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Resilience in knowledge management – the case of natural analogues in radioactive waste management

H.M. Reijonen [a,*], W.R. Alexander [b], S. Norris [c]

[a] GTK (Geological Survey of Finland), PO Box 96, FI-02151 Espoo, Finland
[b] Bedrock Geosciences, Auenstein, Switzerland
[c] NWS (Nuclear Waste Services), Harwell, UK

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ABSTRACT

In the field of radioactive waste management, particularly the geological disposal of higher activity radioactive waste, support for the longevity of engineering solutions in the repository is partly based on studies of natural systems, especially geological examples, often referred to as natural analogues (NA). Since the radioactive waste can be hazardous over hundreds of thousands of years, the long-term safety has to be assessed to very far future, e.g. up to 1 Ma from now. NA studies cover and exceed the time spans of interest. Despite of the long-acknowledged importance of NAs in the safety case for the geological disposal of radioactive waste, there is a lack of guidance and strategic planning to incorporate this information to the safety cases that assess the overall safety of the repositories – this leads to a certain lack of resilience. This paper presents the work undertaken to develop a strategy for utilising natural analogues (NAs) in Nuclear Waste Services (NWS), UK, geological disposal facility (GDF) programme. The work is largely based on the extensive review of the strategic use of NAs in the international context, lessons learnt from various past programmes and by considering how the strategy could look like in the current framework of the UK's GDF programme. The strategy presented aims to support this programme. The main message is that NA information and projects can and should be handled through the same procedures as any research utilising existing and upcoming NWS protocols. This means that NAs need to be a part of knowledge management, rather than, for example, a stagnant database. Including NAs as part of the data screening allows the knowledge base to be updated according to needs arising from the changes in the GDF programme when moving from generic stage towards more site and design specific phases. It is foreseen that key to the best utilisation of NA information is to include it in the NWS' digital safety case, making the information and the related methodology transparent. This paper refers to NWS' GDF siting programme as at September 2023.

1. Introduction

1.1. Process and nature of radioactive waste management programmes

Geological disposal of higher activity radioactive waste deep in the bedrock is a solution on the verge of implementation, solving the final step in the nuclear fuel cycle. Direct disposal of spent nuclear fuel (SF) and other high-level wastes (e.g. vitrified waste) is under consideration in several countries worldwide, Finland, Sweden and France being the most advanced towards operation of a deep geological repository. In the UK, the repository[1] project has moved towards site selection, which in the UK is a community consent-based process. A typical feature of the developing deep geological disposal programme is the increasing quantity of information which is collected (and collated) over time (GRA, 2009 and Fig. 1). In addition to an increase in detail, screening of the relevant data is needed when narrowing down options regarding the disposal site (geological boundary conditions can vary widely) and repository design (which is always adapted to the site properties).

1.2. Repository concepts

Internationally, different concepts exist for implementing geological

* Corresponding author.
E-mail address: heini.reijonen@gtk.fi (H.M. Reijonen).

[1] Referred to as the Geological Disposal Facility (GDF) in the UK context.

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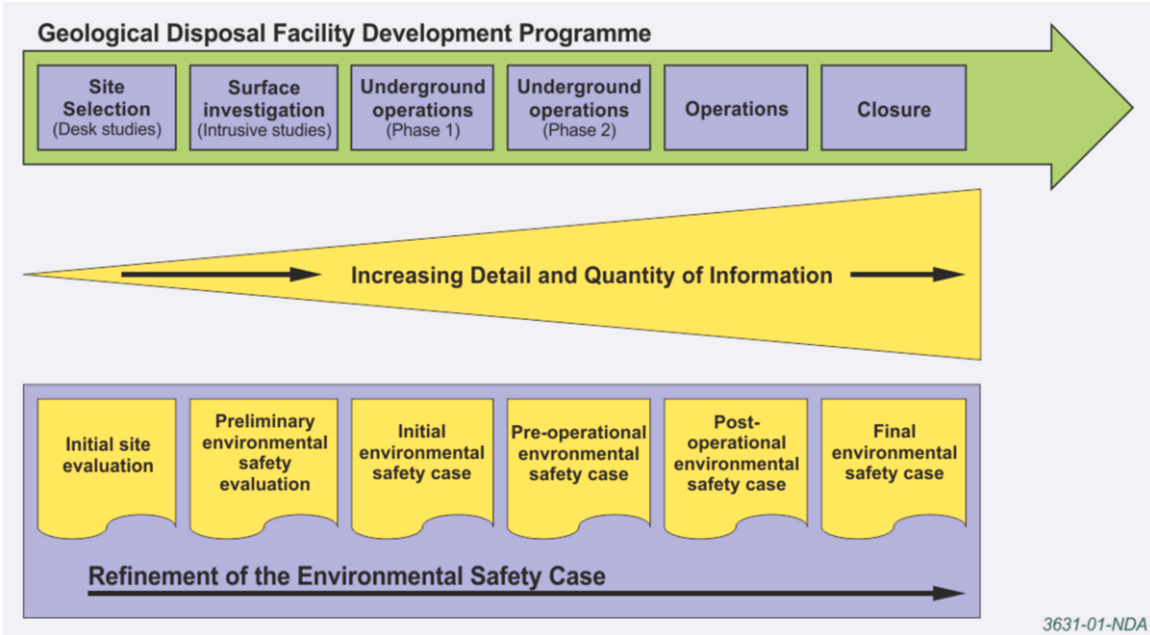


Fig. 1. Refinement of an Environmental Safety Case (ESC) as increasing quantities of information on a possible site for a repository become available as set out in the Guidance on Requirements for Authorisation (GRA, 2009).

disposal depending on the geological setting of the site, the type of waste to be disposed and other regulatory criteria. In the UK, the organisation responsible for the implementation of the Geological Disposal Facility (GDF), NWS, is progressing options at the current stage of the siting programme that consider different potential host rock types and disposal concepts. Depending on the potential host rocks at any site, which acts as a natural barrier, disposal concepts (Fig. 2 presents illustrative generic concepts) include a selection of Engineered Barrier System (EBS) that affect the performance of the system in the long term (see Section 1.3), including concrete, carbon steel, or copper for the waste packaging; various tunnel and shaft backfills; and sealing systems based on cement, clays and crushed rock materials. Safety of the system needs to be demonstrated for both the natural barrier system and the EBS.

1.3. Assessing safety over very long timescales

Each repository programme development takes place over extended periods, including decades of research and technical development to refine the design, test the implementation and assess the safety of the system. A distinctive feature of the safety assessment of geological repositories is the assessment time frame – the safety of the implemented design is assessed for up to 1 million years.[2] This sets a unique demand for integrating scientific knowledge acquired for various time frames: short term laboratory experiments, longer-term underground rock laboratory (URL) experiments and mock-ups, and long-term process understanding from old archaeological artefacts or natural analogues (NA) from the geological record (Fig. 3). NAs are a well-established form of research within the field of radioactive waste management and are in use in various repository development programmes internationally (see e.g. Petit, 1992, Posiva, 2012a).

In this paper, NA is used as a broad term for geological, archaeological, and industrial analogues. One definition, which is still valid and used here, is provided in IAEA (International Atomic Energy Agency) (1999): *"Natural analogues can include both natural and human-made materials provided the processes that affect them are natural. Thus, studies of archaeological and historical artefacts, ancient buildings, anthropogenic sources of radionuclides such as nuclear weapons fallout, and examples of pathways in plants and animals can be regarded as natural analogue studies."* For a detailed discussion of NA concepts, see Miller et al. (2000), Section 1.4).

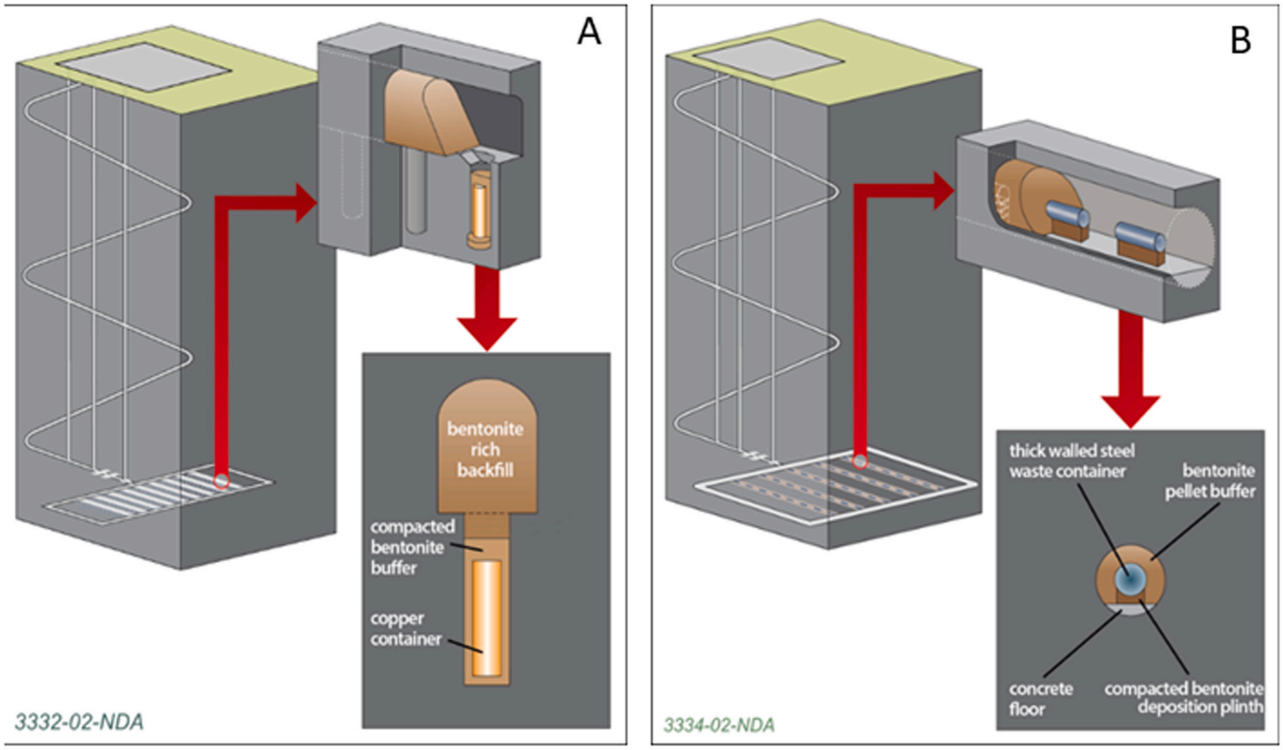
1.4. Strategic planning to build knowledge base for multidisciplinary use

