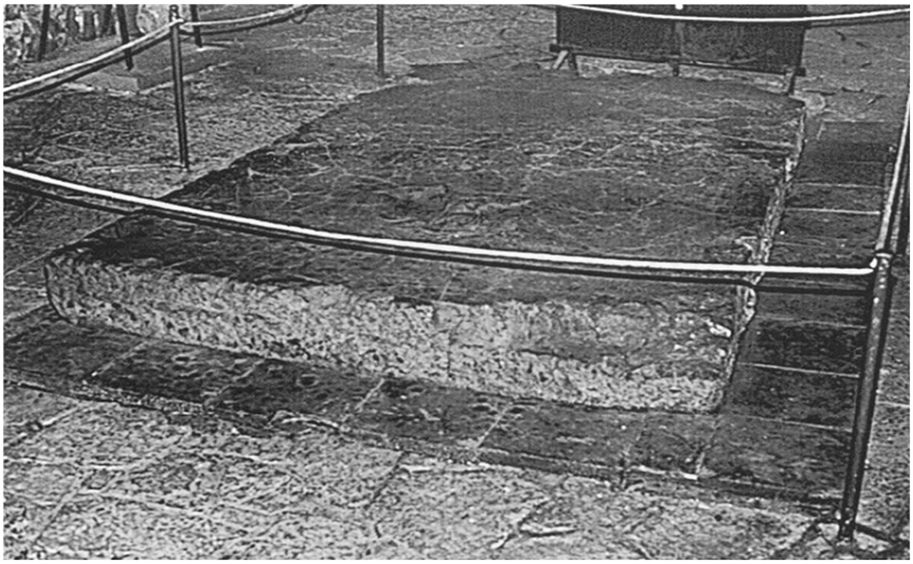


Fig. 8 The glass slab at Bet She'arim, Israel. Dimensions are 3.40 × 1.95 × 0.45 m (from Freestone 2005)

break these slabs up into large chunks for transport to other workshops to be re-melted to make glass vessels locally. It may be worth investigating sites of the original glass foundries (such as at Bet Eli'ezer in Israel where 17 furnaces have been identified) to assess if a range of sizes of glass samples from the same block are available. Potentially, they could provide information on the influence of thermal cracking of vitrified waste by examining the effects of surface area on long-term alteration (although it should be noted that the glass chemistry differs somewhat from vitrified HLW).

2.3.3 Metal waste canisters

Here, two contrasting studies are presented: one, for steel canisters, provided quantitative data on likely corrosion rates for steel canisters which showed that the estimates in the safety case erred markedly on the side of caution. The second, for copper canisters, provided little such quantitative data, but did provide information which suggests that the required corrosion-resistance for a copper canister of 1 Ma is probably quite within reason (cf. also King 1995).

As a 'reality check' on the laboratory-based assessment of the long-term performance of iron or steel as potential canister materials, both Nagra and JAEA carried out natural and archaeological analogue studies of iron artefacts from a range of environments (Fig. 9). Despite the fact that most material studied came from oxic to sub-oxic environments and would therefore be expected to corrode to a much greater extent than in an oxygen-free repository environment (Johnson and Francis 1980), a maximum corrosion depth of 10 mm in 1 ka was calculated by Nagra (Fig. 10). This increases confidence in the results from the short-term experimental data and shows that the assumed (safety assessment Base Case) corrosion depth of 29 mm (Table 3) is a significant overestimate, predicting a much shorter canister lifespan than is likely in reality. For JAEA, a maximum corrosion depth of 15 mm in 1 ka was calculated, again comparing well with the Base Case assumption of 32 mm in the H12 safety assessment (JAEA 2000). The maximum corrosion depth was dropped to <10 mm in JAEA (2005), even though this included data from aerobic environments (Fig. 9).

Sheets of native copper preserved in the Permian age Littleham Mudstone Formation, at Littleham Cove, in south Devon in southwest England, have been studied as a NA to examine the long-term stability of copper enclosed in a clay environment as an analogue of a copper waste canister in a bentonite buffer (cf. Fig. 5). The native copper is 99.9 % Cu, occurring as plates up to 160 mm diameter and up to 4 mm thick, and is closely associated with uraniferous–vanadiferous concretions and reduction spots within the red mudstones (Fig. 11). The mineral fabric relationships indicate that the copper sheets formed prior to the maximum compaction of the strata, which is inferred from the regional geological burial history to have been attained by the end of the Lower Jurassic (about 176 Ma ago). The Littleham Cove NA study (Milodowski et al. 2002) shows:

- that copper metal buried in a compacted clay environment can remain stable and resist corrosion for a very, very long period of time
- in this particular case, after early corrosion and alteration of copper during burial diagenesis, the residual copper (representing 30–80 % of the original copper mass) effectively remained inert and isolated from further corrosion within the naturally-compacted mudstone matrix for at least 170 Ma, until uplift and erosion exposed the native copper to alteration by the

