Swiss J Geosci (2015) 108:111–120
DOI 10.1007/s00015-015-0181-4

Complementary considerations in the safety case for the deep repository at Olkiluoto, Finland: support from natural analogues

Heini M. Reijonen[1] · **W. Russell Alexander**[2] · **Nuria Marcos**[1] · **Anne Lehtinen**[3]

Received: 20 September 2013 / Accepted: 3 March 2015 / Published online: 29 March 2015

Abstract A report entitled "complementary considerations" has recently been published by Posiva, the organization implementing the spent fuel disposal programme in Finland. It is part of the documentation (called TURVA-2012 safety case) submitted in 2012 for the construction license for a deep geological repository at the Olkiluoto site in Finland. The complementary considerations report addresses diverse and less quantifiable types of evidence and arguments for long-term safety which enhance confidence in the outcome of the safety assessment, especially for times greater than a few thousand years. Natural analogues form the core of the "complementary considerations" with the focus very much on geological occurrences of materials and/or processes which mirror those in the repository. For example, native copper is found in fractures in the Fennoscandian Shield and an understanding of its persistence would be of use when assessing the likely lifetime of the copper canister which surrounds the spent fuel. Based on the outcome of this Olkiluoto site specific report, research topics have been identified in relation to processes affecting the performance and future behaviour of the engineered barrier system materials, especially in relation to corrosion of copper and iron (used in waste container outer shell and insert, respectively), alteration and deformation of the bentonite buffer (clay used in the voids between the waste container and bedrock) and interaction with cementitious materials (tunnel supports etc.) "complementary considerations" is not the sole user of natural analogue information within the safety case, but its main aim is to allow thorough discussion and provide background that can be referred to in other safety case documentation, such as process descriptions, assessment of repository performance etc.

Keywords Radioactive waste disposal · Geological analogues · Archaeological analogues · Copper corrosion · Bentonite stability

1 Introduction

Posiva Oy, the company implementing the spent fuel disposal programme in Finland, submitted a construction license application for a geological disposal facility for spent nuclear fuel (Fig. 1) to the Finnish government at the end of 2012. The application is supported by a post-closure safety case assessing the long-term safety of the facility. In addition to a quantitative safety assessment, complementary evaluations of safety, most of a qualitative nature, are of great importance when considering the time scales of up to 1 Ma and beyond in relation to spent nuclear fuel disposal. This is acknowledged both in Finnish national requirements (STUK 2011) and internationally (e.g. NEA

Editorial handling: A. G. Milnes.

This paper is published as part of the special theme: Natural Analogue Research for Deep Disposal of Nuclear Waste.

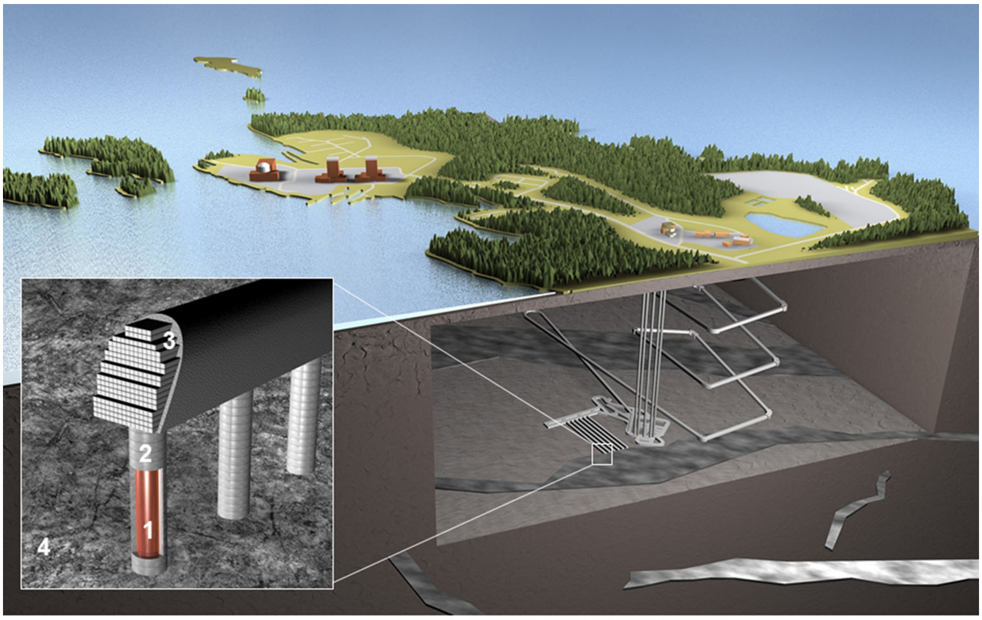
Most of the reports cited in this paper can be downloaded free of charge from the website of the corresponding institution or company. The web addresses can be found after the institution or company entry in Appendix 1 of the introductory review paper (Alexander et al. 2015, this issue).

✉ Heini M. Reijonen
heini.reijonen@sroy.fi

[1] Saanio & Riekkola Oy, Laulukuja 4, 00420 Helsinki, Finland

[2] Bedrock Geosciences, Auenstein, Switzerland

[3] Posiva Oy, Eurajoki, Finland



1. copper canister 2. buffer (clay) 3. deposition tunnel backfill (clay) 4. bedrock

Fig. 1 KBS-3 V Repository overview at Olkiluoto, Finland, showing access tunnel and shafts to the repository level and a close-up index figure of the backfilled deposition tunnel and vertical deposition holes containing copper-iron canister surrounded by bentonite buffer (Figure courtesy of Posiva Oy). See also Alexander and Milodowski (2014)

2009a). NEA (2004, 2009b) describes what we call "complementary considerations" as evaluations, evidence and qualitative supporting arguments that lie outside the scope of the quantitative parts of the safety case.