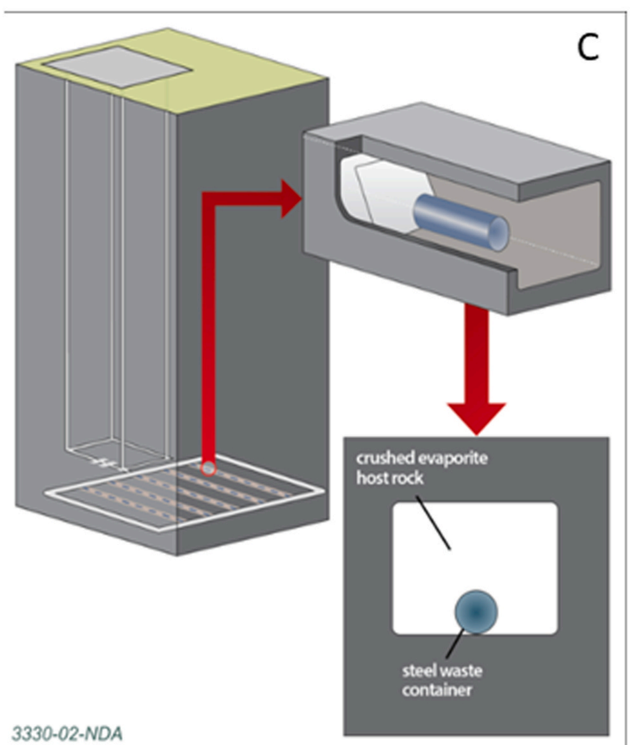
A potential strategy for the use of NA studies in the UK repository programme is introduced in this paper, based on the review of past international and domestic programmes and projects as well as acknowledging the needs in the NWS knowledge management (KM) context as a whole (e.g. development of the practical KM tools). The initial demand for the work has come from the NWS context, but the same requirement of resilience in the KM is common to all waste management organisations and the work presented here is, in most parts, adaptable to other geological disposal programmes worldwide. The full review is reported in Reijonen and Alexander (2023).

2. Background

Utilising natural materials has been a guiding theme in the initial selection of the materials for the repository designs, due to the inherent knowledge of general stability of geological formations. Most EBS materials also occur in nature, such as native metals, metal alloys, clays, even natural cements (see Miller et al., 2000, for details). In addition, some similarities exist between natural UO_2 and SF (although SF contains radionuclides that are not present in natural UO_2). NAs have provided useful input to safety cases of the repository designs for decades (Table 1) for conceptual model development, model testing and as direct input data. The processes covered reflect the wide range of scenarios considered in the long-term repository safety assessments, including not just material degradation considerations based on the current conditions, but also covering foreseen (such as impacts of climate change) and even unlikely scenarios that might happen in the future. To this end, NWS initiated compiling NA information in a form of a catalogue (Milodowski et al., 2015). This catalogue has been recently updated in parallel with the strategic NA programme development (see

[2] This is the general time frame for geological stability and qualitative assessment. Quantitative assessments have, in general, shorter time frames, see e.g. NEA (2012) and ASC (2023).





Host Rock	Disposal Concept	
	Low heat generating waste	**High heat generating waste**
Higher strength rock	UK LHGW Concept (RWM, UK)	KBS-3V Concept (SKB, Sweden) Figure A
Lower strength sedimentary rock	Lower strength Opalinus Clay Concept (Nagra, Switzerland)	Opalinus Clay Concept (Nagra, Switzerland) Figure B
Evaporite rock	WIPP Bedded SalConcept (US DOE, USA)	Gorleben Salt D (DBE Technology, Germany) Figure C

Fig. 2. Concepts for high heat generating waste for UK GDF programme: concept for A. higher strength rock, B: lower strength sedimentary rock and C: evaporite rock.
Table on the bottom right compiles disposal concepts selected as the basis for RWM's illustrative disposal concepts (modified from RWM, 2017).

Alexander and Reijonen, 2023).

In addition to use of NAs in the safety case (Table 1), they have provided input for:

i) siting and site understanding of repositories, in the form of:

a. regional (or self-) analogues to better characterize the potential repository sites (e.g. Nagra, 1997 for the Wellenberg site and Mazurek et al., 2006 for the Opalinus Clay host rock)
b. a regional analogue to support process understanding (e.g. Pearcy et al., 1994, for the long-term behaviour of UO_2 in unsaturated conditions in the Yucca Mountain repository site)

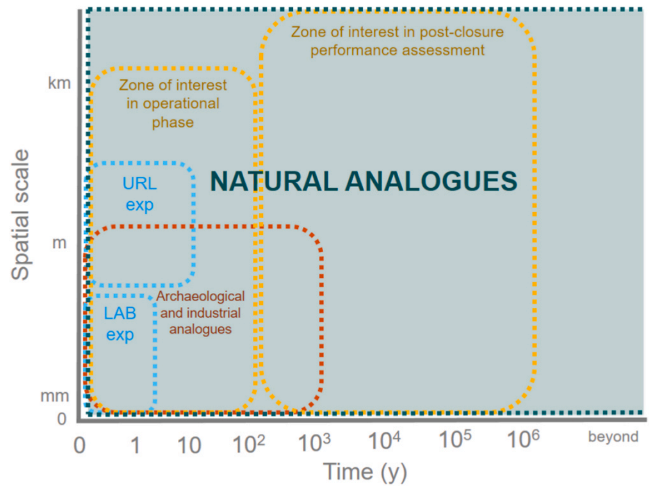


Fig. 3. Spatial and temporal scale of NA studies, experiments, and performance assessment of a repository (Reijonen et al., 2022). URL=underground rock laboratory, LAB=laboratory, exp= experiments, 'operational phase'=period of repository construction, waste disposal and repository closure'.

  c. regional analogues for describing the likely future biospheres for the Olkiluoto site (e.g. Posiva, 2013a, presenting the studies undertaken on regional reference sites to complement the Olkiluoto site description)
  d. regional analogues, providing insights for the processes related to future scenarios, such as glaciation and its potential effects to the repository due to denudation (see e.g. Ojala et al., 2019)

ii) design development, in the form of:
  a. Seal design development (e.g. Kremer and Alexander, 2015, Jefferies et al., 2016)
  b. Exploring the limits of cementitious waste packages (e.g. Alexander et al., 2017)
  c. Usage of low alkali cements (e.g. Milodowski et al., 2016)

iii) communication with various groups of stakeholders, e.g. NAs have been an important communication tool for NWMO in Canada with local stakeholders (e.g. Blyth and Kramer, 2021)

The list above is not exhaustive but illustrates the multidisciplinary and heterogenous nature of the use of NAs (see Reijonen and Alexander, 2023 for more details). Table 1 showcases the various roles of NAs in the past safety cases in the fields of conceptual development, model testing and as a direct source of data.

3. Lessons learnt

NAs are considered in international safety case guidance by the Nuclear Energy Agency (NEA) (e.g. NEA, 2004, 2013) to be a part of the safety assessment. Most safety case work is based on the NEA's approach with modifications. However, the exact use of the NA information varies widely between networks (e.g. Natural Analogue Working Group, NAWG and NA Network, NANet), institutions (NEA, IAEA) and waste management organisations (WMOs) aiming to scrutinise the use of NAs. Strategic development for the use of NAs is scarce and the main findings on the strategy development review performed here are briefly discussed in the below sections. The focus of the NA work has been leaning towards general guidance, communication with various stakeholders, compilation of the data and networking via international projects, while only few programmes have generated programme-specific NA reviews, and even fewer, a published strategy.

Table 1
Examples of the use of NAs in safety cases over the last four decades (Reijonen and Alexander, 2023, updated from Milodowski et al., 2015).

Safety case (reference)	Conceptual model development	Model testing / development	Direct data input
KBS-3 (SKB, 1983)	Radiolytic oxidation of SF		Maximum rate for pitting of copper. Bentonite stability at T < 100 °C
Projekt Gewähr (Nagra, 1985)	Borosilicate glass stability Cement and concrete stability Bitumen stability Radionuclide migration		Long-term corrosion rates of iron SF corrosion rates Estimates of rates of illitisation of bentonite
SKB-91 (SKB, 1992)	Long-term stability of bentonite Matrix diffusion concept Defining relevance of colloids	Redox front propagation Radionuclide solubilities	Radiolytic oxidation rates
TVO-92 (Vieno et al., 1992)	Definition of glacial impact on the repository Copper corrosion processes Impact of colloids and microbes	SF dissolution	Matrix diffusion depths
Kristallin-1 (Nagra, 1994)	Temperature dependence of illitisation of bentonite Radiolytic oxidation of the canister Glass corrosion rates Radiolytic oxidation of SF Microbial radionuclide retardation	Radionuclide solubilities Canister corrosion rates Redox front development	Thermal alteration of bentonite Long-term corrosion rates of iron Matrix diffusion depths Estimates of redox front development rates
AECL EIS (AECL, 1994)	SF and copper canister corrosion rates Long-term behaviour of bentonite Radionuclide retardation	Radionuclide solubilities Colloid and organic complexation of radionuclides Copper corrosion rates	SF stability Radiolysis parameters Copper canister corrosion rates Bentonite illitisation rates Matrix diffusion depths
NRC IPA (1995)	Development of repository disruption scenarios Source-term model development Gas phase transport Relative importance of small- and large-scale fractures on radionuclide migration	Radionuclide transport in unsaturated media Radionuclide transport in fractured media	Definition and relevance of secondary phases following SF corrosion
SFR-1, Project Safe (Andersson et al., 1998)	Long-term stability of cementitious materials Development of a hyperalkaline disturbed zone around a cementitious repository	Blind Predictive Model (BPM) testing of thermodynamic databases for hyperalkaline conditions	Development of secondary CSH, CASH and zeolites within the hyperalkaline disturbed zone pH buffering by reaction with aluminosilicates in the host rock K/Na/CaOH release parameters

(continued on next page)

Table 1 (*continued*)