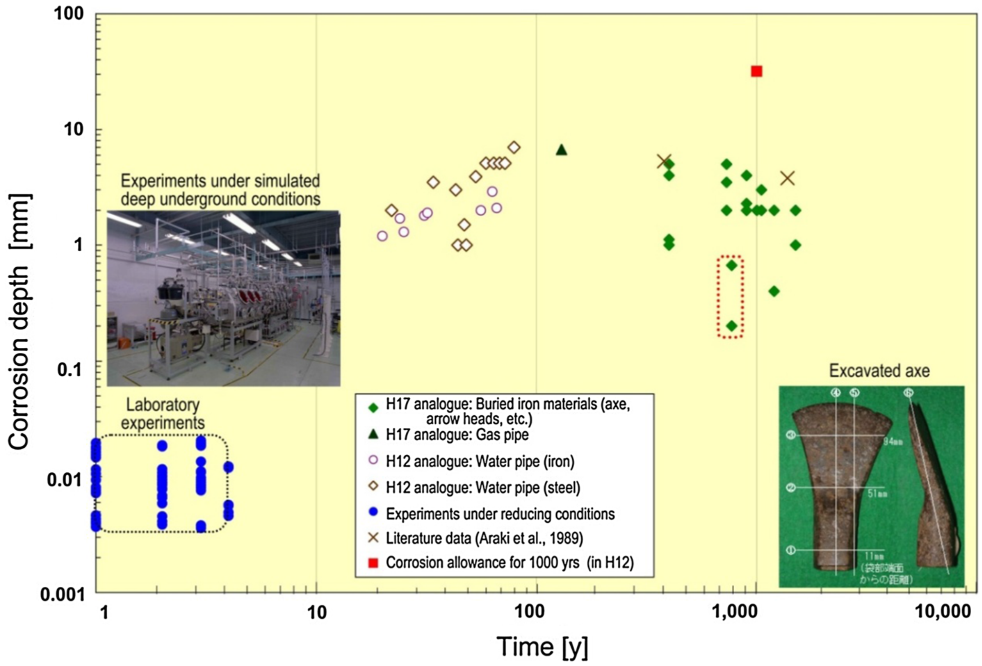


Fig. 9 Integration of iron/steel corrosion data from laboratory experiments and several natural analogue sources (details in JAEA 2005). Note that the H17 safety assessment analogues surrounded by the *red dotted box* are believed to have come from an aerobic environment

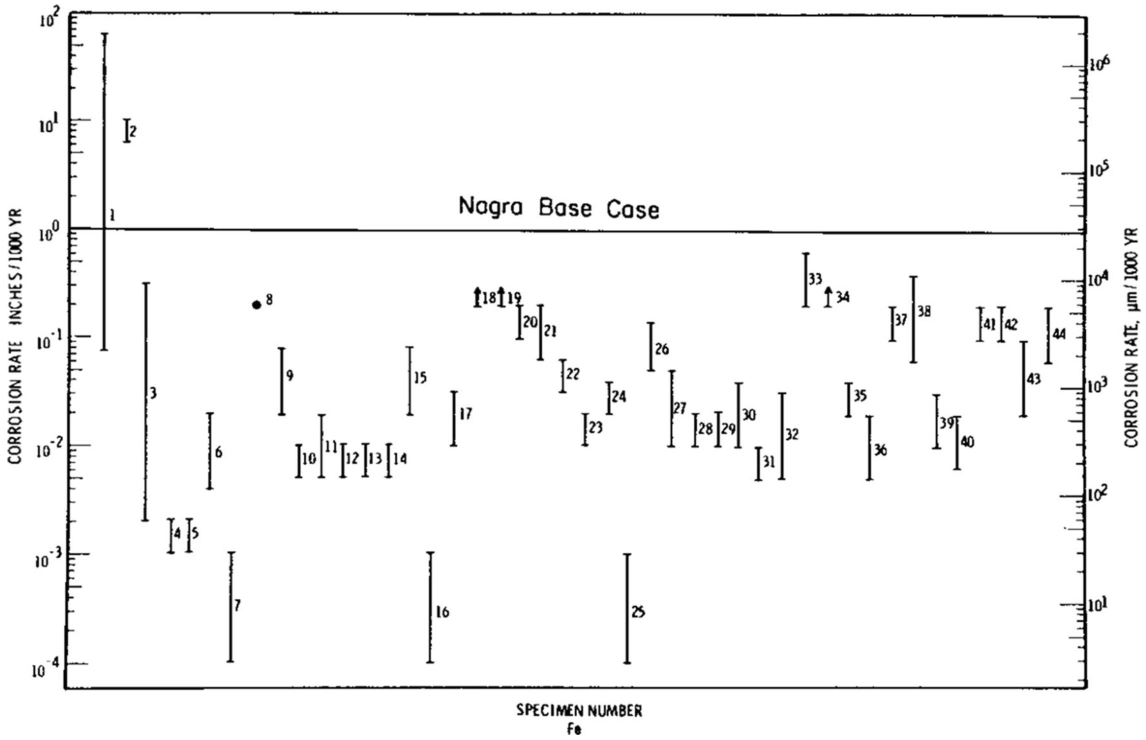


Fig. 10 Corrosion rate data from natural and archaeological analogue studies (from Miller et al. 2000). The corrosion rates for the archaeological artefacts range from 0.1 to 10 µ ma^{-1} (note that samples 1 and 2 are from oxidising marine conditions; details of all other samples included in Johnson and Francis 1980). The Nagra base case corrosion rate for steel canisters from the Projekt Gewähr safety assessment is also shown for comparison

present near-surface weathering environment. This is well in excess of the timescales (up to 1 Ma) considered in a radioactive waste safety case for copper canisters

- unlike a purpose-designed bentonite clay barrier system in a radioactive waste repository, the natural clay matrix of Littleham Mudstone Formation has not been engineered to provide a good seal. Nevertheless, the

Table 3 Comparison of steel corrosion depths cited in the H12 (JNC 2000), Kristallin-1 (Nagra 1994) and H17 (JNC 2005) safety assessments with a range of archaeological analogue data for steel/iron artefacts

Form of data	Corrosion depth (per 1000a)	References	Comments
Short-term lab	31.8 mm	JNC (2000)	Uniform corrosion of carbon steel. Base case value
Short-term lab	29 mm	NWGCT (1984)	Conservative corrosion rate, including an allowance for pitting. Base case value
Natural analogue	0.09×10^{-3} mm	Hellmuth (1991a, b)	Weathering of native iron in basalt (Disko Island). These are very low values which may reflect the site complexity. See discussion in Hellmuth (1991a, b) and Miller et al. (2000)
Archaeological analogue	10 mm	Range of studies cited in Nagra (1994)	Uniform corrosion of iron and steel
Archaeological analogue	<15 mm	Range of studies cited in JNC (2000)	Uniform corrosion of iron and steel
Archaeological analogue	0.1–10	David (2001)	Literature review of archaeological samples
Archaeological analogue	<10 mm	Range of studies cited in JNC (2005)	Uniform corrosion of iron and steel