To meet these requirements, the complementary considerations report (CC) was produced (Posiva 2012a) as part of the safety case for the Olkiluoto site in Finland. The CC report addresses diverse and less quantifiable types of evidence and arguments made to enhance confidence in the outcome of the safety assessment and to demonstrate repository safety at times greater than a few thousand years. This is something which is not possible using only the 'standard' indicators of radiological dose or risk. In addition to the above information, CC report attempts to greatly broaden the range of data used to support the construction license application. The CC report describes also the hazard presented by the waste using alternative safety indicators and gives background for putting the safety assessment results in perspective using complementary indicators.

In this article, the overall approach taken is described and discussed with emphasis on the utilization of natural analogue (NA) information. Further, novel studies are proposed to strengthen the safety case in the future. This work is focussed on Posiva's safety case but, for the most part, covers a topic common to all spent fuel repositories. A glossary of terms and abbreviations used in this Special Issue is appended to the introductory review paper (Alexander et al. 2015, Appendix 1).

2 Posiva's safety case

Posiva's safety case 'TURVA-2012' is composed of a portfolio of reports, which includes the CC report (Fig. 2). Its essence is to synthesize evidence, analyses and arguments that quantify and substantiate the safety, and the level of expert confidence in the safety, of a geological disposal facility for radioactive waste (IAEA 2006, 2011; NEA 2004). The repository system components, i.e. engineered barrier system (EBS) and the underground openings of the host rock, are selected and designed according to the requirements specified in the design basis (Posiva 2012b). The most relevant features, events and processes (FEPs) are then taken into account in analysing the performance of the system during its evolution, in formulating scenarios, and in analysing those scenarios to obtain the end knowledge on the likely radiological impact (in terms of radiation doses and radioactivity fluxes) of the repository on the biosphere. CC report complements the understanding of the performance of the disposal system, including its components and their interrelationships, in the long term. It also presents data that help to put the results of radiological impact analyses into a broader perspective for access to the non-specialists and general public. In fact, parallel application of the CC report to the safety assessment is required by STUK, the Finnish regulator, in order to enhance confidence in the results of the entire analysis or certain aspects of it (STUK 2011). Similar complementary assessments are a feature of many national radioactive waste disposal programmes.

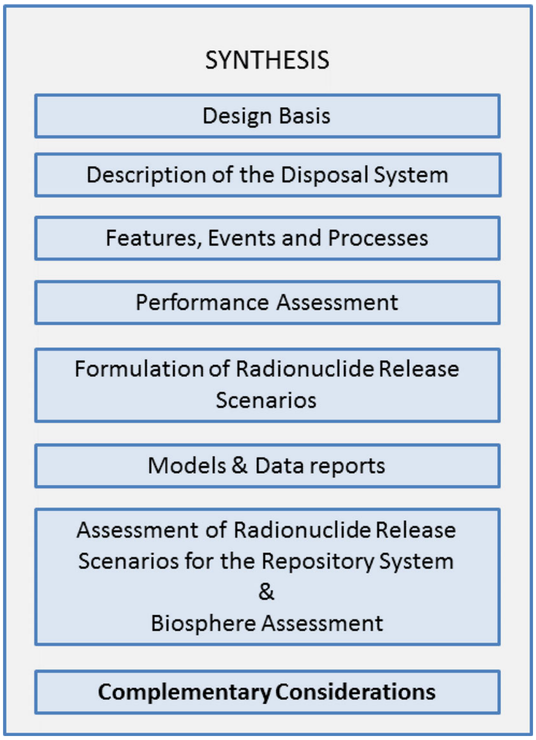


Fig. 2 Simplified illustration of the TURVA-2012 safety case portfolio; modified from Posiva (2012a) (Figs. 1–2)

3 Complementary considerations

The current CC report (Posiva 2012a), and the whole safety case (see Posiva 2012c for synthesis), focus on post-closure safety. The operational phase is accounted for by perturbations that can have long-term impact on the system. In CC report, an overview of NAs is presented against their suitability/relevance to the Olkiluoto site and the KBS-3 V repository design concept (see Appendix C in Posiva 2012a).

Feedback received from STUK for the previous Complementary Evaluations Report (Neall et al. 2007), a part of the safety assessment produced for a KBS-3H repository design concept at Olkiluoto, were also taken into account when setting up the contents of the CC report (Posiva 2012a is considered to be generally valid for both horizontal, KBS-3H, and vertical, KBS-3 V, designs). Many aspects, such as providing simplified bounding calculation cases and utilizing the site information, are covered in other reports, such as performance assessment (Posiva 2013a) and site description (Posiva 2012d). Thus the main content of CC report focusses on showing supporting arguments for the geological stability of the site, the robustness of the EBS system and process understanding via NAs.

4 Natural analogues supporting the safety case

The use of a few simple, naturally occurring materials in the EBS help to improve confidence in predicting long-term safety in both repository designs. The EBS in the KBS-3 V design consists of a copper canister (with a cast iron insert), bentonite buffer, swelling clay based backfill and closure components, and to some extent “foreign materials” (e.g. cementitious grout, rock bolts, etc.). Foreign materials denotes materials that are incorporated in the repository system during operation and installation of the EBS. These materials are not necessarily part of the EBS design as such. By assessing the foreign material inventory, the aim is to provide data on the materials left in the repository after closure due to operation and construction allowing them to be taken into account within the safety case. CC report summarises a summary of the current status of the EBS-related NA studies and presents supporting arguments available in the current literature. In addition, NA studies are also used to enhance the understanding of the site suitability and the consequences of potential impacts on Olkiluoto by external processes, such as conditions during future glaciations. In the CC report (Posiva 2012a), current understanding and available NA studies have been considered for climate driven processes including permafrost and dilute meltwater intrusion, denudation, meteorite impact and the effect of earthquakes. Process understanding is largely based on knowledge of local and regional geological history, which helps to understand the complexities of the system and provides realistic estimates for the system performance.

