

Natural Analogues – A proposed strategy for implementation within the Nuclear Waste Services (NWS), UK, programme of geological disposal



Heini Reijonen & W. Russell Alexander



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Title of report Natural Analogues – A proposed strategy for implementation within the Nuclear Waste Services (NWS), UK, programme of geological disposal			
Abstract <p>This report presents the development work for the strategic use of natural analogues (NAs) for the Nuclear Waste Services (NWS), UK, geological disposal facility (GDF) programme. The development work is based on the extensive review of the strategic use of NAs in the international context considering NWS's own framework as well. The strategy aims to support the GDF development program, and there are several potential activities that may be valid in the near future and during the evolving programme. NA information and projects can and should be handled through the same procedures as any research utilising existing and upcoming NWS protocols. Key to success in utilising NA information is its inclusion in NWS's digital environment. Systematic knowledge management (including recording obsolete data) is proposed. Moving from the generic phase towards site evaluation will drive the research towards additional needs that are site specific. NAs can provide significant new input to future safety cases in addition to existing material.</p>			
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17.4.2023

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Signature/name  Heini Reijonen	Signature/name  Hannu Lahtinen

17.4.2023

Contents

Abbreviations and definitions	3
Executive summary	7
1 Introduction	9
1.1 Scope and objectives	9
1.2 This report	9
1.3 Definitions	10
2 NWS framework	12
2.1 NWS organisation	12
2.2 Regulatory context	12
2.3 UK GDF process and strategy	13
2.4 Safety case and NA	15
2.5 NWS content management	16
2.6 NWS's current and planned involvement in NA projects	19
3 Background	22
3.1 Overview on the use of NA information	22
3.2 Previous work on NA strategy development internationally	25
3.2.1 EU NAWG	25
3.2.2 IAEA	28
3.2.3 NEA	30
3.2.4 EU NANet project	32
3.2.5 Finland	36
3.2.6 Japan	39
3.2.7 Germany	50
3.2.8 Canada	52
3.3 Use of NAs in a waste disposal programmes	54
3.3.1 Use in siting	54
3.3.2 Use in Safety Case	59
3.3.3 Use in design development	74
3.3.4 Examples for stakeholder communication	81

17.4.2023

3.3.5	Overview on NA use during GDF process	92
3.4	Lessons learned	93
4	Strategy development	95
4.1	Feedback from NWS personnel	96
4.2	Knowledge management	96
4.3	Change management and increasing information	102
4.4	Practical implementation of NA screening and gap analysis	102
4.5	Including NAs in different phases of the national programme	105
4.6	Needs-driven and cost-effective approach in commissioning new NA work	107
4.7	Role in training	114
4.8	Role in stakeholder communication	114
4.9	Potential activities and research needs in NWS's evolving programme	115
4.9.1	Activities during consultation	116
4.9.2	Activities during site investigations	116
4.9.3	Activities during construction, operation and closure	123
4.10	Summary of the strategy development	124
5	Concluding remarks	128
	Acknowledgements	130
	References	131
	Appendices	153
	A1: List of NA studies considered in NANet project	153
	A2: Nagra NA-studies 1984-2003	153
	A3: Spuren der Zukunft, Nagra NA brochure from 2007	153
	A4: Long-term safety of a GDF Nagra 2018	153
	A5: Details of two BBC radio programmes including NA information	153

17.4.2023

ABBREVIATIONS AND DEFINITIONS

Term / abbreviation	Definition
AMIGO	Approaches and Methods for Integrating Geological Information in the Safety Case
AEC	Atomic Energy Commission of Japan
AECL	Atomic Energy of Canada Limited
BS	Borehole Sealing
BASE	Bundesamt für die Sicherheit der nuklearen Entsorgung (Federal Office for the Safety of Nuclear Waste Management)
BGE	Bundesgesellschaft für Endlagerung mbH (the Federal Company for Radioactive Waste Disposal)
CASH	Calcium Aluminium Silicate Hydrate
CNSC	Canadian Nuclear Safety Commission
CAE	Claims, Evidence and Arguments
CEC	Commission of the European Communities
CC	Complementary Considerations
CSH	Calcium Silicate Hydrate
CNAP	Cyprus Natural Analogue Project
DSSC	Disposal System Safety Case
EBS	Engineered Barrier System
ESC	Environmental Safety Case
EC	European Commission
EU	European Union
FEP	Feature, Event, Process
GDF	Geological Disposal Facility