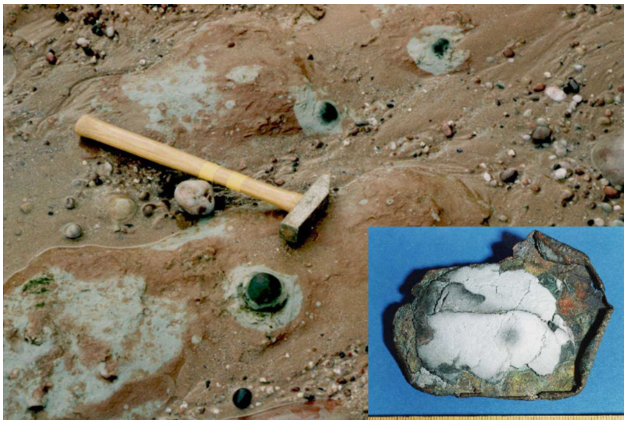


Fig. 11 Native copper plates closely associated with uraniferous–vanadiferous concretions and reduction spots within red mudstones at Littleham Cove, southwest England. Milodowski et al. (2002)

preservation of copper metal in this natural environment provides support to the prediction that copper canisters can potentially resist corrosion within the repository environment for the safety assessment design goal

However, uncertainties remain and these include:

- The porosity and permeability of the mudstone host rocks has not been examined but the permeability is likely to be greater than would be the case for an engineered bentonite buffer in a repository (i.e. more corrosion would be expected at Littleham Cove)
- Similarly, the porewaters in the Littleham Mudstone Formation may have been significantly different to those anticipated in a radioactive waste repository

Nevertheless, the simple fact that the Littleham Cove native copper plates have survived largely intact for such a long time period adds support for those designs which plan to use copper canisters to enclose the wastes.

2.3.4 Bentonite buffer

NA studies of bentonites are adequately covered elsewhere in this issue (Reijonen and Alexander 2015, this issue), but it is worth noting that NA studies have also provided invaluable input that cannot be obtained from any other source. In the particular case of bentonite, Alexander and Milodowski (2015) examined the potential reaction of bentonite in natural high pH (10–12) groundwaters from the Troodos ophiolite in Cyprus as an analogue for the reaction of EBS bentonite and high pH leachates from low alkali cement grouts, concrete seals and roof supports in a repository. Overall, the results indicated that there has been very limited alkaline groundwater reaction with the natural bentonite over a period of 10^5 to 10^6 a, tending to indicate that any long-term reaction of EBS bentonite in a repository with low alkali cement leachates will be minimal. Perhaps of equal importance is the fact that, when compared with most existing NA, laboratory and URL studies of bentonite reaction in alkali solutes, the project is the first to approach repository conditions insofar that the field conditions closely simulate what would be expected in a repository:

- an appropriately large mass of bentonite (hundreds of tonnes) is reacting with the leachates—rather than a small plug of bentonite (tens of grammes) within small-scale laboratory apparatus
- an appropriate alkali leachate can react with the surface of the bentonite in a manner similar to what would be expected in the repository EBS—rather than having a small amount of bentonite dispersed in a unrealistically large volume of alkali leachate, as is standard in laboratory tests
- reaction between the leachate and the bentonite appears to be generally driven by diffusive transport of solutes (especially OH^- and Ca^{2+}) into the body of the

bentonite from the bentonite/alkali leachate contact zone, again as would be expected in a repository
- all of the above mean that the alkali leachate/bentonite ratio is realistic (when compared to the likely evolution of a repository EBS), unlike the majority of existing laboratory and NA studies
- the temperatures of reaction (25–35 °C) are also repository relevant
- the reaction timescales (hundred thousand to a million years) are of much more relevance to a repository than accelerated laboratory and URL studies (months to several years)

Overall, it is these physical and temporal similarities between the natural bentonite/ophiolite high pH groundwater environment and that expected for industrial bentonite in a repository EBS exposed to low alkali cement leachates which argues most strongly for limited reaction of the industrial bentonite in the repository.

2.3.5 *Cementitious materials*

NAs to cementitious materials exist at both natural and in archaeological sites. NAs to modern OPC (Ordinary Portland Cement) are naturally-occurring, but rare, cement minerals which can be found in a small number of unusual geological environments (see Sidborn et al. 2014 for examples). Some of these minerals have been stable for tens of millions of years in locations where they are isolated from rapid influx of low pH or carbonate-rich waters. The most comprehensively investigated natural analogue for cementitious materials and high pH environments is Maqarin, Jordan where the pH of the groundwaters (up to pH 12.9) is controlled by the solubility of naturally-occurring cement phases, by the same mechanism that would occur in an ILW repository (see discussion in Alexander 1992). As a consequence, the Maqarin system has been used to undertake detailed testing and evaluation of the thermodynamic codes which will be used in SAs for ILW repositories to predict near-field chemical evolution and radionuclide solubilities. The alkaline groundwaters at Maqarin interact with the host marls and this has caused the dissolution of some aluminosilicates and the precipitation of a range of secondary calcium–silicate–hydrate compounds and zeolites. These processes have caused significant changes to the bulk porosity of the rock and modifications to the groundwater flow paths. Observations from these reactions have been used to develop conceptual models for the interactions between leachate plumes from a repository and the far-field rock (Smellie 1998; Sidborn et al. 2014). To date, this likely disturbance to the host rock has not been treated in detail in any SA, but the evidence from Maqarin makes it clear that these processes should be addressed in a future SA of an ILW repository.