Safety case (reference)	Conceptual model development	Model testing / development	Direct data input
TILA-99 (Vieno and Nordman, 1999)	Support for the assumed conservativism of the SF dissolution model		Copper canister corrosion rates
SR-97 (SKB, 1999)	Inclusion of permafrost data in the glacial scenarios Inclusion of post-glacial tectonics information in the glacial scenarios	Radiolytic oxidation of SF Radionuclide retardation via matrix diffusion Redox front propagation Mixing of different groundwaters	Bentonite illitisation rates Bentonite thermal stability Bentonite as a barrier to microbial activity Low colloid populations in deep groundwaters Gas transport in the host rock Maximum depth penetration of oxidising surface waters Long-term redox buffer capacity of the host rock
JNC (2000)	Temperature dependent mineralisation of the bentonite		Conservative corrosion rates for steel canister Conservative dissolution rates for vitrified waste Matrix diffusion depths Bedrock stability from the Tono site
Opalinus Clay (Nagra, 2002)	Interaction of the hyperalkaline leachates from the near-field with the far-field High temperature interaction of the host rock and bentonite Chemical alteration of bentonite Impact of radiolysis		Radionuclide solubilities Corrosion rates of the steel canister Dissolution rates of SF
JAEA (2007)	Impact of secondary mineral crystallisation on radionuclide retardation on cementitious materials		
TURVA-2012 e.g.Posiva (2012a, 2012b)	Use of complementary data from NAs for uranium migration, copper corrosion, iron corrosion, and thermal, mechanical and chemical alteration of bentonite buffers, and cement-rock interactions for input to the safety case for the disposal of SF at Olkiluoto (Posiva, 2012a) Inclusion in FEP[a] report (Posiva, 2012b).		Copper canister corrosion rates Support for conservative dissolution rates of SF
SR-Site (SKB, 2011)	Complementary considerations approach + wide use in specific process discussion (FEP based approach, see example on the right)		Support for conservative dissolution rates for SF (SKB, 2010) NAs supporting the data on speciation of radionuclides and colloid formation (SKB, 2010)
Forsmark 2014 (Sidborn et al., 2014)	Development of evolutionary models for a hyperalkaline plume from OPC grouts, and its interaction with bentonite backfill material, and the development of the geochemical environment within an alkaline disturbed zone in the host rock for a repository. Development of conceptual models to evaluate the impact of climate change.	Integration of information from NA studies with laboratory, URL and modelling studies	
NUMO (2021)	Safety case supporting evidence Specific system support	"Safety will be demonstrated in a logical manner by way of a "safety assessment", together with "supporting evidence", such as that provided by natural analogues, that will reinforce/support the assessment results." Alkali cement leachate/host rock interaction	Direct use of NA information on siting
Posiva's operating licence application 2021 (Posiva, 2023a)	Case specific review on natural analogues supporting safety case as complementary considerations (Posiva, 2023a) on SF, canister, buffer & backfill, closure, foreign materials, and geosphere. Biosphere analogues are included in various reports (see right).	Input via process understanding (Posiva, 2023b) + input in biosphere modelling: overburden properties and sorption (Lahdenperä and Kuusisto, 2021), aquatic environment (Kirkkala and Mikkilä, 2021), forests and mires (Aro, 2021), agriculture (Salo, 2021) and fauna (Haavisto and Toivola, 2021).	E.g., Support on conservative estimates on dissolution of SF. Support on low corrosion rates of copper. Support on stability of buffer and backfill materials including concrete. Support to low seismic risks via palaeoseismic studies.

[a] Features, events and processes

3.1. NAWG

Promoting a strategy of using NAs in national programmes was never an actual aim of the original founders of NAWG (cf. Come and Chapman, 1985) and, due to the significant differences between individual disposal programmes (in waste streams, host rock types, repository designs and regulatory environments), this is arguably beyond the objectives of such an international group. However, in the first workshop report (Come and Chapman, 1985), the ad hoc group already noted that:

The study of natural analogues of a nuclear waste repository is one method for providing assurance that a proposed repository site and design will be safe. Results from natural analogue studies must be combined with laboratory experiments and field studies to provide as large a database for safety assessments of repository performance as is scientifically feasible. Multiple data sources will maximise confidence that a repository will actually behave as predicted.

They went on to point out:

*The predictive models which comprise a safety analysis are based on mathematical descriptions of processes which are known or are expected to take place. In many cases the processes involved are very complex and involve many separate mechanisms. Most of our experience and data have been obtained from experiments performed over timescales ranging from days to years and on size scales which are suitable to laboratory experimentation. However, the predictions drawn from these studies are expected to cover timescales which range from thousands to millions of years. To gain added confidence in these predictions, it is important to obtain observations on longer time and size scales. The study of naturally occurring phenomena where the processes of interest play a major role may provide the necessary information. One of the primary uses of natural analogues is thus to validate the models used. This means that the processes which are described in the models must be observable in nature and behave as predicted. A further important use is to ascertain that no processes occur in the complex real environment over long time scales which were not anticipated in the modelled system. Analogues may also be used to obtain data on processes which are not obtainable in other ways (*e.g. *if no experimental technique is feasible).*

They also added caveats to the use of NAsin the safety case, stating:

There are, however, inherent difficulties in using natural analogues to obtain unambiguous quantitative data on processes. The initial and boundary conditions of Nature's own experiments cannot usually be fully reconstructed. In such cases the data extracted from the observations may have a considerable uncertainty. Often a single clear-cut mechanism has not dominated the process and the end result cannot be unambiguously interpreted. However, the overall observation may still be of considerable qualitative use, especially if it is consistent with other similar observations. This adds to the confidence that no essential, and as yet unknown processes occur.

In this way, the group initiated both the formal use of NAs in support of the safety case (via the above statements) and, to enhance communication about the correct use of this new tool, the regular meetings which remain an essential part of NAWG to the current day. To date, there have been 17 NAWG workshops since the first in 1985.

3.2. NAnet

NAnet was an EU-funded project which brought together a partnership of 10 European organisations who were either users or providers of NA information. NAnet ran from January 2003 to December 2004 with the overall aim of promoting *"....more considered applications of analogue information in safety assessments of radioactive waste repositories and for communication purposes."* (NAnet, 2006a). Despite noting the value of integrating NA studies with modelling, laboratory, and URL studies, it was decided to specifically exclude consideration of modelling work, laboratory, and field scale experiments, so weakening the conclusions of the reviews from the onset. Many of the studies reviewed were of little relevance to the safety case or communications in the first place and questions must be asked as to how the 78 examples were chosen (indeed, the comprehensiveness and relevance of the list was raised in the mid-project workshop, see NAnet, 2006b). Although the NAnet review ran for only two years, it was intended from the beginning that the project would continue in some form beyond 2004. Indeed, in the conclusions of NAnet (2006a) it was stated:

"It is hoped that the thinking presented in this report may be useful and that the database of analogue reviews generated by the project could be expanded and evolve over time in subsequent projects, to support radioactive waste and other programmes. This work could be funded by the EC, possibly within the remit of the Natural Analogue Working Group (NAWG). This is important because, without keeping these reviews up to date, the suggested relevance of these analogues to evolving safety assessments will change and the recommendations provided here will become outdated."

Since the end of the project, the database has not been further developed and, as such, the NAnet database does not add much when developing a strategy for the use of NA studies and knowledge in the UK repository programme and safety case, since there already exists a programme-specific catalogue (Milodowski et al., 2015) which has recently been updated (Alexander and Reijonen, 2023).

3.3. IAEA

The IAEA became actively involved in promoting the use of NAs in the safety case following the initiative of NAWG, with Vovk (1988) introducing a report (IAEA, 1989) on the subject at the third NAWG workshop. After this early start by the IAEA, most of their output over the following 15 years was focussed on specific technical studies (e.g. Mazurek et al., 1992), but no specific advice on strategic planning was included. Such attempts were made later e.g. in IAEA (1993, 1994), but at a very generic level. IAEA (1989) was followed up by IAEA (1999) where the authors attempted to address strategic issues (but the report was focussed on the quantitative applications for model development and testing in geochemistry and coupled transport models, which were felt to be the most useful applications of NAs at the time). IAEA (1999) states: *"The report provides an overview of various natural analogues as reference for those planning to develop a research programme in this field. Recommendations are given on the use of natural analogues to engender confidence in the safety of disposal systems."*

Overall, the report provides both a useful overview (e.g. IAEA, 1989, Table II) of the technical uses of NAs in safety case up to that point and a helpful set of guidelines for the overall use of NAs in the safety case, for example: *"Confidence can only be built gradually, with the progressive increase in knowledge and understanding. The choice of future natural analogue studies should aim at improving our information base, for example, by guiding the closer integration of laboratory and* in situ *studies at both analogue and potential GDF sites. This is essential for further refinement of models and for the detailed optimization of disposal systems."*

In addition, IAEA (2005) and IAEA (2003a) have offered some examples of the use of natural safety indicators and natural (radionuclide) concentrations and fluxes in supporting the safety case and more concrete statements were made in IAEA (2003b):

"Natural analogues have the unique advantage of being readily understood and can provide better justification of some aspects of a programme than the more arcane outputs of SA/PA[3] *modelling. Consequently, it can be expected that any future safety case, especially at a late licensing stage of a repository development programme, will utilize analogue information quite widely in support of assumptions and conclusions. In fact, some national regulations already require this (see* e.g. *Section 3.2.5)"*. This was the first time the IAEA addressed the less tangible aspects of NA use (see section 5.5 in IAEA, 2003b) on confidence building in the results of SA/PA reporting the key issues in confidence building:

[3] SA/PA refers to the safety assessment/performance assessment of the entire repository.