17.4.2023

GAP	Greenland Analogue Project
GRS	Research organisation in Germany
GRA	Guidance on Requirements for Authorisation
HSR	Higher Strength Rock
HYDROCOIN	A project for the study of groundwater flow modelling in the context of radioactive waste disposal
IGSC	Integration Group for the Safety Case
IAEA	International Atomic Energy Agency
IBL	International Bentonite Longevity project
INTRAVAL	A project addressing the validation of models of the transport of radioactive substances through groundwater in the geosphere
JAEA	Japan Atomic Energy Agency
JNC	Japan Nuclear Fuel Cycle Development Institute
KINA	Kiruna Natural analogue project
KBS-3H	Geological disposal concept developed in Sweden and Finland for horizontal emplacement of the waste packages
KBS-3V	Geological disposal concept developed in Sweden and Finland for vertical emplacement of the waste packages
LHGW	Low Heat Generating Waste
LSSR	LSSR (lower strength sedimentary rocks)
L/ILW	Low and Intermediate level Waste
MICA	Michigan International Copper Analogue project
MIRAGE	MIRAGE project
MAA	Multi-attribute analysis (MAA)
Nagra	Nagra, waste management organisation in Switzerland

17.4.2023

NA	Natural Analogue
NAnet	Natural Analogue network
NAWG	Natural Analogue Working Group
NDA	Nuclear Decommissioning Authority
NEA	Nuclear Energy Agency
NUMO	NUclear waste Management Organisation (in Japan)
NPP	Nuclear Power Plant
NWMO	Nuclear Waste Management Organisation (in Canada)
NWS	Nuclear Waste Services
ONR	Office for Nuclear Regulation
OPG	Ontario Power Generation Inc.
ONKALO	Posiva's underground facility
OPC	Ordinary Portland Cement
PA	Performance Assessment
PNAS	Philippines Natural Analogue Study
Posiva	Posiva, waste management organisation in Finland
PNC	Power Reactor and Nuclear Fuel Development Corporation (in Japan)
GEOTRAP	Radionuclide Migration in Heterogeneous Geological Media
RWM	Radioactive Waste Management Ltd (UK)
RWMC	Radioactive Waste Management Funding and Research Centre (RWMC) (in Japan)
R&D	Research and development
SA	Safety Assessment
SC	Safety Case

17.4.2023

SKB	Swedish nuclear waste management organisation
SF	Spent Fuel
STUK	Radiation and Nuclear Safety Authority in Finland
THMC	thermal, hydrological, mechanical and chemical (THMC)
TVO	TVO, Power company in Finland
UKDoE	UK Department of Energy
URL	Underground Rock Laboratory
USDOE	U.S. Department of Energy
USNRC	US Atomic Energy Commission
ViSI	Visualisation of System Information
WMO	Waste Management Organisation

17.4.2023

EXECUTIVE SUMMARY

This report presents a strategy for the use of natural analogue (NA) studies in the UK geological disposal facility (GDF) programme and safety case (mainly Environmental Safety Case, ESC within the UK context). At the time of writing, NWS¹ has been focussing on general level considerations (several potential site types and concepts for the GDF) but, in the future, the evolving programme will move towards the site evaluation stage. In this report, a review of the strategic uses of NA information at the international level is presented and, based on this, a strategic approach for the UK programme is proposed. This report is linked to an update of RWM's NA catalogue (see Alexander & Reijonen 2023), work that has been ongoing simultaneously with this strategy development study.

In this report, 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 (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.”* In addition to geological systems, biological processes can also be studied via the NA approach, so these are also included in this report.

In the review of international developments, it was found that information on the strategic implementation of NA information is not readily available. This may be partly due to lack of strategic thinking, or simply because waste management organisations (WMO) do not publish internal strategic discussions. Nevertheless, it is seen important that the topic is discussed here in order to increase the visibility of NA information and its implementation in national geological disposal programmes, such as RWM's GDF development. Another conclusion from the review is there is a cultural aspect to treatment of NAs in international fora, which is present as inherited/predefined complementary/alternative status of NA information. Often the emphasis is set on the uncertainties and qualitative nature of NA. However, this is to ignore the fact that uncertainties are also present in experimental work and modelling studies, they are simply in different places: NA uncertainties are related generally to uncertain boundary conditions, while short term experiments have uncertainties in both spatial and temporal scales. The repeated emphasis of NA uncertainties leads to thinking that the overall uncertainties are somehow bigger than in experimental or modelling work and it has to be acknowledged that NAs provide the only source of data that has relevant time (and often, spatial) frames to geological disposal. When NAs are used only as “alternative” lines of evidence, there is a risk that the information is devolved from the other evidence (experimental lab and URL, modelling). This creates a risk of over or

¹ Nuclear Waste Services (NWS) integrated the expertise of Low Level Waste Repository (LLWR), Radioactive Waste Management (RWM), and the Nuclear Decommissioning Authority (NDA) group's Integrated Waste Management Programme (IWMP). This created an organisation focused on the management of the UK's nuclear waste, safely and securely for generations to come.