Overviews of NAs of concrete durability have been given by McKinley and Alexander (1992), Miller et al. (2000) and Metcalfe and Walker (2004) and, more recently, the evidence was re-examined in the Finnish programme (Posiva 2013a). NA studies of OPC (Ordinary Portland Cement) have shown that the material is incredibly durable, with the oldest reported cements at Maqarin in north Jordan being some 2 Ma old (Alexander 1992). Milodowski et al. (1989) also reported the presence of unreacted natural cements from the Scawt Hill and Carneal Plug sites in Northern Ireland. These phases were produced during the thermal metamorphism of the host limestone and are estimated to be some 58 Ma old. In both these examples, the natural cements are effectively impermeable and remain unchanged until accessed by groundwaters (through tectonic damage, for example). However, the tendency is for the system to reseal following disturbance, either with secondary $CaO–SiO_2–H_2O$ (CSH) phases (e.g. Linklater 1998) or carbonates following carbonation reactions (e.g. Clark et al. 1994). The implications of these reactions to the long-term behaviour of a cementitious repository (Fig. 4) have been examined by Alexander and Neall (2007) and Sidborn et al. (2014) but, although the NA data exist, the process has not been addressed quantitatively in any safety assessment to date.

Low alkali cement is essentially the same as the pozzolanic cements developed by the Romans in the 3rd century BC (although there are suggestions that it was first used in Tiryns and Mycenae a millennium earlier; Middleton 1888). Consequently, numerous historical cements and concretes have been investigated as archaeological analogues (e.g. Jull and Lees 1990; Thomassin and Rassineux 1992) and these point to long-term stability of the cements as long as no major physical disruptions occur (see also discussion in Sidborn et al. 2014). Recent studies (e.g. Oleson and Branton 1992) of Roman cements exposed to marine salinities for several thousand years tend to support this, the preliminary results (e.g. Vola et al. 2011) suggesting little degradation of the cement. Unfortunately, the data have not yet been fully reported in the open literature and so a full assessment of the implications of these studies for a repository safety assessment will only be possible in the future.

2.3.6 *Host rock studies*

It is clear from the above examples that much effort has focussed on studies of mechanisms and processes in the EBS but, precisely because of the spatial and time scales involved, host rock studies could be seen as the raison d'être of NA in waste disposal. Here, two quite different studies illustrate the breadth of the NA approach in this case

Clay host rocks: an example from Switzerland Observations in the Mont Terri URL (Bossart and Thury 2007) and in surface exposures of the formation (Mazurek et al. 1996) indicated that groundwater transport was predominantly diffusive. To extend these small scale studies to provide data for Nagra's Opalinus Clay safety case, it was decided to upscale the studies (cf. Mazurek et al. 2006) and look at natural tracers across the entire Mont Terri site. Borehole data showed that Cl and He in the formation porewaters display smooth, regular profiles with depth, with some profiles being more symmetric than the others. When modelling the profiles, it was assumed (following the local erosion pattern) that the upper aquifer (Dogger Limestone) was activated first, followed by the lower (Gryphaea Limestone). The results are shown in Fig. 12 and indicate an excellent model fit for activation of the upper aquifer at 6.5 Ma and lower aquifer at 0.5 Ma, times which are within the geologically plausible range. Laboratory-derived diffusion coefficients were used in the modelling, showing that they could also be upscaled to the formation level, something of great value when actually assessing the safety of the potential repository site.

Glaciated host rocks: an example from Greenland When the next glaciation encroaches upon high latitude repository sites (cf. discussion in Sect. 1.3 on Base Case and Alternative Case scenarios), significant changes to the original site hydrogeology, hydrochemistry and rock mechanics are likely (cf. Boulton et al. 1993, 2001). The Greenland Analogue Project was initiated in 2009 to advance the understanding of these processes and their impact on the long-term performance of a deep geological repository. The study site encompasses a land terminus of the Greenland ice sheet, east of Kangerlussuaq, and is considered to be an appropriate analogy of the conditions that are expected to prevail in much of Canada and Fennoscandia during future glacial cycles. In the case of the Greenland Analogue Project, a novel analogue is being used (to date, only preliminary results are available—see Harper et al. 2012) to improve understanding of the hydrological, hydrogeological and hydrogeochemical processes associated with future cold climate conditions and glacial cycles and their potential impact on the long-term performance of deep geological repositories below ice sheets.

3 Conclusions

This has been a brief introduction to some aspects of radioactive waste disposal, including consideration of how the study of natural (and, in particular, geological) systems can be used to build confidence that radioactive waste disposal is both practicable and safe. Although many alternative designs for waste repositories have been considered over the last few decades, the principal sub-units of

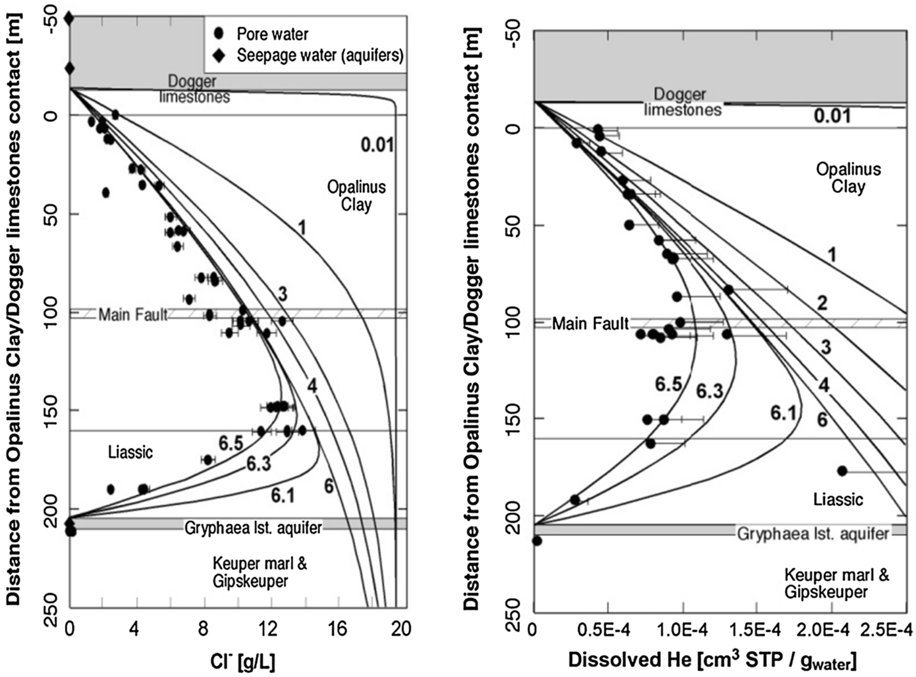


Fig. 12 Model fits for Cl (*left*) and He (*right*) profiles across Mont Terri, Switzerland (from NEA 2009)

the EBS (wasteform, waste containers and buffer/backfill) and the repository host rock types are much as originally envisaged in the late 1950s when scientists and engineers chose well known, proven and tested materials and rock types to isolate the wastes.