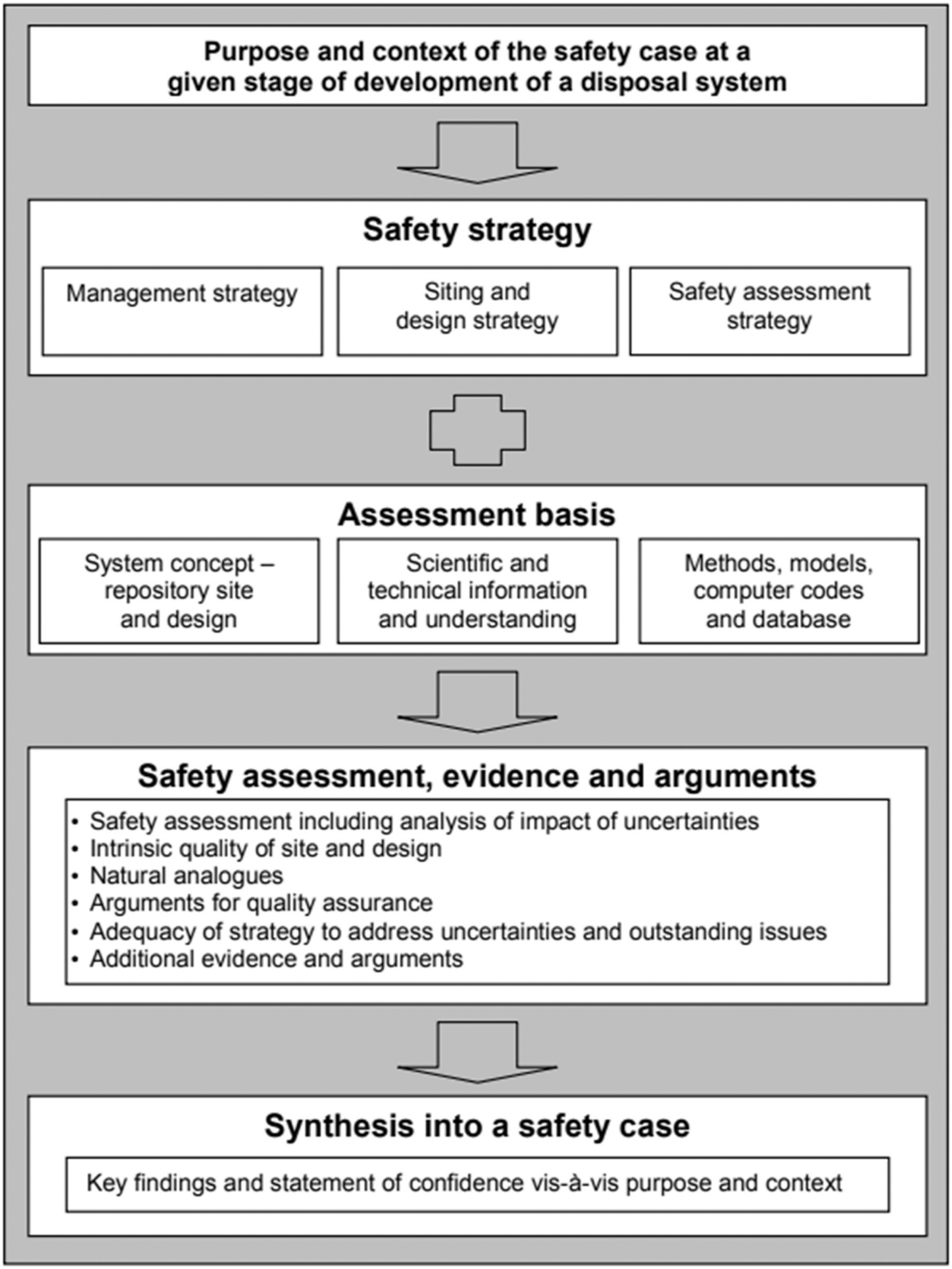


Fig. 4. An overview of the relationship between the different elements of a safety case by NEA (2004).

- *"How to ensure that everything which potentially could significantly affect the performance of the repository system has been considered*
- *How to ensure the reliability of the knowledge used to describe the behaviour of the geological environment and the engineered repository system*
- *How to evaluate the changes that might take place in the geological environment surrounding the repository in the future"*

Some ideas for solving these issues were also provided: *"The two first issues can be resolved, and confidence be built, to a great extent by carrying out systematic high-quality work in SA/PA, which is also open for review. Typical examples of such systematic work will include URLs and 'demonstration' or 'pilot plant' activities. Owing to the long time periods which must be dealt with in SA/PA modelling, it can be difficult to provide a direct and convincing resolution of the third issue. This limitation applies in particular to processes and properties which have to be extrapolated to long time periods on* *the basis of short-term measurements alone. Two well developed techniques exist which can assist in this matter; the use of 'NAs' and the application of palaeohydrogeological analysis. The former has been used extensively for the last twenty years; indeed, the concept of deep geological disposal is based, to some extent, on the containment analogy provided by deeply buried bodies of ore, and the widespread use of 'natural' materials in the EBS is based on their demonstrable longevity. Palaeohydrogeological analysis has been developed more recently, has not yet been applied to any great extent in the support of PA and is only now starting to drive the data gathering specifications of site characterization programmes."*

How NA information can be employed in a generic safety case has been discussed in IAEA (2003b) but no attempt was made to propose how to actively encourage the use of NAs in national programmes nor how to lay down strategic plans to encourage any such use.

While the broad reach of the IAEA waste programme means that any of their documentation on NAs has surely helped promote at least awareness of NA issues, the general nature of the material published (e.g. IAEA, 1975, 1989, 1999, 2003b, 2005) to date means that the impact on the strategic development has been relatively small. It could be argued that developing national programme strategies is not in the IAEA's remit, however, the IAEA has produced 'how to do it' documentation for other topical areas of waste disposal (e.g. IAEA, 1993, 2018).

3.4. NEA

In many areas of radioactive waste disposal, the NEA has been very active in pushing strategic planning in national programmes. In 2000, they initiated the Integration Group for the Safety Case (IGSC), the mission of which is to assist NEA member countries develop effective safety cases supported by a robust scientific-technical basis. In addition to the technical aspects in all developmental stages of repository implementation, the IGSC also provides a platform for international dialogues between safety experts to address strategic and policy aspects of repository development. The NEA has published reports outlining the main components of a safety case (Fig. 4 and NEA, 2004), including NAs and some examples where to use them, however, no detailed discussion at strategic level has been included.

Since the 1980s, NEA has participated in projects focussed on the verification, testing and validation of models of the transport of radionuclides in groundwater through the geosphere: the HYDROCOIN 1984–1990[4] project (see HYDROCOIN, 1992) and the INTRAVAL (1987–1993) project Phase I (e.g. INTRAVAL, 1994) and Phase II (e.g. Rasmussen et al., 1996). These projects (summarised in Larsson et al., 1994) indicated a lack of appropriate geoscientific information for input to safety cases, and this led to the initiation of the NEA's GEOTRAP (Radionuclide Migration in Heterogeneous Geological Media, 1996 – 2001; see, for example, Alexander et al., 1997) project, which took a broader view of the use of geoscientific data (i.e. beyond simply model development and testing of the previous projects). GEOTRAP, which focussed more on field and URL-produced information, led directly to the foundation of the AMIGO (Approaches and Methods for Integrating Geological Information in the Safety Case) project (see NEA, 2002, for details). AMIGO had a much broader remit than the previous NEA initiatives, but the only statement in the final report of relevance to NA strategy as to note that the NA data are "underused" in the safety case (NEA, 2004, Table 1).

In the AMIGO project, information from different organisations was collected (via workshops and questionnaires) on using geoscientific data in the safety case. While progress was made in the use of geoscientific information (NEA 2010), the NAs were considered as realm of practical challenges and areas of debate. However, the project report (NEA 2010) acknowledges the importance of using NAs and even comments on the topic of negative NAs *"...as well as analogues that provide clear support for safety assessment hypotheses and the safety case, there may be other 'negative analogues' that need to be explained in order that they do not undermine the safety case"*. For the negative analogues, NEA (2010) does not refer to earlier work where the topic was discussed and clarified already in 1991.[5] In addition, Miller et al. (2000) provided a clear description regarding reasoning by analogy, including the statement *"This concept of searching for a negative instance is crucial to the idea of natural analogues"*.[6]

Another NEA initiative, a report on the self-sealing of fractures in argillaceous formations, was also produced in 2010 (Bock et al., 2010). Here, the information utilised was sourced from laboratory, URL and *"geologic and geotechnical analogues"* and the authors concluded that the scientific understanding for self-sealing in *"soft to moderately indurated argillaceous formations"* had progressed to the point that sealing processes could be included in the safety cases for deep geological repositories.

In 2012, the NEA's Salt Club[7] held a three-day workshop in Braunschweig (Germany). The proceedings (NEA, 2013) included many recommendations for both the strategic use of NAs in a safety case for an evaporitic host rock and also included comments on developing a strategic plan for the German national programme at the time.

3.5. Country specific lessons

In addition to the international groups and agencies, some programmes have published work in relation to the strategic use of NA information. Here, the cases of Finland, Japan, Germany, and Canada are discussed in more detail as they provide various aspects promoting strategic development of NAs (for organisations using NAs in their safety case in general, see Table 1).

3.5.1. Finland

For the Finnish nuclear waste management organisation, Posiva, the use of NAs in the safety case is partially based directly on requirements placed by the regulatory body, STUK which require inclusion of complementary considerations in the safety case (e.g. STUK, 2018):

"9.8 Complementary considerations.

A10. Where necessary, the actual safety analysis shall be supported by complementary considerations that may include, for example, calculations by stylized methods, comparisons with natural analogues, observations of the geological history of the disposal site, "what if" type considerations that test the robustness of barrier performance and probabilistic assessments.

A10a.The significance of complementary considerations grows as the assessment period increases; safety evaluations extending beyond the time horizon of one million years can mainly be based on such considerations.

[4] HYDROCOIN succeeded the INTRACOIN project (1981–1986) which was directed solely by SKI (see, for example, INTRACOIN 1984, for details).

[5] As noted in Come and Chapman (1991) "The concept of negative analogues was discussed. It was emphasized that it is equally important to understand both those observations of natural systems that support performance assessment and those that apparently invalidate it. The need to understand the processes occurring in these 'negative analogues' was illustrated by discussing examples such as the thorough degradation of granite by kaolinization, and the formation of uranium ore deposits requiring a massive movement of uranium."

[6] Negative analogues are inherently included in process understanding, such as solubility limits for different radionuclides in various conditions or modes and rates of corrosion in different environments.

[7] The Salt Club is an NEA focussed working group on the Safe Disposal of Long-Lived and Heat Generating Radioactive Waste in a Deep Geological Repository in Rock Salt which was set up in 2011 and is still in existence today. The Salt Club lists NA as an area of interest (see https://www.ha.nea.fr/jcms/pl_31091/expert-group-on-repositories-in-rock-salt-formations-salt-club for details). The Salt Club held a joint meeting with GRS (Germany) in 2013 with the aim of identifying NA information of relevance to a rock salt host rock and providing a future plan to focus work on relevant safety case issues (in the German national programme).

A10b.Complementary considerations shall also be made parallel to the actual safety analysis to enhance the confidence in the results of the analysis or certain part of it."

Not only is the use of NAs recommended, but also it is required that the complementary considerations are made in parallel to the actual safety assessment (referring here to performance assessment and dose calculations based on modelling).