4.1 Qualitative and quantitative support for the safety case—a few examples

Metallic copper is the main material to be used in the canister in the EBS for containment and isolation of spent fuel. The main concern for the long-term durability of metallic copper in fractured crystalline bedrock is corrosion. Sulphide-induced corrosion is the main corrosion mode that has for long been considered as the major threat for copper canisters under repository conditions and is handled in performance assessment by means of modelling (Posiva 2013a). Recently, pure anoxic water-induced corrosion has also received much attention (e.g. Hultqvist et al. 2008; Szakálos et al. 2007). In previous safety assessments (e.g. Vieno and Nordman 1999), copper corrosion in the Finnish bedrock was addressed by examination of the 1.7–1.8 Ga Hyrkkölä copper mineralisation in south-western Finland. A special feature of the Hyrkkölä mineralisation is the occurrence of copper as native metal (Fig. 3). Mineral assemblages of native copper–copper

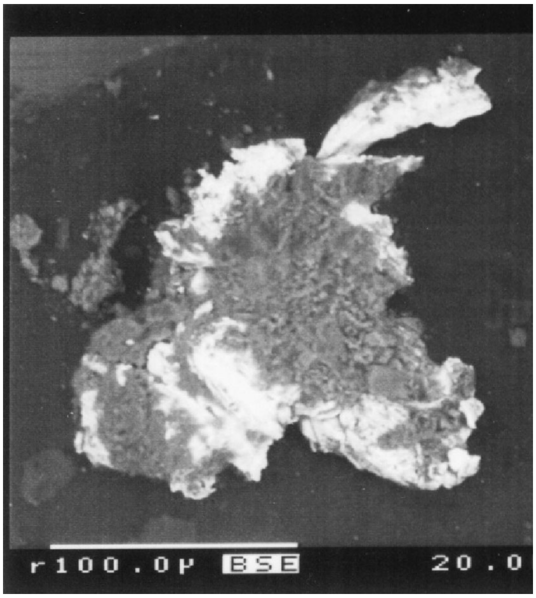


Fig. 3 Metallic copper grain (*light grey*) embedded in smectite (*medium grey*) from a water-conducting fracture at about 80 m depth (Marcos 2002)

sulphide and native copper–copper oxide occur at depths between 10 and 100 m. Mineralogical and geochemical investigations (Marcos 1996; Marcos et al. 1999) have shown that native copper has been/is in contact with evolving groundwaters (or different groundwater types) during extended time periods since it precipitated within the granite pegmatites (Fig. 4).

In the CC report, a broad range of additional studies was addressed in order to support the safety case, especially in performance assessment (Posiva 2013a), noting that elemental (or 'native') copper has persisted for millions of years in a range of geological environments such as (Marcos 1989):

- In sedimentary rocks: Keweenaw Peninsula, Lake Superior region, Michigan, U.S.; Corocoro, Bolivia; South Devon, United Kingdom;
- In basaltic lavas: Keweenaw Peninsula, Appalachian States from central Virginia to southern Pennsylvania, U.S.; Coppermine River area, NWT, Canada; Dalane, Norway;
- In granitic rocks: Hyrkkölä (Figs. 3, 4) and Askola, Finland;
- In the oxidised zones of sulphide deposits (many places in the world, including Finland, Chile, Japan etc.).

Further, a wide body of archaeological data was also provided (Table 1) and compared with the Japanese H12 and H17 safety assessments (JNC 2000 and 2005, respectively) where corrosion data from archaeological analogues were used to increase confidence in the data produced in short-term laboratory corrosion tests for copper canisters.

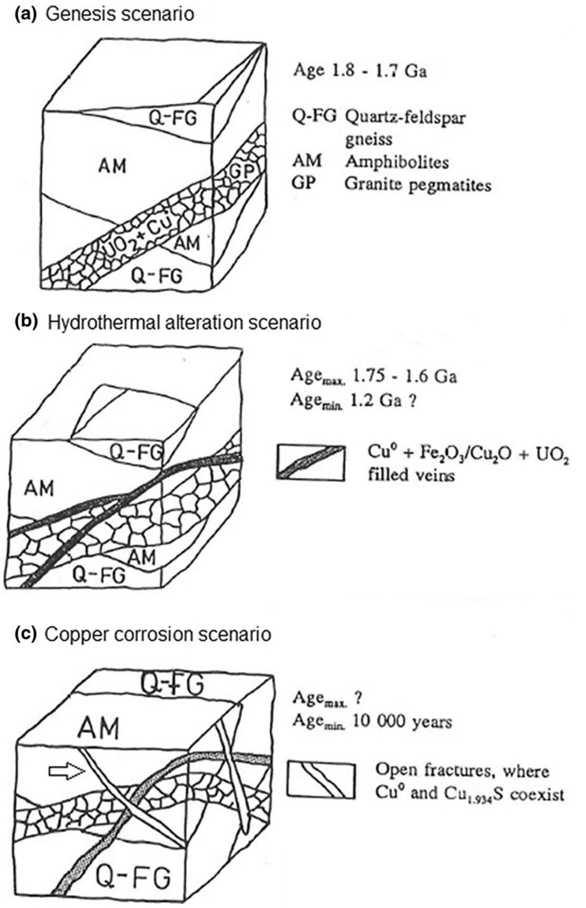


Fig. 4 Simplified representation of the evolution of the Hyrkkölä mineralization, which has been used as a natural analogue for indicating the rate of corrosion of copper canister in groundwater over a very long period of time (thousands of years; modified after Marcos 1996, Fig. 8). **a** The original bedrock consisting of quartzo-felspathic gneisses, amphibolites and granite pegmatites, ages of formation 1800–1700 million years. **b** The period of hydrothermal mineralization, age 1750–1200 million years, in which the cross-cutting veins filled with native copper (Cu^o), hematite and uraninite were formed. **c** The period in which uplift/erosion brought this part up into the zone of circulating groundwater and the formation of open fractures, at the latest 10,000 years ago (possibly long before). The native copper/smectite association (open fracture indicated with an *arrow*) shown in Fig. 3 represents this period. The copper corrosion data in Marcos (1996) represents this period in the evolution

In this case, CC report noted that both the archaeological and natural analogue studies argue that the corrosion rates for copper assumed in the safety assessment significantly over-estimate observed rates (and this is generally supported by the few long-term laboratory experimental data that are available, e.g. Smailos et al. 2004). This is especially the case when it is considered that the majority of materials studied to date have come from environments that are likely to have been more oxidising (e.g. flood plain soil, river beds–see Table 1) than is expected in the repository near field.