The initial use of NAs focussed on improving understanding of key processes and model/database testing (e.g. McKinley 1989) and, indeed, this is still a major justification for some NA projects. More recently, however, additional roles in public communication (e.g. Alexander 1995; West et al. 2002; Wolf and Noseck 2015, this issue) and staff training (e.g. Alexander et al. 2008) have received greater emphasis. In particular, using NAs to provide general support for the safety case (by studying the evolution of relevant systems over geological timescales) and to increase confidence in extrapolating results from laboratory and field experiments to the repository environment (e.g. Alexander et al. 1998; Posiva 2013a; Sidborn et al. 2014; Noseck et al. 2015, this issue) have been a recent focus.

The examples described here also indicate that the form of input from NA to the safety case can vary widely from very general support for spent fuel stability (Sect. 2.3.1), to broad indications that the bentonite clays used as buffers and backfill are likely to be highly resistant to degradation from low alkali cement leachate reaction (Sect. 2.3.4), to specific corrosion rates for steel canisters which indicate that previous safety assessment assumptions were overly pessimistic (Sect. 2.3.3). In addition to elucidating the intrinsic stability and radionuclide transport barrier rôle of clay host rocks (Sect. 2.3.6), it was also noted that studying the current situation in appropriate natural systems can provide indicators to what may happen to a host rock and the repository when major disturbances such as glaciations occur (Sect. 2.3.6). If nothing else, then, it seems that studying natural geological systems can teach us much about the likely long-term safety of deep geological repositories for radioactive wastes.

The advantage of NAs over short-term laboratory experiments is that they enable study of repository-like systems (e.g. uranium ore bodies, Sect. 2.3.1) which have evolved over the geological timescales of relevance to a radioactive waste repository safety assessment (rather than the days to months usual in laboratory tests). However, by their very nature, NAs often have ill-defined boundary conditions (e.g. the native copper of Littleham Cove, Sect. 2.3.3) which may be better assessed under the well constrained (if less relevant) conditions of a laboratory. Although this remains an elusive goal in most national programmes, it is clear that the best way to answer open questions on the long-term repository evolution is by using a properly integrated approach to laboratory experiments, testing in underground rock laboratories, modelling and natural analogues (Fig. 13).

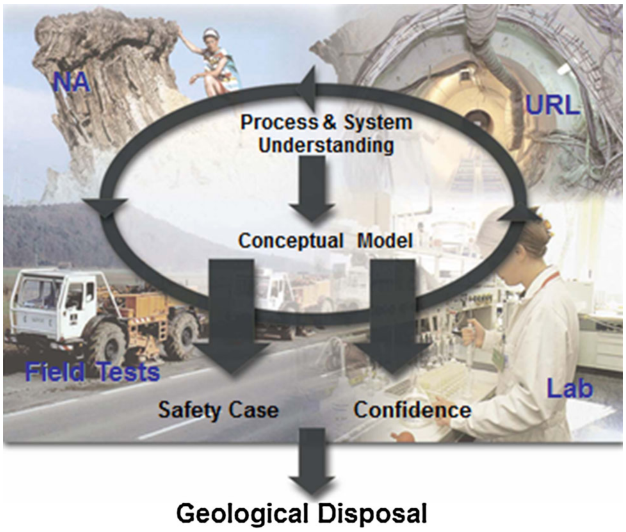


Fig. 13 Comprehensive system understanding through the integration of NA (natural analogue), analytical laboratory and URL (underground rock laboratory) data—a critical factor in building a safety case (Alexander et al. 2014)

Overall, while natural, archaeological, self and anthropogenic analogues can never solely ‘prove’ the safety of a repository, they can add highly valuable support to any safety analysis. Quite simply, this is due to the above noted fact that either the EBS materials themselves are directly analogous to natural systems or the repository-relevant processes can be studied either in natural materials or in the geological environment. Indeed, some national programmes go further and base the rationalisation of the very selection of some EBS materials on natural system information. For example, for the bentonite buffer in Posiva’s KBS-3V repository concept, the design basis states that “Only natural swelling clay materials are considered, because smectites, including the montmorillonite in bentonite, are known to be remarkably stable minerals in low temperature environments in spite of their large structural and chemical heterogeneity on the nano-to-micrometre scale.” (Posiva 2012). That rather says it all.

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Appendix

Glossary of terms and explanation of acronyms for all papers in the Special Issue “Natural analogue research” (for additional information, see also http://www.sepa.org.uk/radioactive_substances/glossary.aspx#A).

ARAP

Alligator Rivers Analogue Project. A natural analogue study of uranium migration at shallow depths around the Koongarra uranium deposit in Northern Australia. See http://apo.ansto.gov.au/dspace/handle/10238/1034 for an overview.

Backfill

Material (e.g. clay, crushed rock, cement) filling voids around waste containers and in the access tunnels and shafts.

Bentonite

A type of smectite-rich clay used extensively in waste disposal due to its ability to swell on contact with water, so providing a very tight seal. See also Reijonen and Alexander (2015) in this issue.

Blind predictive modelling

Concerning radionuclide solubility limits: as part of testing and validation, it is possible to compare geochemical model predictions with field observations in a natural system which has some geochemical similarity with repository conditions. Trace element solubilities and speciation can be predicted using as input only the major chemical variables (major element concentrations, Eh, pH and temperature). The predicted trace element trace element solubilities and speciation can be predicted using as input only the major chemical variables (major element concentrations, Eh, pH and temperature). These predictions can then be compared to actual field measurements and the degree of agreement between model predictions and reality indicates the degree of confidence which can be placed in the databases. See Pate et al. (1994) for further details.