In the Finnish case, the strategy for NAs used has been quite straightforward during the 2000 s in a sense that the NA knowledge base is included in the safety case plan reports (Posiva, 2008, 2017) for the Olkiluoto site and KBS-3[8] concept. In addition, based on the output from each iteration of the safety case, further, focussed, development has been carried out via participation in new NA studies in order to strengthen the knowledge base for topics relevant to Posiva's disposal concept, Olkiluoto site and future scenarios, most recently including data from the projects:

- Greenland Analogue Project (GAP) (Kontula et al., 2016)
- Cyprus Natural Analogue Project (CNAP) (e.g. Alexander and Milodowski, 2017)
- Post-glacial fault studies (Ojala et al., 2019)

However, no official strategy has been published by Posiva regarding the use of NAs and their development in the safety case.

Nevertheless, Posiva has provided an example of handling NA information as complementary considerations (Neall et al., 2007; Posiva, 2012a, 2023a), mainly focusing on presenting alternative lines of evidence. NAs have also been mentioned in the process (Posiva, 2012b) and performance assessment (Posiva, 2013b, 2023b) reports and cross referred to in other safety case reports (e.g. Posiva, 2023c).

Posiva presented in their 2012 safety case a state-of-the-art review specific to the Olkiluoto site and KBS-3 concept (Posiva, 2012a). This was further propagated towards use in international programmes in a publication by Reijonen et al. (2015), providing a future outlook on potential new research on key processes. In addition, it was concluded by Reijonen et al. (2015) that, while it is emphasized that the complementary considerations 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 this report were defined, in addition to satisfying the national regulations, to reflect the overall contents of the current Finnish safety case. Posiva produced recently (at the end of 2021) a new safety case for the operational licence application, which includes the utilisation of NAs and update of the previous complementary consideration report (see Posiva, 2017, 2023a).

3.5.2. Japan

The input here is included as an example of an approach to define and develop relevant NA studies to be applied by RWMC (Radioactive Waste Management Corporation of Japan: described in detail in McKinley and Alexander (2007a, 2007b), Alexander et al. (2007)). The process was formally structured as a step wise process: 1) a bottom-up critical assessment of internationally published NA literature with a focus placed on the safety case needs for the national programme 2) an assessment of the weighting given to the wider aims of the NA programme (taking account of secondary aims associated with the "safety strategy" and practical constraints, such as schedule), 3) specification of optimised NA project(s) in a top-down manner, representing the main goals of the national programme and 4) a process for NA site selection considered useful for the programme.[9]

The method employed led to the establishment of a novel NA study: the Philippines Natural Analogue Project (PNAP), focussing on the potential reaction of industrial bentonite with alkaline leachates from low alkali cements (see Fujii et al., 2015 for details). The approach taken was used in the Japanese context, but it is applicable to any GDF programme.

However, the long-lasting impact of this work has been limited so far (i.e. only used within RWMC). Nevertheless, the methodology could still be of relevance, if it is appropriately altered to better reflect the programme in question as a 'living document' which can be updated as the programme matures and moves through the repository development cycle.

3.5.3. Germany

One of the wider studies related to the potential to dispose heat-producing radioactive wastes in three host rock types (evaporites, claystones and hard rocks) was carried out by Brasser et al. (2008) including the potential role of NAs (a dedicated appendix to the main report). Overall, this review produced few, if any, new insights, but generic conclusions were made regarding the role of NAs as 'complementing' the lab-based studies by examining real systems, supporting the safety case as general arguments and increasing confidence in process understanding. However, NA studies were being seen as an important factor when developing future safety cases in the German national programme. A much broader review (Brasser et al., 2014ab) was produced later after a decision was taken in Germany to focus ongoing safety case studies on a repository in an evaporitic host rock.

The conclusions of Brasser et al. (2014a) were simply that existing evaporite NA studies have significantly improved understanding of the long-term processes expected to take place in a repository. Brasser et al. (2014b) focussed on the processes identified in the safety case to be of potential relevance (range of site and EBS processes).

The review of Brasser et al. (2014a) is a helpful model to follow when a repository waste stream, design and host rock have been chosen and Brasser et al. (2014b) even provides a good, step-by-step plan to follow, providing sections within each identified process (e.g. metal corrosion) on:

1) Role in the safety case
2) Knowledge base from laboratory, in situ experiments and modelling studies
3) Example NAs
4) Valuation (of the input NA information)
5) Limits of the applicability/time scale/uncertainties (of the input NA information)
6) Possible uses in the safety case
7) Evaluation of the possible NA input to stakeholder communication programmes
8) Open questions (generally focussed on the scientific, rather than safety case, uncertainties/unknowns)
9) References

Unfortunately, as with Brasser et al. (2008), there is no overall conclusion offered by Brasser et al. (2014a) on how to initiate and maintain the use of NAs in future safety cases.

3.5.4. Canada

Similarly to Finland, the use of NAs in supporting key assumptions in the safety case and adding credibility to its findings is recommended in Regulatory Guide G-320 (CNSC, 2006) stating: "*NA information should be used to build confidence that the system will perform as predicted by demonstrating that natural processes will limit the long-term release of*

[8] Geological disposal concept developed in Sweden and Finland for crystalline bedrock utilising copper-iron waste packages and bentonite-based backfilling of the rock cavities.

[9] Can also be carried out in a structured way using some form of multi-attribute analysis (MAA – cf. Alexander and Milodowski, 2008)

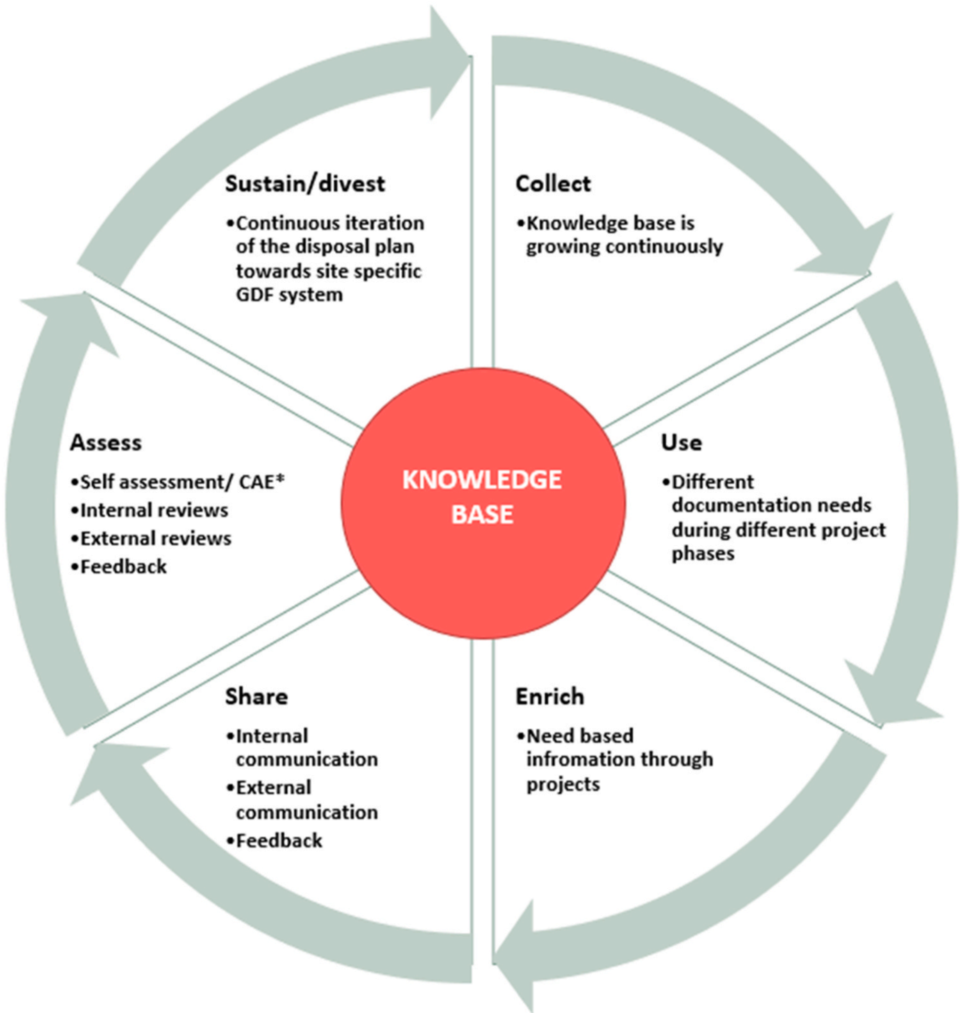


Fig. 5. General knowledge management continuous cycle and main repository programme related aspects. *CAE: Claims, evidence and arguments; GDF: Geological Disposal Facility.

contaminants to the biosphere to levels well below target criteria."

In addition to G-320, NWMO's strategy for the use of NA information in the safety case is guided by NWMO's approach of learning from local, traditional knowledge at potential repository sites. NAs are a natural ground for discussions as they provide examples from the environment. For example, indigenous societies have explored the copper deposits around the Great Lakes since before 3000 BC (Emerson et al., 2000). These are the same deposits that can be used as NAs for the long-term durability of copper containers within the repository (e.g. Aaltonen et al., 2022). As noted in Blyth and Kremer (2023) "*NWMO developed its Indigenous Knowledge Policy (*NWMO, 2016*) to ensure decisions are guided by a clear set of principles, to recognize the role of Indigenous knowledge in the planning and development of the repository and to protect Indigenous rights to intellectual property. Through the site selection process, the NWMO is building sustainable, long-term relationships with interested Canadians and the Indigenous peoples of Canada. This experience has illustrated that using NAs to support assessments of repository safety greatly helps to improve confidence that a deep geological repository is a safe and secure method for isolating used nuclear fuel from the environment.*".

3.6. Summary of lessons learnt on strategy development

In many programmes, NA screening has been carried out via FEP analyses, but in very few programmes have strategic plans been published. Thought is also needed as to when a strategic plan covering the role of NAs in a national programme is initiated in relation to the associated ongoing repository programme (which itself will have many different stages) and what the trigger points there are that could result in the strategic plan subsequently being subject to reconsideration, revision and re-issue. In addition, the guidance by international organisations (IAEA, NEA etc.) is at very general level. In many general statements there is an inherited/predefined complementary/alternative status of NA information. Defining a source of information inherently as less important poses a risk of detaching relevant information from other evidence. Highlighting the importance of using combined sources of information is a more valid approach (cf. Miller et al., 1994, 2000; Alexander et al., 1998).