Table 1 Comparison of copper corrosion depths cited in the safety assessment H12 (JNC 2000) with existing and new archaeological analogue data for copper/bronze artefacts

Form of data	Corrosion depth (per 1000a)	References	Comments
Short-term lab	13 mm	JNC (2000)	Uniform corrosion of copper
Archaeological analogue	<3 mm	Range of studies cited in JNC (2000)	Uniform corrosion of copper and bronze
Archaeological analogue	0.26–39 mm	Bresle et al. (1983)	Pitting corrosion of copper
Archaeological analogue	0.025–1.27 mm	Tylecote (1979), Johnson and Francis (1980)	Uniform corrosion of mixed artefacts
Archaeological analogue	0.15 mm	Hallberg et al. (1987)	Kronan cannon
Archaeological analogue	0.13–1.13 mm	Appendix A in IAEA (2005)	Bronze artefacts from a river
Archaeological analogue	<0.27 mm	Appendix B in IAEA (2005)	Bronze artefacts in soils
Archaeological analogue	0.4–1.2 mm	Appendix D in IAEA (2005)	Copper artefacts in flood plain soil
Archaeological analogue	0.01–1.91 mm	Appendix D in IAEA (2005)	Bronze artefacts in flood plain soil

Looking at the role of CC report in broadening the perspective further, the process of dilute water intrusion and the chemical erosion of bentonite buffer are worth-noting. The scenarios based on the possibility of the intrusion of dilute oxygenated water of glacial origin, proposed to affect fractured host rocks at repository-relevant depths (e.g. Boulton et al. 1993), have been thoroughly assessed in Posiva's safety case, even if the process of meltwater intrusion may be over-simplified (cf. Jansson 2010). Processes suggested to occur via dilute water intrusions include chemical erosion of bentonite (e.g. Neretnieks et al. 2009) and a loss of chemical buffering capacity (in particular, that of buffering oxidants in the water) of fracture gouge minerals (cf. Banwart et al. 1994). The CC report provides background data to show that NA studies undertaken at crystalline sites in Finland have provided valuable information on the limited extent of glacially induced intrusion of oxidising waters. These indicate it is likely that the >400 m of rock between the biosphere and the repository will most certainly buffer the redox system in any originally oxidised dilute waters, removing all oxidants before they reach the bentonite and canisters at repository depth. Indeed, the thin soil layers lying on the Fennoscandian Shield are often enough to significantly buffer the redox state of any dilute waters before they even penetrate the host rock itself.

It was also pointed out that chemical erosion of bentonite is not a process generally observed in nature as it is limited by the impurities in the bentonite. Although not yet studied in detail, several sites exist that would allow this to be defined more precisely. For example, it is generally known that within glaciated terrains, bentonite deposits have survived without erosion and that smectite dissolution in dilute groundwater conditions is not currently considered as a significant process in soil science (e.g. Puura and Kirsimäe 2011). Potential targets for future NA studies in relation to chemical erosion of bentonite could include:

- Weathering/erosion profiles of bentonite deposits (e.g. Puura and Kirsimäe 2011), this could include detailed investigations on the effects of the accessory minerals and their dissolution on the exchangeable ion composition.
- Fracture gouge montmorillonite stability (Arthur and Savage 2012; and Reijonen and Alexander 2015, this issue), to better estimate the resulting exchangeable cation composition and mode of occurrence of montmorillonite on site.

In addition, the CC report contributes further discussion related to the regional understanding of the hydrogeochemistry of coastal sites, supporting the site understanding (Posiva 2012d), which all point in the direction of limited dilution of the groundwater during glacial water infiltration at relevant depths (see also discussion in Milodowski et al. 2005; Smellie et al. 2008; Amano et al. 2011).

4.2 The value of case-specific review of NAs and future outlook

The NA data available and their relevance to Posiva's current safety case have been evaluated in CC report in relation to EBS and radionuclide migration (Appendix C in Posiva 2012a). These data are now extended here to include a look ahead at the possibilities of attaining additional safety case-relevant NA data (Table 2), including cross references to reviews to be published in this issue of the SJG. In addition to this, opportunities to increase process understanding via NAs remain. For example, based on currently available information, there are possibilities to extend the overall understanding of the subglacial hydraulic pressure driving the groundwater flow and on understanding groundwater mixing and penetration behaviour from studies on currently glaciated terrains (e.g. from the Greenland Analogue Project, Harper et al. 2012) as well as from investigation of fracture gouge minerals in relation to bentonite buffer stability under changing groundwater conditions (Reijonen and Alexander 2015, this issue).

5 Discussion and conclusions

Benefits for safety case development flow from a review of this nature as it allows presentation of complementary information that support other parts of the safety case in a well-structured manner; additionally, gaps in the NA database can be illuminated, identifying possible needs for further research (see examples in Table 2).

It should be noted that the CC report has not been the sole user of NA data within the TURVA-2012 safety case; the information serves also for FEP descriptions (Posiva 2012e), performance assessment (Posiva 2013a), and assessment of the radionuclide release and transport through the repository EBS and geosphere (Posiva 2013b).