BMU (now BMUB)

Acronym, in German (Bundesministerium fuer Umwelt, Naturschutz, Bau und Reaktorsicherheit), of the name of the nuclear (and hence radioactive waste) regulator in Germany. The official name in English is the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (see http://www.bmub.bund.de/en/).

BTV

Borehole televiewer logging tools are used to obtain oriented images of borehole cores when core recovery is difficult, expensive or otherwise unavailable. Two different methods are employed: the first uses the acoustic signal from a rotating sonar transducer and is called an acoustic televiewer. The second uses a high resolution digital colour camera with a light source and is called an optical televiewer. In both, image analysis allows borehole structural data (bedding, joints etc.) to be presented in terms of depth, direction and angle of dip and strike.

Buffer

Material (e.g. clay, cement) used to fill voids in and around the waste containers and to maintain stable physico-chemical conditions in their immediate vicinity.

Buffer bentonite

Artificial bentonite mixtures produced industrially to achieve maximum buffer and sealing capacity.

CANDU

CANada Deuterium Uranium reactor is a Canadian designed, pressurised heavy water reactor used for generating electricity. The acronym refers to its deuterium-oxide (heavy water) moderator and its use of (originally, natural) uranium fuel. See http://www.candu.org/candu_reactors.html for details.

CC (complementary considerations)

Complimentary considerations is a term which is recognized internationally to describe evaluations, evidence and qualitative supporting arguments, including those derived from the study of natural analogues (NA), that lie outside the scope of the quantitative parts of the safety case (NEA 2004, 2009). See Reijonen et al. (2015) in this issue.

CRZ

Acronym for Containment-providing Rock Zone. Under German Federal regulations, this is the part of the repository system that ensures the containment of the waste.

CSH phases

Under standard cement industry nomenclature, C denotes CaO, S is SiO2, H is H_2O etc. According to Taylor (1990), “C–S–H is a generic name for any amorphous or poorly crystalline calcium silicate hydrate. The dashes indicate that no particular composition is implied and are necessary because CSH in cement chemical nomenclature denotes material specifically of composition $CaO\Sigma\ SiO_2\Sigma\ H_2O$”.

DECOVALEX (Development of coupled models and their validation against experiments) The DECOVALEX project is an international research and model comparison collaboration, initiated in 1992, for advancing the understanding and modeling of coupled thermo-hydro-mechanical (THM) and thermo-hydro-mechanical-chemical (THMC) processes in geological systems. See http://www.decovalex.org/.

EBS (Engineered Barrier System)

Repository designs rely on a multi-barrier system to isolate radioactive wastes from the biosphere. The multi-barrier system typically consists of the natural barrier system (the repository host rock) and the EBS. The EBS represents the man-made, engineered materials placed within a repository, including the waste form, waste canisters, buffer materials, backfill, and seals. The EBS plays a significant role in the containment and long-term retardation of radionuclide release.

EDZ

Excavation damaged (or disturbed) zone. That volume of rock behind a tunnel wall which has suffered damage due to excavation (regardless of the methodology). Of interest in radioactive waste disposal as this volume of rock could, under certain circumstances, provide an additional transport route for groundwater.

ENSI

Acronym, in German (Eidgenössische Nuklear-sicherheitsinspektorat), of the name of the nuclear (and hence radioactive waste) regulator in Switzerland. The official name in English is Swiss Federal Nuclear Safety Inspectorate (see http://www.ensi.ch/en/ for details).

Exemption limits

Waste with an activity level below a prescribed limit meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes (as described in IAEA Safety Standards Series No. RS-G-1.7, 2011). The precise activity limits vary from country to country and, to an extent, from waste stream to waste stream.

FEP (features, events and processes)

The initial step in a repository safety assessment is to identify all factors that are important for the evolution of the repository and that should be studied in order to gain a good understanding of the safety of the repository. This is done in a screening of all features, events and processes (FEPs) that are thought to be of importance for the evolution of the repository and long-term safety.

FORGE

Acronym of the EU project “Fate of repository gases”. See http://www.bgs.ac.uk/forge for details.

FSC

Forum on Stakeholder Confidence is a committee of the NEA (defined below) which addresses the societal dimension of radioactive waste management. See http://www.oecd-nea.org/fsc/ for details.

Geoarchaeology

The branch of geology which studies the effects of slow geological processes on archaeological objects, especially those of known age.

GRS

Acronym, in German (Gesellschaft für Anlagen- und Reaktorsicherheit), of an independent, non-profit research and expert organisation. It is a TSO (Technical Safety Organisation), supporting BMUB in its work as the regulator in Germany. There is no alternative acronym in English, see http://www.grs.de/en/ for details.

HLW

High level radioactive waste (see Table 1 of this paper).

Host rock

A defined volume of bedrock that contains the repository, particularly that which will act as the main barrier in the geosphere (see host rock barrier function).

Host rock barrier function

This varies with the overall repository design, but includes providing a stable physico-chemical environment for the EBS, isolation of the radioactive waste from the biosphere and retardation of the migration of any radionuclides released from the waste to the biosphere.

Hydrogeochemistry

The branch of geology which deals with the chemistry and chemical variations of groundwater, and their interpretation in terms of bedrock evolution and water–rock interaction.

IAEA (International Atomic Energy Agency)

Based in Vienna, the IAEA is the UN agency responsible for dealing with all aspects of nuclear science, including waste disposal. It was set up in 1957 as the world’s “Atoms for Peace” organisation within the United Nations family. The Agency works with its Member States and multiple partners worldwide to promote safe, secure and peaceful nuclear technologies. See http://www.iaea.org.

ILW

Intermediate level radioactive waste (see Table 1 of this paper).

Implementer

In every national programme, an organisation is appointed which is responsible for the preparation for, and later implementation of, radioactive waste disposal. These are usually funded and directed by the waste producers, but may also be funded and directed by central government. For a list of national implementing organisations, see http://www.oecd-nea.org/rwm.