Based on the above review, there is a lack of critical screening strategies that would also point out to potential future study needs. This leads to the development of the overall science around single process specific needs (which is also important), but not to the development of new NA studies that would have wider meaning at the national programme level. Critical reviews are called for in the safety case and screening of existing material for both relevance and significance to current sites and designs is required.

As noted previously, NAs are used in various areas, for example safety case, siting and communication. However, what was not seen in the current review was the potential of NAs to be used in the repository design development (specifically EBS materials). This may be since only recently the topic of optimisation of the repository systems has been brought forward. Optimisation might include assessing changes in the materials used or the expected conditions, where the examination of the original material source sites may be an important asset for broadening the boundary conditions of material stability.

4. Proposed approach

Based on the lessons learnt from international studies (above) and the overall aims of the NA strategy development work undertaken in the UK programme, an approach for further development has been proposed (see detailed discussion in Reijonen and Alexander (2023)). While the approach is based on the full integration of the NA research to overall knowledge management, it must be emphasised that the assessment of the requirements for specific NA input will evolve as the national programme evolves. This is evident in the changes to the original NA catalogue of Milodowski et al. (2015) and the updated version previously mentioned here (see Alexander and Reijonen, 2023 for details) which reflect developments in the UK national programme over the last decade. For example, as repository design began considering the use of low alkali concretes in place of OPC concretes (see the discussion in Alexander and Neall (2007); Rozalén et al. (2009); Sidborn et al. (2014)), then the requirement for information on the long-term interaction between the leachates from the low alkali concretes and other EBS materials such as bentonite became apparent and were supported by focussed NA studies (e.g. Milodowski et al., 2016; Alexander and Milodowski, 2017) which quickly indicated the compatibility between the novel use of the low alkali concretes and the existing EBS designs.

NWS is developing a digital safety case providing a flexible platform for the storage, use and update of NA information. While the knowledge base is a storage system, actually managing knowledge is a dynamic process which needs constant re-assessment and active input to keep it abreast of new developments (in both the national programme in general and in science and technology in particular) and usually follows the overall scheme presented in Fig. 5. Below, the main aspects of the steps in knowledge management are discussed here from the NA information point of view:

Step 1: The NA Catalogue serves as a starting point for collecting information of relevance to the evolving NWS repository programme This information forms a database, which requires to be connected to other parts of the safety case.

Step 2: Utilisation of the NA Catalogue should contain several aspects:

- Use as a reference in ongoing work
- Mapping of the NA content (evidence) in NWS' systems, including information such as the FEP database, CAE (claims-arguments-evidence) and, through requirements, for the repository design
- The information needs to be made accessible to the whole organisation (design, siting, safety case, public relations) to maximise the benefit and to have a coherent approach for utilising the data. In the optimal case, the natural analogue providing the data directly to the safety case can be used for PR purposes as well, providing solid tracking from the communications to hard data (assuring transparency and consistency)

Step 3: Updates of the information should be based on a gap analysis and effort/gain assessment. Main sources of updates are:

- At a national and international level, knowledge gaps must be discussed, prioritised and strategies for their resolution postulated. Where appropriate, such strategies could include NA studies (which could assist one national programme or several programmes at the same time). Note that the relevant scheduling of NA studies in an evolving repository programme needs to be considered, with appropriate input preferably being available in advance. Scientific literature is often useful, even if not reporting dedicated NA studies. Note that this includes general scientific networking as this can ensure that the repository programme remains at the cutting edge of science and technology
- New methods that have become available, which could provide NA type information to the safety case can be utilised (either new studies or revisiting old ones). For example:
  - o the post-glacial fault studies (Ojala et al., 2019) by Posiva, only became possible when Lidar[10] data became available
- Revisiting previous work: the final remarks in the Cigar Lake reappraisal report (Smellie and Karlsson, 1996) states: "*This Cigar Lake exercise has underlined the advantages of reviewing and reappraising existing analogue data when the dust has settled. Three important areas to repository assessment have been addressed and considerable progress has been made since the initial interpretation of the data. The other aspect that came to light was the need to pursue certain lines of interest which require limited additional field and/or analytical data. Time and resources should be available for this to be realised, and every completed analogue study should retain some degree of on-site infrastructure to facilitate this possibility.*"
- Dedicated NA projects planned solely for NWS purposes (e.g. some site-specific process that is not of international interest)

Step 4: Sharing information in a timely manner is a challenge for any organisation. Collective use and continuous update of a linking database, such as the FEP database, would provide a platform that would keep the various disciplines (siting, engineering, safety assessment) updated about the new work and its meaning to the overall systems and safety case.

- Part of knowledge management is networking and exposing the staff to open scientific discussion via scientific meetings where non-waste management academics/engineers/safety assessors also present their work. NAWG, for example, provides a good framework to keep discussion active among radioactive waste management professionals interested in NAs, as discussed in section 3.2.. Overall, to identify ongoing or planned national and international work, various conferences are worth following, but also research funding schemes and related planning (for example EURAD,[11] IGD-TP,[12] EURADSCIENCE[13] and similar, where impact can be made proactively)

Step 5: The usefulness of NA information needs to be assessed alongside the updated analysis of long-term safety, e.g.

- Relevance screening against
  - o Iteration process, needs arising from design changes, site or safety case (e.g. FEP screening)
  - o Scientific relevance
  - o Significance screening against readiness levels
- Gap analysis
- How the information feeds into the CAE

It is worth noting that this may also lead to substituting some existing NA data with information which is of more relevance to the current national disposal programme (while, at the same time, ensuring the substituted information is clearly recorded in the system). The ViSI tool[14] provides a good starting point for re-assessing the relevance of existing data based on screening against design, assessment results or site properties. Again, the FEP database would provide a natural platform for maintaining an up-to-date system which acts as the connection between disciplines.

In addition to self-assessment, the usefulness of NA information

[10] "laser imaging, detection and ranging".

[11] European Joint Programme on Radioactive Waste Management.

[12] Implementing Geological Disposal of radioactive waste Technology Platform (IGD-TP).

[13] "EURADSCIENCE", a network of research organisations for radioactive waste management science within Europe (Bruggeman et al., 2019).

[14] NWS has established a novel internal information platform to aid knowledge management and report production called the Visualisation of System Information tool or "ViSI tool".

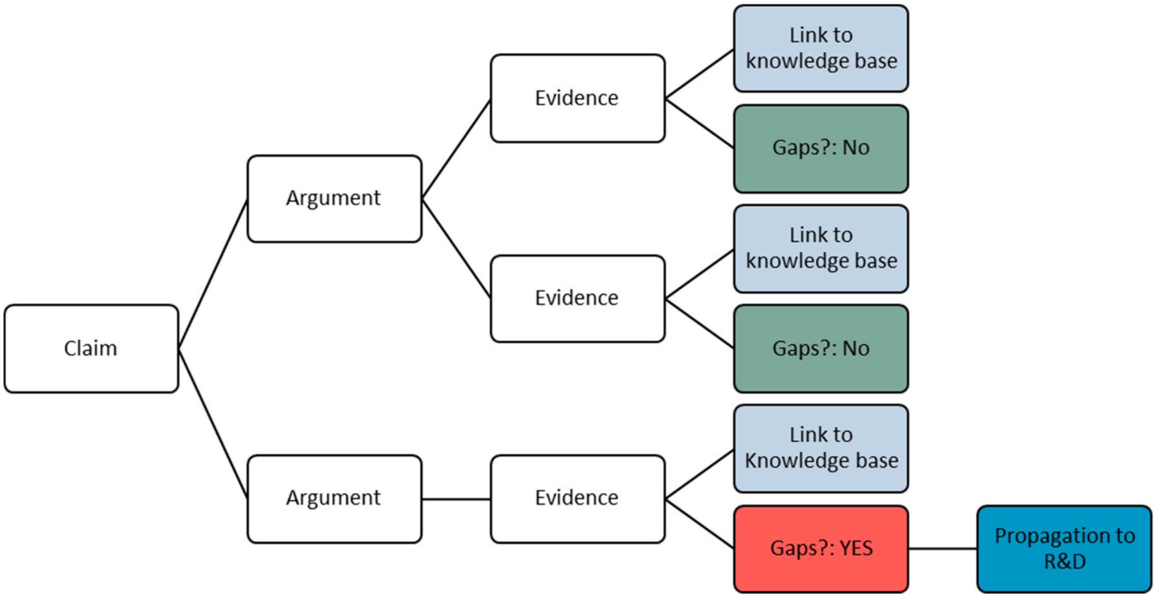


Fig. 6. Simplified schematic illustration of the NWS CAE process guiding the R&D programme (Reijonen and Alexander, 2023).

can be obtained via external review process.

Step 6: Sustain/divest

- Adequate/appropriate data do not require updating solely because they are old. However, in some cases, availability of new methods might be a reason to repeat some older studies to make sure the results are still valid
- Further, the QA status of data may be drawn into question, something that could guide further work (e.g. re-analysing already available samples, as well as potentially collecting new data)
- In addition to updates, divesting some information is also inevitable in any process that moves towards more detailed and more strictly bound conditions. As mentioned in point 5 above, data which are no longer suitable should be marked obsolete

5. Knowledge management tools

As noted above, NWS has established the ViSI tool, and the main objectives of the development have been to (Bailey et al., 2020): 1) aid in

Table 2
General objectives for ESC process and activities and outcomes of NA studies. In addition to needs mentioned here, safety case needs for specific studies may arise at any time of the disposal programme.