In addition, the benefits of the use of complementary considerations in stakeholder communication should be considered, since the same source of data (i.e. Posiva 2012a), relevant and case specific examples are used to explain both the technicalities (e.g. West et al. 2002) and advantages (e.g. McCombie 1997) of geological disposal of radioactive waste to the public.

With respect to the CC report itself, it is focused specifically on presenting support for the Swedish disposal concept KBS-3, and for the suitability of geological disposal of spent nuclear fuel at the Olkiluoto site using this

Table 2 Case-specific analogues for EBS containment and radionuclide retardation in the far-field reviewed for KBS-3 V repository planned to be constructed at Olkiluoto, Finland: current status (mainly based on Posiva 2012a, Appendix C) and recommendations for future work

NAs for:	FEP	Current status—case specific	Future outlook
Fuel	Criticality	Few relevant studies have been carried out	It is unlikely that an appropriate NA other than Oklo exists, so no further studies necessary unless criticality could weaken the safety case
	Radiolysis	Data available from several ore bodies implying that radiolytic change will be minimal. But not enough information on fluxes of oxidants at natural analogue sites is known to allow a direct comparison with the likely situation in and around a SF canister	No further studies necessary unless a more appropriate site can be shown to exist. Best characterised site, Cigar Lake, has now been heavily disturbed by mining
	SF corrosion	Numerous NA studies available. Dissolution rates cannot be quantified readily from natural analogue data, but abundance of naturally occurring uraninite may be taken as a general indication of its stability in the geological environment. Extrapolation of this apparent longevity to spent nuclear fuel should be done cautiously, due to differing boundary conditions	No further studies necessary unless a more appropriate site can be shown to exist (see also McKinley et al. 2015, this issue)
Canister	Cu-corrosion	Numerous studies available, including studies of localised corrosion of copper, such as Kronan (quantitative; Hallberg et al. 1987; King 1995), Littlehampton (qualitative; Milodowski et al. 2002) and rare pitting studies	Additional studies would be useful to support the understanding of localised corrosion in safety assessment. Laboratory copper pitting studies suggest that that the assumed pitting factors in safety assessment are conservative, although arguably additional NA studies in this area would strengthen these arguments
Buffer	Fe-corrosion	Wide range of studies providing quantitative and qualitative data which support the conservative assumptions in safety assessment exists. No pitting data are available. Best examples of use are in the Kristallin-1 and H12 safety assessments	Studies would be very useful to support safety assessment treatment of localised corrosion (see also Posiva 2012a)
	Thermal alteration/ cementation	Generally, the vast majority of the natural analogue data available is of little value as the environments studied have little relevance to repository conditions	Return to more relevant sites (e.g. Busachi) and apply a range of more relevant analytical techniques to better understand the site history and temperature profiles. Only then should the site be re-sampled and standard clay analyses carried out. For detailed discussion, see Reijonen and Alexander (2015, this issue)

Table 2 continued

NAs for:	FEP	Current status—case specific	Future outlook
	Freezing/thawing	Only general considerations are available	Some deposits quarried are prone to seasonal freeze/thaw cycles and are located in areas of current or palaeo permafrost. Additional information is possible to seek if required (see also Reijonen and Alexander 2015, this issue)
	Canister sinking	N/a	The approach of Keto (1999), focussing on deformation of natural bentonites, should be repeated plus the process should be included into current URL experiments (e.g. FEBEX). See also comments in Reijonen and Alexander (2015, this issue). Recently, new sites have been identified in Cyprus
	Chemical alteration–saline	Various sites have been studied but no full characterisation of 'reacted' samples have been published	Find an appropriate site and carry out a more rigorous analysis of all relevant parameters. For detailed discussion, see Reijonen and Alexander (2015, this issue)
	Interactions with copper	Qualitative data is available from Kronan cannon	Data could be more rigorously integrated with existing/new laboratory data
	Interaction with iron	No relevant data available	Existing natural analogue are not relevant enough, although general observations from natural systems and the near-field processes URL experiment suggest uptake of iron could reduce swelling pressures. These data need to be integrated with a more appropriate natural analogue study. Possibility exists in the Philippines bentonite study; see Fujii et al. (2010)
	Interaction with cement	Qualitative data available from Khushaym Matruk	Needs study of samples from outwith the thermally altered zone. Important to do this as it is the only OPC analogy available (see also comments in Jackson et al. 2014)
		Quantitative data available from Cyprus	Preliminary results strongly suggests minimal reaction of bentonite in low alkali cement leachates (see also Alexander and Milodowski (2014)
		Qualitative data available from Philippines	Generally supports Cyprus data, but closer study of potential reaction zones is necessary (see also Fujii et al. 2010)
		Qualitative data available from Searles Lake	Conditions are far from repository-relevant, but results fully consistent with Cyprus and Philippines. Different reaction pathways when compared to Cyprus may be a reflection of the open nature of the system
	Chemical erosion	NA studies not available	Potential exists in the montmorillonite fracture gouges at certain sites (e.g. Forsmark and Olkiluoto). No detailed review has been conducted on the stability of montmorillonite at Olkiluoto. The controls of the mineralogical parageneses and groundwater circulation should be well described in order to assess stability. Paleohydrogeological data could then be utilised to address also dilute conditions at relevant depths. See Reijonen and Alexander (Reijonen and Alexander 2015, this issue) for detailed discussion. See also Puura and Kirsimäe (2011)
Foreign materials	Cements–longevity of OPC	NA data available from Jordan (quantitative) and Scawt Hill (qualitative)	Some very old natural cements, but survival may be dependent on isolation from groundwater (e.g. due to low permeability of the material). This requires further assessment
	Cements–longevity of low-alkali cements	Mainly archaeological analogues available, generally restricted to shorter timescales (2–5 ka), e.g. Roman cements (qualitative)	Archaeological cements not usually from environments relevant to a deep geological repository, but worth re-analysing as analogues of modern low alkali cements. New NA site has been recently identified in the Naples region, Italy, and should be investigated
	Cement-host rock interaction	NA studies available from Jordan for OPC (quantitative) as well as Cyprus and Philippines for low alkali systems, but both currently qualitative (see also Jackson et al. 2014)	Focussed analysis of the potential impact on the Olkiluoto site would be worthwhile when more data on the site hydrogeology are available (cf. discussion in Alexander and Neall 2007). Low alkali cement leachate/host rock interaction sites available for study if this was felt necessary