Inventory

The detailed list of wastes expected to be produced in a national programme. Depending on the maturity of the programme, an inventory can be purely a model of the expected wastes or can, if sufficient knowledge exists, be based on real waste data (McGinnes 2007). See, for example, details of the UK inventory at http://www.nda.gov.uk/ukinventory/.

IRF (Instant release fraction)

The fraction of radionuclides which are expected to be released rapidly when water contacts spent fuel after container breaching in a geological repository (e.g. Johnson et al. 2005).

JAEA (Japan Atomic Energy Agency)

Japanese R&D organisation responsible for basic research on all aspects of nuclear energy. This includes supporting the Japanese implementers (NUMO and JNFL) and the Japanese regulator (NRA) in the field of radioactive waste disposal. See also http://www.jaea.go.jp/english/about/index.html for details.

JNC (Japan Nuclear Cycle Development Institute)

Precursor to JAEA and successor to PNC (see http://www.jaea.go.jp/jnc/jncweb/ for details).

JNFL (Japan Nuclear Fuels Ltd)

Acronym for the Japanese implementer responsible for the disposal of LLW (see http://www.jnfl.co.jp/english/ for details).

KAERI (Korea Atomic Energy Research Institute)

Korean R&D organisation responsible for basic research on all aspects of nuclear energy (see http://www.kaeri.re.kr:8080/english/ for details).

KBS-3

Acronym used for the deep geological repository design which has been the basis of Swedish radioactive waste disposal research since the early 1980s, and has since been adopted by the Finnish authorities. At the present time, two variants of the KBS-3 design are being studied: KBS-3V, which envisages the insertion of spent fuel canisters in spaced vertical holes in the floor of the deposition tunnels, and KBS-3H, which envisages spaced horizontal placement of spent fuel canisters along the axis of the deposition tunnels.

KINS (Korea Institute for Nuclear Safety)

Is the nuclear (and hence radioactive waste) regulator in Korea (see http://www.kins.re.kr/en/ for details).

KURT (KAERI Underground Research Tunnel)

Is KAERI's URL (see http://www.kaeri.re.kr:8080/english/sub/sub03_02_01_05.jsp for details).

Low alkali cement

A cement containing very low amounts of NaOH/KOH. Its use is necessary with certain types of aggregate that would otherwise react with high levels of alkali. In the field of radioactive waste disposal, it is of interest as the low NaOH/KOH levels means that any cement leachates will have a lower pH (10–12, depending on the precise cement formulation) than Ordinary Portland Cements (OPC) with initial leachate pH of >13. This means that the low alkali cement leachates are much less likely to chemically degrade other EBS components, especially bentonite.

LLW

Low level radioactive waste (see Table 1 of this paper).

LPG

Liquified petroleum gas.

Ma

Million years (i.e. 1 Ma = 1,000,000 a).

Multiple-barrier concept

See EBS, host rock and host rock barrier function.

MIU

Mizunami underground research laboratory (URL), in central Japan. See http://www.jaea.go.jp/04/tono/miu_e/index.html.

NA (natural analogue)

The generally accepted definition of the term ‘natural analogue’ (Côme and Chapman 1986) is “…an occurrence of materials or processes which resemble those expected in a proposed geological waste repository.” This has subsequently been refined by the addition; “The essence of a natural analogue is the aspect of testing of models—whether conceptual or mathematical—and not a particular attribute of the system itself.” (McKinley 1989). In essence, natural analogue studies use information from the closest possible approximations, or direct analogies, of the long-term behaviour of materials and processes found in, or caused by, a repository to develop and test models utilised in the safety assessment and to otherwise support the safety case in the widest sense. See also http://www.natural-analogues.com.

NDA (Nuclear Decommissioning Authority)

A public body set up by the British Government in April 2005 with responsibility for the UK’s public sector civil nuclear liabilities, and their subsequent management. In October 2006, the Government also gave the NDA the responsibility for developing and ensuring delivery and implementation of the programmes for interim storage and geological disposal of the UK’s HLW. From March 2007, the NDA was also given responsibility for developing a UK wide strategy for managing the UK nuclear industry’s LLW and for securing disposal capacity for LLW generated by non-nuclear industry users and so established NDA-RWMD an acronym for Nuclear Decommissioning Authority, Radioactive Waste Management Directorate). RWMD is now RWM Ltd. See http://www.nda.gov.uk/rwm/what-we-do/ for details.

Nagra

Abbreviation of the name, in German (National Genossenschaft fuer Entsorgung radioaktiver Abfaelle), of the radioactive waste implementer in Switzerland. The official name in English is National Co-operative for the Disposal of Radioactive Wastes (see also http://www.nagra.ch).

Natural nuclear reactors

The uranium ore bodies at Oklo (Republic of Gabon) contain the only known examples of natural fission reactors and are, therefore, unique in nature. Just as in a man-made nuclear power plant, the fission reactors at Oklo generated many waste radionuclides in the form of fission products and actinides, including transuranic nuclides. See Miller et al. (2000) for details.

NEA (Nuclear Energy Agency)

This agency is a specialised institution within the Organisation for Economic Co-operation and Development (OECD), an intergovernmental organisation of industrialised countries based in Paris. The NEA’s mission is to “….assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes.” See http://www.oecd-nea.org for details.

NORM

Acronym for Naturally Occurring Radioactive Material which potentially includes all radioactive elements found in the environment. The term is used more specifically for all naturally occurring radioactive materials where human activities (e.g. uranium mining, fertiliser production) have increased the potential for exposure compared with the untreated, natural material. See http://www.world-nuclear.org/info/Safety-and-Security/Radiation-and-Health/Naturally-Occurring-Radioactive-Materials-NORM/ for details.

OP

Acronym for overpack or waste canister.

OPC

Ordinary Portland Cement.

PHWR (Pressurised heavy water reactor)

Another acronym (along with PWR) for the CANDU reactor design.

Plugs and seals

Materials (e.g. cement, clay, metals) used to close deposition and transport tunnels, shafts and boreholes.