NWS' evolving programme	Safety Case stage	Objectives (of safety case)	Activities in NA knowledge base	NWS NA research needs	NA research outcomes
Consultation – establishing partnerships with communities (ongoing in 2023)	Generic ESC	Statement of confidence for long-term safety Stakeholder communication Feedback to design	Compilation of the NA Catalogue Participation in international NA projects Networking Update of the NA Catalogue Integration with the ViSI tool FEP mapping Use of NAs in stakeholder communications	Participation in relevant projects (safety case driven) Additional NA studies relevant to 1. Potential site areas and/or EBS 2. Communication with the local community via NAs	NA Catalogue mapped to the general FEP list allows gap analysis Additional mapping with requirements and arguments Improved understanding on the geological context of potential siting areas
Site investigations	Site specific ESC	As above Screening of FEPs for their relevance to site (and design) specific ESC Stakeholder communication	Screening of FEPs (relevance and significance) Clear indications on keeping / omitting data Gap analysis Project work Use of NAs in stakeholder communications	Additional NA studies relevant to 1. Site characterisation[1] 2. Site selection 3. Selected site 4. Design 5. Operational safety 6. Communication with the local community via NAs	Update of the NA database (preferably to NA Catalogue format) Gaps identified Potential new research identified New NA results
Construction	Site specific ESC with increasing detail and monitoring data Potential optimisation of the design	Statement of confidence for long-term safety Stakeholder communication Feedback to design Screening of FEPs complete	Final FEP list, new additions if new processes are encountered State-of-the-art NA update Use of NAs in stakeholder communications	As above	As above
Operation and closure	Periodical ESC including potential optimisation	Checking the robustness of the system Stakeholder communication	As above	As above	As above

1 See Alexander and Reijonen (2023) for details.

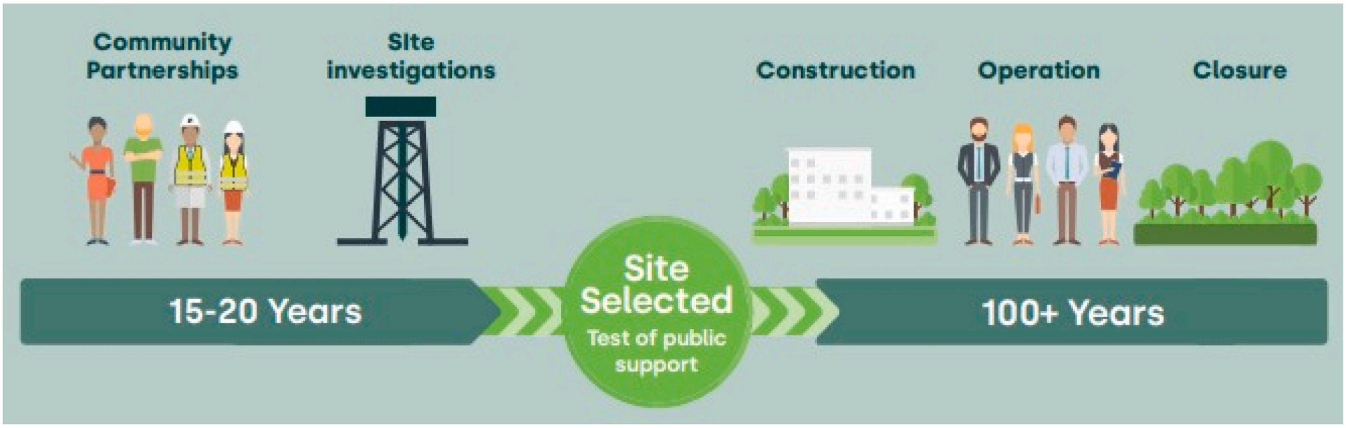


Fig. 7. The UK view of the operational timeline of a repository programme (NWS, 2023).

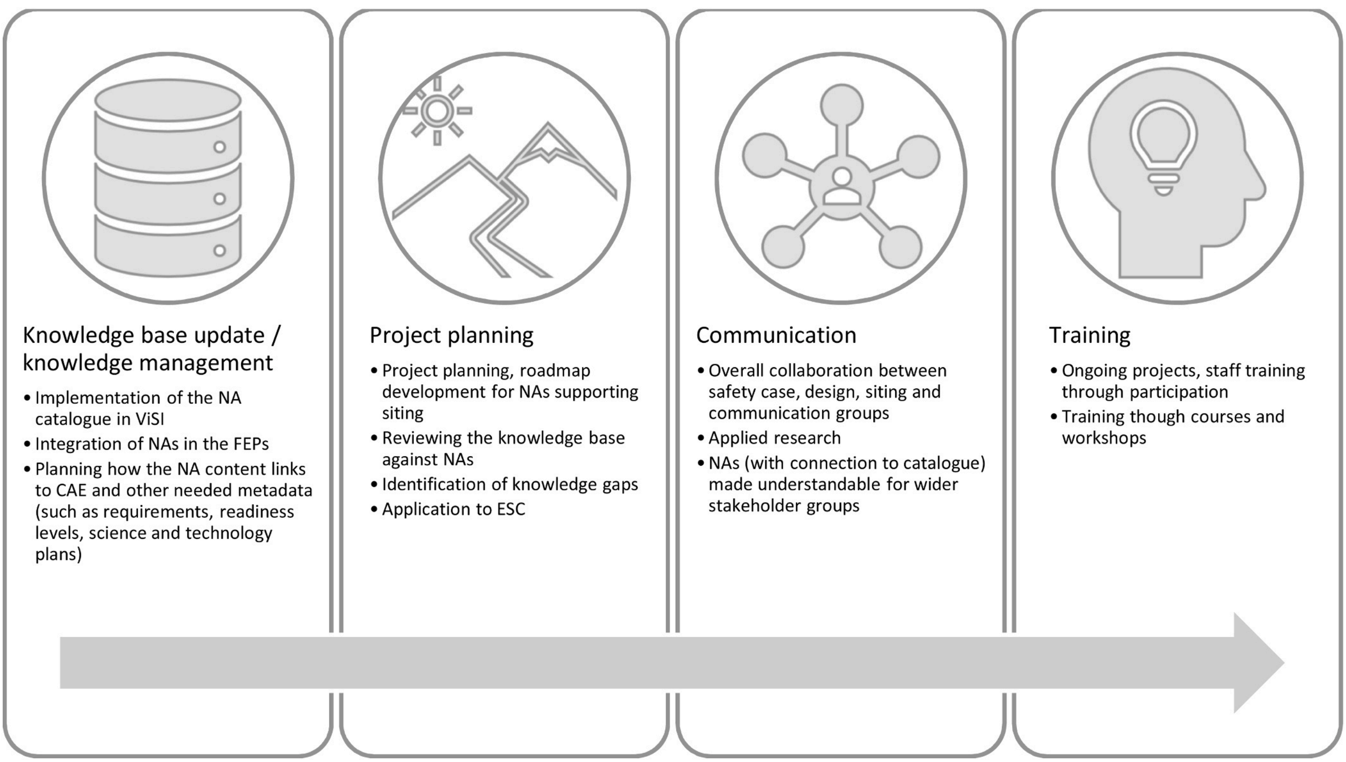


Fig. 8. Main components of assuring effective use of NAs in NWS' framework in the near future. The overall order of the activities follows the arrow, but activities can be simultaneous/overlapping. Knowledge base update is a continuous process. NA Catalogue refers to Alexander and Reijonen (2023).

the knowledge management process, 2) make information more accessible. 3) help needs-driven research planning and 4) help to increase the robustness of the safety case. ViSI supports the NWS Business Cycle via a CAE tree structure. CAE is a common framework for reasoning and communicating supporting the Environmental Safety Case (ESC) which is based on the claims made on the safety of the given system that need to be supported by the arguments and the underpinning evidence. The use of NAs is part of this evidence.

The ViSI framework should support an integrated workflow (Fig. 6), where consideration of different aspects of evidence, supporting the argument, comes into the work process of all disciplines more or less automatically, including identification of gaps.

To achieve an integrated workflow, the content management system should provide enough internal links that connect the different users of information (i.e. metadata). There are many ways of doing this, but starting from the FEP list is good, since it forms the integral basis for system understanding.

The NA catalogue should be seen as starting point as it already has a FEP linked structure. Information is also connected to different host rocks and repository designs. In the future, the same NA study may be used in many places and it may even be that different aspects of the same NA study may be used in different parts of the safety case (see Table 1 for some examples of different uses). This requires scrutiny in recording which parts of the statements made are linked to elsewhere in the documentation. In addition to this, the objectives of the ESC process may change during NWS' evolving programme (Table 2).

6. Implementation within the UK context

As at 2023, NWS is in the consultation phase with community partnerships (Fig. 7) in relation to the UK GDF siting programme. Different stages in NWS' evolving programme will guide whole research programmes including NAs (Table 2) and they will also pose a need for periodical reviews and reassessment of the NA data relevance and significance. In the objectives of the safety case[15] process, stakeholder communication plays a major role. As NAs are often used in discussing geological disposal safety aspects with wider (often non-technical) audiences, care should also be taken when simplifying the messages, ensuring that the overall message stays the same.

The main components of assuring the effective use of NAs in NWS' context, also applicable elsewhere, includes knowledge management, project work, communication and staff training (Fig. 8). If one of these aspects is lacking, the knowledge may be lost and only data or information remains. This is obviously true for any knowledge in the knowledge base but the general lack of consideration of NA information (as noted above) means greater care must be taken here.

In connection with the site evaluation and related considerations, NWS has listed some examples of typical matters that might be assessed during the site evaluation phase. They are presented in Annex B of RWM (2020) and provide some examples of the typical points that NWS is likely to need to assess in order to show compliance with the regulatory requirements. These examples are not an exhaustive list of the areas which could be assessed, but it provides an overall list of themes to be considered. Some of the topics are not related to NAs (e.g. transport or value for money), some are on the borderline between site selection/characterisation and other areas but, in many cases, there are several aspects that could benefit from NA type additional studies (literature surveys or field-investigations). In Tables 3 to 5, the most relevant topics (Safety and Security, Environment, Engineering Feasibility) presented in Annex B of RWM (2020) are listed and an estimation is provided as to whether they are of relevance to NA strategy or not and, if so, what type of NAs could be considered.

As can be seen from Tables 3 to 5, the NA approach can potentially help in many aspects of the siting process (although note that, in some cases, it is difficult to distinguish between site investigations and regional analogues).

7. Conclusions

The strategy presented here for the potential future use of NA information in NWS' work related to the UK's national GDF programme is described in detail in Reijonen and Alexander (2023), including the full review of the strategic use of NAs by other WMOs worldwide. The main outcome of the review is that very few other national programmes consider the use of NA information in a structured manner and, although strategic approaches have been proposed for other WMOs in the past, a full implementation of the proposed methods is, to date, lacking. There seems to be even an oversight which is based on the mistaken view that NA information is somehow more uncertain than information produced in a laboratory or URL or from a model calculation. The reality is that uncertainties for NAs are generally related to their less certain boundary conditions, while short-term, small-scale laboratory and URL experiments have the biggest uncertainties in extrapolation of the results into the far future. For a 100,000 to 1-million-year safety assessment time frame, NAs may be the key pillar of the safety case.