Table 2 continued

NAs for:	FEP	Current status—case specific	Future outlook
	Cement carbonation	N/a	Ignoring carbonation in safety assessment may be over-conservative, a short scoping study would be worthwhile to assess if additional natural analogue data are required
Silica Sol longevity	No identified NAs	Potential site has not been selected so far	
Radionuclide retardation in the geosphere	Retardation in clays	Numerous NAs available worldwide, several associated with URL projects. Quantitative data on long-term diffusion processes in clay formations and some are on a scale representative of the clay buffer in the engineered barrier system	No further studies are required for most radionuclides. But the case of high pH leachate alteration of clay CEC may impact certain radionuclides (see also Alexander and Milodowski 2014)
	Retardation in fractured crystalline rocks	Very few, directly relevant natural analogue studies available. Quantitative data exists for matrix diffusion, but qualitative for other retardation processes	Very difficult to find appropriate sites, perhaps better dealt with in URLs (but note caveats on use of data; see also Alexander et al. 2003)
	Matrix diffusion	One of the most thoroughly studied aspects of retardation in fractured rocks. Clear long-term, long-distance quantitative information available	No further generic studies are required, but a small, site specific study would be useful for Olkiluoto
	Redox fronts	Numerous NA studies worldwide, but very few, directly relevant natural analogue studies available	A focussed study in an appropriate environment would be very useful, but no further qualitative studies are required for Olkiluoto. Useful for steel canister designs (see also McKinley et al. 2015, this issue)
	Colloids	One of the most thoroughly studied aspects of retardation in fractured rocks, but one of the least understood	No more work is necessary until convincing sampling methods are developed (see Alexander et al. 2011)

FEBEX full scale engineered barriers experiment at Grimsel, Switzerland, *OPC* ordinary portland cement, *CEC* cation exchange capacity, *URL* underground rock laboratory

concept. While it is emphasized that CC report should be focussed on a specific site and in a case-specific manner, the overall approach is also sound for any other repository design(s) and site(s). The contents of the CC report were defined, in addition to satisfying the national regulations, to reflect the overall contents of the current Finnish safety case. However, the contents of similar future documents can be modified and extended into some areas that are not currently discussed in detail in Posiva (2012a). These may include, depending on the structure of the overall safety case:

- Consideration of operational safety (see also Alexander et al. 2015, this issue)
- Additional discussion on “operational analogues”, including use of URL monitoring data
- Regional considerations in relation to site stability, a topic that would serve especially well at the siting phase of the disposal programme
- Site selection process in detail, and,
- Additional discussions on process understanding (i.e. FEP descriptions) and screening of FEPs (c.f. Alexander and Neall 2007).

The approach taken in the CC report allows more thorough and broader discussion on the NAs supporting the safety case than is possible to include elsewhere, for example in performance assessment documentation. However, the authors would contend that this additional discussion is needed to build confidence in the outcome of performance assessment (Posiva 2013a) as well as in the outcome from the analysis of radionuclide release scenarios (Posiva 2013b, c). The gaps identified regarding NA studies on EBS processes and radionuclide migration (see Table 2) have, for the major part, already been taken forward by the scientific community. Adopting the CC report’s approach allows broader consideration of the complementary information relevant to the safety case, while not limiting the use of such considerations in other parts of the safety case.

References

Alexander, W.R., Berry, J.A., Kelly, M.J., Swanton, S. (2011). Review of colloids in the geosphere and their treatment in performance assessment. *Report to NDA-RWMD, Serco/TAS/002924/01*. Serco, Didcot.

Alexander, W.R., & Milodowski, A.E. (Eds.) (2014). Cyprus Natural Analogue Project (CNAP) Phase IV Final Report. *Posiva Working Report 2014-02*. Posiva Oy, Eurajoki.

Alexander, W.R., & Neall, F.B. (2007). Assessment of potential perturbations to Posiva’s SF repository at Olkiluoto caused by construction and operation of the ONKALO facility. *Working Report 2007-35*. Posiva Oy, Olkiluoto.

Alexander, W.R., Reijonen, H.M., McKinley, I.G. (2015). Current status of natural analogue studies. *Swiss Journal of Geosciences Spec. Publ. Proc 13th NAWG Workshop,* Nagoya, May, 2013 (in prep.).

Alexander, W. R., Smith, P. A., & McKinley, I. G. (2003). Modelling radionuclide transport in the geological environment: a case study from the field of radioactive waste disposal. In E. M. Scott (Ed.), *Modelling radioactivity in the environment* (pp. 109–145). Amsterdam: Elsevier.

Amano, K., Niizato, T., Yokota, H., Ota, K., Lanyon, B., Alexander, W.R. (2011). Development of comprehensive techniques for coastal site characterisation: integrated palaeohydrogeological approach for development of site evolution models. In Proc. ICEM 2011 Conference, Reims, France, September, 2011. ASME, Washington.

Arthur, R., & Savage, D. (2012). Equilibrium constraints on buffer erosion based on the chemistry and chemical evolution of glacial meltwaters. In Proc. of 5th International meeting on clays in natural and engineered barriers for radioactive waste confinement. 22–25 October, 2012, Montpellier.