17.4.2023

underestimating processes if extrapolated. NAs should be equal part of the knowledge base (no need to label them as alternative).

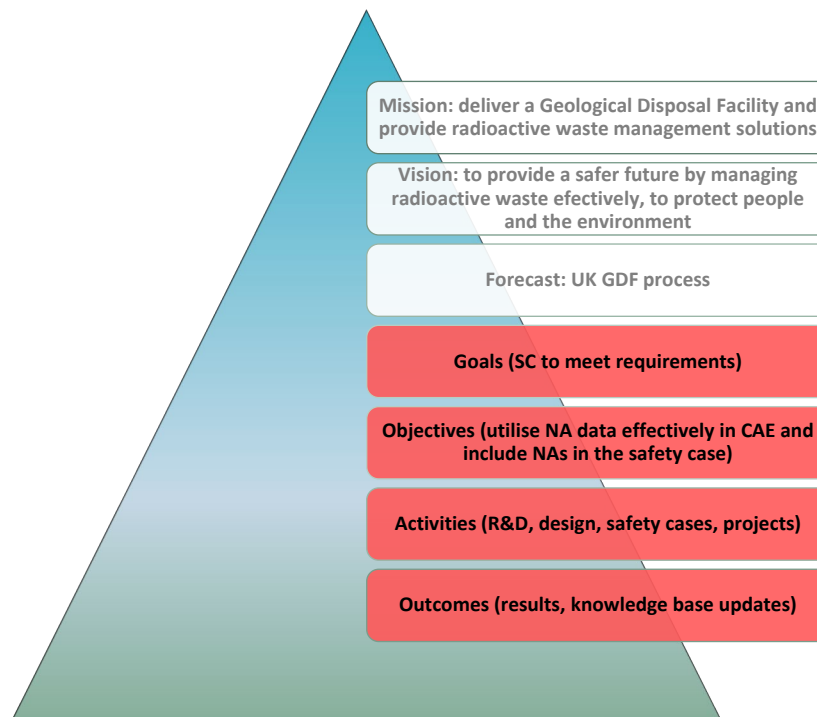
The strategy presented here supports the overall mission of NWS, and highlights the importance of:

- Knowledge management and systematic approaches
- The value and continuous review of existing NA information
- The potential benefits of new NA projects in the future
- The significance and experience of communication with NA information (at various levels with a broad range of stakeholder groups)

Development of a strategic approach to utilise NA information naturally leads to activities to be undertaken in the future and one of the activities emphasised in this report is the potential use of regional analogues. This is timely for NWS when moving towards the site evaluation phase. The emphasis and requirements for NA research will evolve and change as the focus in the geological disposal programme shifts, so preliminary discussion on the operational phase is also included here.

The strategy components are summarised in the figure below. The overall goal is to meet the requirements of the GDF, meaning effective use in the safety case (as a part of the claims, evidence and arguments, CAE, chain). The knowledge base can, and will, grow in the future through GDF activities including NA work, but as the GDF site and design become more specific, screening of the knowledge base is inevitable (e.g. when some materials that may have been part of the generic phase are no longer of interest).

17.4.2023



NWSs mission, vision and forecast are assumed to stay the same. Goals, objectives, activities, and outcomes needed to reach them will change. These are included in the Figure from the NA point of view.

1 INTRODUCTION

1.1 Scope and objectives

The objective of this report is to present strategy for the use of natural analogue (NA) studies and knowledge in the UK GDF programme and safety case (mainly Environmental Safety Case, ESC within the UK context). The scope is set in the current general level considerations (several potential site types and concepts for the disposal) with understanding that the programme will evolve, as the process is taken forward (see section 2.3).

The aim is to review international context and propose a way forward at a strategic level.

1.2 This report

The report content is planned to provide a short introduction to the NWS framework (chapter 2) and background for the strategy development in the form of a review of ongoing and past activities

17.4.2023

internationally (chapter 3). The strategy development is presented in chapter 4. A summary of the strategy is provided in chapter 5 and this aims to provide a concise presentation of the proposed strategy. Plans for disseminating the results of this work is presented in chapter 6. Finally, chapter 7 summarises the main contents and results.

The strategy development work is based on the following aspects:

1. NWS's current framework (see chapter 2)
2. Lessons learned from other waste disposal programmes (see chapter 3)
3. Feedback obtained from NWS staff (questionnaire and workshop)

The final strategy provides answers and suggestions to the following questions regarding the future overall NA strategy:

1. What processes should be followed for knowledge management of NA data? (see section 4.2)
2. How does the evolving programme affect the information quality and quantity and what is the role of the change management? (see section 4.3)
3. What is the role of a gap analysis and screening? (see section 4.4)
4. What type of approaches can be taken at different phases of a GDF programme? (see section 4.5)
5. How to commission NA work in a need based and cost-effective way? (see section 4.6)
6. What role NA projects can play in training of the staff? (see section 4.7)
7. What type of activities are foreseen for the evolving NWS GDF programme (see section 4.8)

1.3 Definitions

In this report NAs are used as a broad term for geological (local or regional), archaeological, and industrial analogues. A definition, that describes the use of the term here as well, is provided by IAEA (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.”