Posiva Oy

Posiva is the expert organisation responsible for the final disposal of spent nuclear fuel of the Finnish reactor owners. See http://www.posiva.fi/en/posiva for details.

Pyroprocessing

Processes (including sintering and ore-roasting) in which materials are subjected to high temperatures (typically over 800 °C) in order to bring about a chemical or physical change.

R&D

Research and Development.

Radiation doses

Radiological consequences to humans (and potentially also other biota) assessed for a repository system. Radiation doses are calculated for various scenarios and are compared to regulatory guidelines and/or complementary indicators. Unit is Sievert (Sv).

Radioactive waste

"Any material that contains or is contaminated by radionuclides at concentrations or radioactivity levels greater than the exempted quantities established by the competent authorities, and for which no use is foreseen." IAEA (1994).

Radiotoxicity

Radiotoxicity is a measure of how noxious a radionuclide is to health. The type and energy of rays, absorption in the organism, residence time in the body, etc. influence the degree of radiotoxicity of a radionuclide (see also http://www.euronuclear.org).

Regulator

Generally refers to the competent authority or authorities with legal responsibility for regulating nuclear safety and environmental protection within a national programme. Typically, these authorities today are either under supervision of a Ministry (such as Health or Environment) which is not overseeing the nuclear industry, or are formed as independent institutions, often reporting to the country's Parliament, Council of Ministers, or even the President. For more details, see NEA (2012).

Repository

A specially designed facility for the geological disposal of radioactive waste.

Rock matrix diffusion

Rock matrix diffusion is the process by which a solute, flowing in distinct fractures in a rock, penetrates the surrounding rock matrix. Diffusion into this matrix occurs in a connected system of pores or microfractures. The importance of matrix diffusion in the context of a radioactive waste repository is that it greatly enlarges the area of rock surface in contact with advecting radionuclides from just the fracture surface to a portion of the bulk rock.

Safety assessment (or SA)

"…systematic assessment of radiation hazards, an integral part of a safety case." (IAEA 2012). The basic objective of a safety review and assessment is to determine whether the operator's submissions demonstrate that a nuclear activity (in this case radioactive waste disposal) complies with the stipulated national and international safety objectives or requirements. See, for example, IAEA (2012) for further discussion.

Safety case

A safety case is a structured argument, supported by evidence, intended to justify that a system is acceptably safe. According to the IAEA (2012), it is "…the collection of scientific, technical, administrative and managerial arguments and evidence in support of the safety of a disposal facility, covering the suitability of the site and the design, construction and operation of the facility, the assessment of radiation risks and assurance of the adequacy and quality of all of the safety related work associated with the disposal facility." A safety case also aims to show that specific safety claims are substantiated. UK Defence Standard 00-56 (4) (http://www.dstan.mod.uk/standards/defstans/00/056/02000400.pdf) states "Such an evidence-based approach can be contrasted with a prescriptive approach to safety certification, which require safety to be justified using a prescribed process. Such standards typically do not explicitly require an explicit argument for safety and instead rest on the assumption that following the prescribed process will generate the required evidence for safety."

Safety function

A safety function is a role by means of which a repository component, such as a barrier, contributes to the long-term safety of the repository.

Scenario

A scenario is an outline or model of an expected or supposed sequence of events. In a radioactive waste disposal safety assessment, in order to analyse how uncertainties in the reference evolution affect the conclusions of the safety assessment, scenarios are defined where alternative evolutions are studied.

Self-analogue

A self-analogue is a case where some feature of a repository site is studied to provide information on long-term repository relevant processes. For example, definition of the likely long-term behaviour of bentonites utilised in the EBS and backfill of a deep geological repository can best be carried out by examining smectite samples from candidate repository sites. Such a self-analogue has several advantages in that the site boundary conditions, including palaeohydrological evolution, are usually much better characterised than most NA sites due to the much greater site characterisation budgets involved. In addition, there is clearly enhanced confidence that the results are directly site relevant, unlike data from areas which do not share the repository site's geological history.

SFR

Acronym of the name, in Swedish, of the final repository for low and intermediate-level operational waste at Forsmark in Sweden, which has been in operation since 1988. In 2014, a licence application to extend the repository was submitted to the Swedish authorities by the operator, SKB.

SKB

Acronym of the name, in Swedish (Svensk Kärnbränslehantering AB), of the radioactive waste implementer in Sweden. The official English name is Swedish Nuclear Fuel and Waste Management Company. See also http://www.skb.se.

Stakeholder

An entity that can be affected by the results of that in which they are said to be stakeholders, i.e. that in which they have a stake. In terms of a national radioactive waste disposal programme, stakeholders may therefore be expected to include a wide spectrum of people and organisations such as members of a community neighbouring a repository, shareholders in electricity producers, members of the national government, etc.

STUK

Acronym of the name, in Finnish (Säteilyturvakeskus), of the nuclear waste regulator in Finland. The official English name is Radiation and Nuclear Safety Authority. See also http://www.stuk.fi/en_GB/.

URL (Underground Rock (or Research) Laboratory)

Tunnel systems where methods (e.g. site characterisation tools, waste emplacement technology) can be developed and tested under repository relevant conditions. See, for example, the Mont Terri facility in the Swiss Jura (http://www.mont-terri.ch/internet/mont-terri/en/homepage.html) and the Grimsel Test Site in the Bernese Alps (http://www.grimsel.com).

Waste acceptance criteria

Quantitative or qualitative criteria specified by the regulatory body, or specified by an operator and approved by the regulatory body, for radioactive waste to be accepted by the operator of a repository for treatment and/or disposal, or by the operator of a storage facility for storage (IAEA 2003). See, for example, European Standard, BS EN 12457-3 (2002)—(http://www.standardsdirect.org/standards/standards5/StandardsCatalogue24_view_9359.html) and, in USA, 49 CFR—http://www.phmsa.dot.gov/…/Files/RAM_Regulations_Review_12-2008.pdf.

WIPP

Acronym for the Waste Isolation Pilot Plant, a pilot repository for US defence-related ILW (see http://www.wipp.energy.gov/index.htm for further details).

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