Banwart, S., Gustafsson, E., Laaksoharju, M., Nilsson, A.-C., Tullborg, E.-L., & Wallin, B. (1994). Large-scale intrusion of shallow water into a vertical fracture zone in crystalline bedrock: Initial hydrochemical perturbation during tunnel construction at the Äspö Hard Rock Laboratory, southeastern Sweden. *Water Resources Research, 30*(6), 1747–1763.

Boulton, G. S., Slot, T., Blessing, K., Glasbergen, P., Leijnse, T., & van Gijssel, K. (1993). Deep circulation of groundwater in overpressured subglacial aquifers and its geological consequences. *Quaternary Science Reviews, 12*(9), 739–745.

Bresle, A., Saers, J., Arrhenius, B. (1983). Studies in pitting corrosion on archaeological bronzes. *Technical Report TR 83-05*. SKB, Stockholm.

Fujii, N., Arcilla, C.A., Yamakawa, M., Pascau, C., Namiki, K., Sato, T., Shikazono, N., Alexander, W.R. (2010). Natural analogue studies of bentonite reaction under hyperalkaline conditions: overview of ongoing work at the Zambales Ophiolite, Philippines. *Proc. ICEM 2010 Conference*. ASME, Washington.

Hallberg, R.O., Östlund, P., Wadsten, T. (1987). A 17th century cannon as analogue for radioactive waste disposal. In Côme, B. & Chapman, N.A. (Eds.). Natural analogues in radioactive waste disposal. *Radioactive Waste Management Series, EUR 11037*, 135-139. Luxembourg: Commission of the European Communities.

Harper, J., Hubbard, A., Ruskeeniemi, T., Claesson Liljedahl, L., Lehtinen, A., Booth, A., Brinkerhoff, D., Drake, H., Dow, C., Doyle, S., Engström, J., Fitzpatrik, A., Frape, S., Henkemans, E., Humphrey, N., Johnson, J., Jones, G., Joughin, I., Klint, K. E., Kukkonen, I., Kulessa, B., Landowski, C., Lindbäck, K., Makahnouk, M., Meierbachtol, T., Pere, T., Pedersen, K., Petterson, R., Pimentel, S., Quincey, D., Tullborg, E.-L., van As, D. (2012). The Greenland Analogue Project Yearly Report 2010, *Working report 2012-16.* Posiva Oy, Eurajoki.

Hultquist, G., Szakálos, P., Graham, M.J., Sproule, G.I., Wikmark, G. (2008). Detection of hydrogen in corrosion of copper in pure water. In *17th International Corrosion Conference 2008, Proceedings, Paper No. 3884.* Las Vegas, USA: ICC 2008. p. 9.

IAEA (2005). Anthropogenic analogues for geological disposal of high level and long lived waste. Final report of a coordinated research project 1999–2004. *IAEA-TECDOC-1481.* IAEA, Vienna.

IAEA (2006). Fundamental Safety Principles. *IAEA Safety Standards Series No. SF-1*. IAEA, Vienna.

IAEA (2011). Disposal of radioactive waste. *Specific Safety Requirements SSR-5*. IAEA, Vienna.

Jackson, C.P., Jefferies, N.L., Alexander, R., Smith, J., Frieg, B., Gauss, I., Vomvotis, S., Metcalfe, R., Marsden, R. (2014). Sealing site investigation boreholes. Phase 1 report. *AMEC Report to NDA-RWMD (RWMD/03/042).* AMEC, Harwell.

Jansson, P. (2010). Ice sheet hydrology from observations. *Technical Report TR-10-68*. SKB, Stockholm.

JNC (2000). H12: Second progress report on R&D for the geological disposal of HLW in Japan. *JNC TN1410 2000-001*. JAEA, Tokai.

JNC (2005). H17: Development and management of the technical knowledge base for the geological disposal of HLW–knowledge management report. *JNC TN1400 2005-022*. JAEA, Tokai.

Johnson, A. B., & Francis, B. (1980). Durability of metals from archaeological objects, metal meteorites and native metals. *Battelle Pacific Northwest Laboratory, PNL-3198*. PNL, Washington State.

Keto, P. (1999). Bentonite deposits as a natural analogue to long-term barriers in a final repository of nuclear waste. *Research Report TKK-IGE-A-24*. Engineering Geology and Geophysics Laboratory, Helsinki University of Technology, Helsinki.

King, F. (1995). A natural analogue for the long-term corrosion of copper nuclear waste containers—reanalysis of a study of a bronze cannon. *Applied Geochemistry, 10*, 477–487.

Marcos, N. (1989). Native copper as a natural analogue for copper canisters. *Report YTJ-89-18*. Nuclear Waste Commission of Finnish Power Companies, Helsinki.

Marcos, N. (1996). The Hyrkkola native copper mineralization as a natural analogue for copper canisters. *POSIVA Report 96-15*. Posiva Oy, Helsinki.

Marcos, N. (2002). Lessons from nature—the behaviour of technical and natural barriers in the geological disposal of spent nuclear fuel. *Acta Polytechnica Scandinavica, Espoo, Civil Engineering and Building Construction Series No 124*. Espoo.

Marcos, N., Ahonen, L., Bros, R., Roos, P., Suksi, J., & Oversby, V. (1999). New data on the Hyrkkölä native copper mineralization: a natural analogue for the long-term corrosion of copper canisters. *Materials Research Society Symposium Proceedings, 556*, 825–832.

McCombie, C. (1997). In the eye of the beholder: different perceptions of the problems of waste disposal. In Which is more stable: a rock formation or a social structure? *Bulletin, 30 (15-23).* Nagra, Wettingen.

McKinley, I.G., Kawamura, H., Hardie, S.M.L., Klein, E., Beattie, T. (2015). Key NA input to build a safety case for direct disposal of SF in Japan. *Swiss Journal of Geosciences Special Publication.* In Proceedings of 13th NAWG Workshop, Nagoya, May 2013 (submitted).