As discussed above, NA data can, and should, be handled with the same procedures as any other laboratory-derived and model-derived information, data and parameters (and, in the UK national programme, utilising existing and upcoming NWS protocols on managing knowledge). In this paper, an overarching proposal is provided, with a stepwise description for incorporation of NA data in the knowledge base.

Systematic knowledge management of NA information (including recording substituted data) is an integral part of the recommended strategic approach, for which NWS' digital environment provides an apt methodology. Utilisation of NA information successfully is greatly

[15] Mainly Environmental Safety Case (ESC) in NWS case.

Table 3
Evaluation Considerations for the Siting Factor – Safety and Security) and potential for seeking support through NAs (Reijonen and Alexander, 2023).

Evaluation Consideration	Description	NA relevance (Y/N)	Details
Safety during Investigation	The ability to investigate areas and sites safely within the constraints of the area/site and the long-term implications of those investigations.		
The ability to safely carry out investigations from a surface environment either onshore or inshore.		N	
The ability to carry out investigations so as to protect the long-term safety functions of the geological environment.		Y	Regional analogues, locally (e.g.Alexander and Reijonen, 2023, section 6.3.1)
Safety during Construction	The ability to build a GDF safely and the long-term implications of that construction.		
The ability to construct a GDF safely.		Y	Industrial analogues, local mines, quarries and other underground facilities can provide valuable lessons
The implications of natural and other external hazards such as flooding.		Y	Part of hazard assessment. For example, tsunami – e.g.DEFRA (2005)
The ability to design and construct a GDF in such a way as to protect the safety functions of the geological environment.		Y	Regional analogues (for example impact of GDF construction and operational phase on the host rock, cf. Alexander and Neall, 2007)
Safety during Operations	The ability to operate a GDF safely and the long-term implications of that operation.		
The implications of natural and other external hazards.		Y	Regional analogues (for example impact of GDF construction and operational phase on the host rock and EBS)
The implications of nearby hazardous facilities or protected military areas.		Y	Industrial analogues
The ability to develop and implement emergency and contingency plans.		N	
Safety after closure	The ability to isolate and contain radioactive waste for the time required for the radioactivity to naturally reduce to acceptable levels.		
The suitability of the host geological environment including the consideration of: ◦ *rock type;* ◦ *rock structure;* ◦ *groundwater;* ◦ *natural process; and* ◦ *resources.*		Y	Several potential analogue considerations: 1. regional analogues for host rock, groundwater etc. 2. host rock – EBS analogues: such work has been reported for bentonite/host rock interactions (e.g.Alexander, 2018), but are there any interesting local analogues for interactions (e.g. graphite, bentonite, bitumen, cements, metals)? Local examples would be useful in communication with the local communities (cf. NWMO approach; Blyth & Kramer 2023)
The ability of the potential site to isolate radioactive waste from people and the biosphere over the long-term after closure.		Y	Biosphere transport analogues (e.g.Posiva, 2023d, chapter 3), other near-surface transport analogues (anthropogenic contaminants) Geosphere transport analogues of natural elements (e.g.Brookins, 1986)
The natural evolution of the site which could cause it to be disturbed at some point in the future, including long term climate change and long-term geological changes. *Other events such as seismic activity*		Y	Regional consideration of the groundwater dynamics and potential impacts of coastal transgression/regression (cf. Amano et al., 2011). Analogues for glaciation

(continued on next page)

Table 3 (*continued*)

Evaluation Consideration	Description	NA relevance (Y/N)	Details
or glaciation which could cause the site to be disturbed at some point in the future.			related processes (elsewhere, where such conditions prevail), local studies for glaciation related implications (e.g. faulting related to land depression/uplift, forebulge etc.), impact on groundwater flow and chemistry (e.g. Posiva, 2022)
The likelihood of human intrusion at some point in the future.		N	
The ability for a GDF to provide adequate protection against any non-radiological hazards.		Y	At least two things to consider: 1. overall understanding of the site geochemistry will clarify how toxic wastes will behave. 2. Can use examples of 'targeted' studies of specific non-radiological hazards (e.g. Pb from SF), by looking at Pb mines in the area (or elsewhere)
Management Requirements	The ability to satisfy the relevant administrative Requirements within the constraints of the area/site.		
The likely period required after closure to address institutional control requirements. *The arrangements for maintaining the information on a GDF.*		N	
Security	The ability to design, construct, operate and close a GDF such that the relevant security Requirements are satisfied.		
The ability to design, construct and operate a GDF to protect against: ◦ *any deliberate release of radioactive material;* ◦ *theft or misappropriation of nuclear or radiological waste material; and* ◦ *sabotage of all or parts of a GDF and its processes.* *The ability to develop and implement emergency and contingency plans.*		N	
Safeguards	The ability to design, construct, operate and close a GDF such that the relevant safeguarding Requirements are satisfied.		
• *The ability to safeguard the wastes and ensure it is not diverted for military uses or other undeclared purposes.*		N	

improved when made easily accessible.

Moving in the UK GDF programme towards evaluations of specific sites will drive research (including regional analogues) towards additional needs that are site specific; examples are provided in the recently updated NA Catalogue (Alexander and Reijonen, 2023) on how existing and new NA information can support this development.

Incorporating NAs directly in the ESC CAE – not only as an external discussion, but rather as part of a holistic approach - should lead to better conceptual models and therefore a more realistic safety case. The link to communicating NAs then becomes more transparent as well.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Table 4

Evaluation Considerations for the Siting Factor – Environment and potential for seeking support through NAs (Reijonen and Alexander, 2023).

Evaluation Consideration	Description	NA relevance (Y/N)	Comment
Environmental Implications	The implications of the investigation, construction, operation and closure of a repository on the environment.		
Air quality, including effects on existing air quality and sensitive receptors. *Noise, vibration and lighting, including effects on existing baseline levels of noise and sensitive receptors.* *Biodiversity and nature conservation, including effects on flora and fauna, habitats and designated sites.* *Climatic factors including effects of climate change and ability to use low carbon technologies and renewable energy sources.* *Historic environment implications, including effects on the historic landscape, heritage assets and their setting as well as archaeological and palaeontological assets.* *Land use, including effects on and compatibility with existing land uses.* *Landscape and visual implications, including effects on the character of the landscape, townscape and seascape (as appropriate).* *Waste management, including the ability to adhere to the waste management hierarchy and management of waste, such as spoil.* *Resources, including the ability to utilise resources efficiently.*		N	Site investigation and construction of other repositories (e.g Olkiluoto in Finland), underground laboratories, mining operations etc, can be used as industrial analogues to provide insight of the potential environmental impacts
Flood risk and coastal change, including drainage and hydrology implications. *Water quality, including surface and groundwater quality.*		Y	Regional hydrogeological analogues (see also above Table 3) and Tsunami risks, (see Table 3)
Geology and soils, including effects on soil quality and features of geological interest.		Y	Regional analogues as a source of information (see Alexander and Reijonen, 2023, for details)
Any mitigation measures which are required as a consequence of satisfying relevant Requirements.		N	
Protected Habitats and Species	The implications of the investigation, construction, operation and closure of a GDF on Protected Habitats and Species.		
Any likely significant impacts on internationally, nationally and locally designated sites of ecological or geological conservation importance (including those outside the UK) including: ◦ *International Sites;* ◦ *Sites of Special Scientific Interest (SSSIs);* ◦ *Marine Conservation Zones (MCZs);* ◦ *Regional and Local Sites;* ◦ *Ancient Woodland, and Ancient and Veteran Trees;* ◦ *Biodiversity within and around developments; and* ◦ *Protection of Other Habitats and Species*		Y	E.g., biosphere reference site investigations (cf.Posiva, 2023d, chapter 3)

Table 5
Evaluation Considerations for the Siting Factor - Engineering Feasibility and potential for seeking support through NAs. (Reijonen and Alexander, 2023).

Evaluation Consideration	Description	NA relevance (Y/N)	Comment
Flexibility	The ability to apply a variety of design solutions to a given area or site.		
Whether there are particular characteristics of an area or site which may provide greater flexibility in terms of design, construction, operation and closure		Y	Regional studies help to understand the site properties. See 'regional analogues' in Alexander and Reijonen (2023). Site investigations require drilling, in most cases for properties at depth (specifically those that change as a function of depth).
Ability to Characterise	The ability to characterise an area/site within the constraints of the area/site.		
The size, shape and topography of the surface areas and ground conditions and the implications on the ability to characterise the area or site. *The availability of utilities to enable the characterisation activities.*		Y	Regional analogues will be useful. See examples of regional analogues used by Posiva (2023b).
Ability to Design and Construct	The ability to design and construct a GDF within the constraints of the area / site.		
The geological environment including the depth, size, and geometry of accessible host rock(s). *The size, shape and topography of the potential surface areas and likely ground conditions.* *The nature, volume and timing of the spoil that will be generated.* *Access to existing infrastructure and the ability to deliver new infrastructure if it is required.*		N	Site characterisation, but the comments inTable 4 on industrial analogues utilising information from other repositories, URLs etc. apply here too.
Inventory for Disposal	The ability to design, construct and operate a GDF such that the agreed waste inventory can be disposed.		
Whether there is sufficient volume of suitable rock available at a suitable depth. *The ability to accommodate potential changes in waste quantities.*		N	Site characterisation
Sustainable Design	The ability to design, construct and operate a GDF in a sustainable manner.		
The ability to deliver sustainable infrastructure that is sensitive to its location and demonstrates good aesthetics. *The ability of a GDF to remain resilient to climate change, sea level rise and the potential for adaptation to more extreme, but credible, climate change scenarios.*		Y	Regarding the latter: Future scenarios related analogues (see Alexander and Reijonen, 2023).
Waste Conditioning and Packaging	The ability for waste that is already or still to be packaged to be accepted at a potential site.		
Whether there are any particular characteristics of an area or site which may prevent wastes that have already been packaged from being accepted. *Whether there may need to be significant changes to current waste packaging advice.*		Y	Regional analogues (providing information that prevents usage of the already implemented packaging). Could impact/change the existing waste acceptance criteria too (cf.IAEA, 1990).
Retrievability	The ability to design, construct and operate a GDF such that waste could potentially be retrieved during the operational phase if there is a compelling reason to do so.		
The host geological environment, depth and likely underground rock stresses. *The types of engineered barriers that are likely to be used.*		Y	Industrial analogues can provide valuable lessons, see for example studies on mechanical stability of the host rock by Posiva (2023a).

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