Milodowski, A.E., Styles, M.T., Horstwood, M.S.A., Kemp, S.J. (2002). Alteration of uraniferous and native copper concretions in the Permian mudrocks of south Devon, United Kingdom. *SKB Technical Report, TR-02-09*. SKB, Stockholm.

Milodowski, A.E., Tullborg, E-L., Buil, B., Gómez, P., Turrero, M-J., Haszeldine, S., England, G., Gillespie, M.R., Torres, T., Ortiz, J.E., Zachariáš, J., Silar, J., Chvátal, M., Strnad, L., Šebek, O., Bouch, J.E., Chenery, S.R., Chenery, C., Shepherd, T.J. & McKervey, J.A. (2005). Application of mineralogical, petrological and geochemical tools for evaluating the palaeohydrogeological evolution of the PADAMOT study sites. *PADAMOT Project Technical Report WP2*. p. 228 EU 5th Framework Contract Number FIKW-CT-2001-00129, EU, Luxembourg.

NEA (2004). Post-closure safety cases for geological repositories. Nature and purpose. *OECD/NEA report 3679*. Paris.

NEA (2009a). Considering timescales in the post-closure safety of geological disposal of radioactive waste. *OECD/NEA report 6424*. Paris.

NEA (2009b). International experiences in safety cases for geological repositories (INTESC). Outcomes of the INTESC project. *OECD/NEA report 6251*. Paris.

Neall, F., Pastina, B., Smith, P., Gribi, P., Snellman, M., Johnson, L. (2007). Safety assessment for a KBS-3H spent nuclear fuel repository at Olkiluoto—complementary evaluations of safety. *POSIVA report 2007-10*. Posiva Oy, Eurajoki.

Neretnieks, I., Liu, L., Moreno, L. (2009). Mechanisms and models for bentonite erosion. *SKB Technical report TR-09-35*. SKB, Stockholm.

Posiva (2012a). Safety case for the disposal of spent nuclear fuel at Olkiluoto–complementary considerations, 2012. *POSIVA report 2012-11.* Posiva Oy, Eurajoki.

Posiva (2012b). Safety case for the disposal of spent nuclear fuel at Olkiluoto—design basis, 2012. *POSIVA report 2012-03,* Posiva Oy, Eurajoki.

Posiva (2012c). Safety case for the disposal of spent nuclear fuel at Olkiluoto—synthesis, 2012. *POSIVA report 2012-12*. Posiva Oy, Eurajoki.

Posiva (2012d). Olkiluoto site description, 2011. *POSIVA report 2011-02.* Posiva Oy, Eurajoki.

Posiva (2012e). Safety case for the disposal of spent nuclear fuel at Olkiluoto—features, events and processes, 2012. *POSIVA report 2012-07.* Posiva Oy, Eurajoki.

Posiva (2013a). Safety case for the disposal of spent nuclear fuel at Olkiluoto—performance assessment 2012. *POSIVA report 2012-04.* Posiva Oy, Eurajoki.

Posiva (2013b). Safety case for the disposal of spent nuclear fuel at Olkiluoto—assessment of radionuclide release scenarios for the repository system 2012. *POSIVA report 2012-09.* Posiva Oy, Eurajoki.

Posiva (2013c). Safety case for the disposal of spent nuclear fuel at Olkiluoto—biosphere assessment BSA-2012. *POSIVA report 2012-10*. Posiva Oy, Eurajoki.

Puura, E., & Kirsimäe, K. (2011). Impact of the changes in the chemical composition of pore water on chemical and physical stability of natural clays. A review of natural cases and related laboratory experiments and the ideas on natural analogues for bentonite erosion/non-erosion. *SKB Technical report, TR-10-24*. SKB, Stockholm.

Reijonen, H.M., & Alexander W.R. (2015). Bentonite analogue research related to geological disposal of radioactive waste: current status and future outlook. *Swiss Journal of Geosciences, 108*. doi:10.1007/s00015-015-0185-0.

Smailos, E., Cuñado, M.Á., Kurste, B., Azkarate, I., Marx, G. (2004). Long-term performance of candidate materials for HLW/SF disposal containers: final report. *EC Report. Contract No. FIKW-CT-2000-00004*. Luxembourg: European Commission.

Smellie, J.A.T., Tullborg, E-L., Nilsson, A-C., Sandström, B., Waber, H.N., Gimeno, M. Gascoyne, M. (2008). Explorative analysis of major components and isotopes. SDM-Site Forsmark. *SKB Report, R-08-84*. SKB, Stockholm.

STUK (2011). *YVL Guide D.5*. Helsinki (unpublished, available at https://ohjeisto.stuk.fi/YVL/D.5e.pdf).

Szakálos, P., Hultquist, G., & Wikmark, G. (2007). Corrosion of copper by water. *Electrochemical and Solid-State Letters, 10*(11), C63–C67.

Tylecote, R. F. (1979). The effect of soil conditions on the long-term corrosion of buried tin-bronzes and copper. *Journal of Archaeological Science, 6*(4), 345–368.

Vieno, T., & Nordman, H. (1999). Safety assessment of spent fuel disposal in Hästholmen, Kivetty, Olkiluoto and Romuvaara, TILA-99. *POSIVA Report 99-07.* Posiva Oy, Helsinki.

West, J.M., Alexander, W.R., Kaku, K., McKinley, I.G., Shimmura, A. (2002). Communication of nuclear power concepts to stakeholders–the use of nature's own laboratories. In Proceedings of NUCEF 2001–scientific bases for criticality safety, separation process and waste disposal. 31 Oct to 2 Nov 2001, Tokai, Japan. Japan Atomic Energy Research Institute Report JAERI Conf 2002-004, 47–54. JAEA, Tokai.