In addition to geology, biological and climatic processes can be studied via analogues. These are also included under NAs in this report.

In this report, the following terms are used:

- Natural analogue: a site where longevity of repository relevant material or host rock type has been studied for one or several safety relevant processes.

17.4.2023

- Regional (or self) analogue: as noted in Alexander et al. (2015) “A self-analogue is a case where some feature of a repository site is studied to provide information on long-term repository relevant processes. For example, definition of the likely long-term behaviour of bentonites utilised in the EBS and backfill of a deep geological repository can best be carried out by examining smectite samples from candidate repository sites. Such a self-analogue has several advantages in that the site boundary conditions, including palaeohydrological evolution, are usually much better characterised than most NA sites due to the much greater site characterisation budgets involved. In addition, there is clearly enhanced confidence that the results are directly site relevant, unlike data from areas which do not share the repository site’s geological history.” As noted in Alexander et al. (2014), such studies are usually classified as a self or regional analogue and, here, it is felt that the term ‘regional analogue’ is more appropriate than ‘self analogue’.
- Archaeological analogue: a study of an archaeological artefact of repository relevant materials or processes, shorter time frames than in natural analogues, but the materials (e.g., Roman concrete, see section 4.1.2 in Alexander & Reijonen 2023) may be a closer analogy.
- Industrial analogue: analogue that covers an even shorter time frame, for example, relatively recent industrial examples of longevity of materials. Once again, the materials (e.g. OPC, see section 2.1.4 in Alexander & Reijonen 2023) may be a closer analogy.

17.4.2023

2 NWS FRAMEWORK

2.1 NWS organisation

NWS as an organisation has personnel with various fields of expertise working in multidisciplinary fields of science and development related to geological disposal of radioactive waste. NAs being mainly geological information, needs to be accounted for at the strategic level, as the knowledge base should be accessible for personnel with different scientific and technical backgrounds. In addition, NAs are used in stakeholder communication, which sets yet another need for presenting information in an understandable form, yet not altering the underlying scientific understanding and complexity.

2.2 Regulatory context

Considering the specific topic of utilizing NAs in the GDF development, there are currently no specific regulatory requirements in UK. The regulatory context guiding the overall ESC work has been based on the requirements set by the authorities (jointly by the Office of Nuclear Regulation (ONR) and either the Environment Agency (EA), Natural Resources Wales (NRW) or the Northern Ireland Environment Agency (NIEA), depending on whether it is sited in England, Wales or Northern Ireland) and in consideration of IAEA recommendations (see chapter 1.3 in RWM 2016a).

The main requirements (GRA 2009) relevant for the context of the current report are UK R3 (requirement for the environmental safety case) and UK R4 (requirement for environmental safety culture and management system). Below, the latest ESC is referred to for how these requirements have been handled most recently:

Requirement R3: Environmental Safety Case

This generic ESC demonstrates how the safety objectives defined by the environmental regulators and the IAEA for geological disposal can be met by addressing the regulatory principles and requirements contained in the GRA [guidance on the requirements for authorization by EA] as far as is possible before a site for the GDF is available. The generic ESC provides an understanding of the long-term environmental safety of geological disposal for a GDF constructed in a range of geological environments based on sound scientific and engineering principles. Section 2.1 [in the ESC] explains how an ESC will be maintained and refined as information is obtained on possible sites for the GDF. (RWM 2016a, Appendix A1)

See also section 2.3 here for the predicted process in the UK.

Requirement R4: Environmental safety culture and management system

RWM's Management Strategy (RWM 2016b) provides confidence that GDF planning and delivery can be achieved in a coherent, integrated way, with appropriate quality and management accountability and a positive environmental safety culture. The Management Strategy is

17.4.2023

summarised in Section 2.2 (RWM 2016a); the broader description of the Management Strategy that was presented in the 2010 generic ESC [NDA 2010, §3.3] is not repeated in this generic ESC. (RWM 2016a, Appendix A1)

2.3 UK GDF process and strategy

Currently, the UK GDF process is moving towards the site selection phase. The foreseeable future will be dominated by activities related to this, while the implementation is expected to start at the earliest in about 20 years' time (Figure 2-1). However, the long-term safety assessment will develop continuously as new information becomes available over the next 20 years along the lines shown in Figure 2-2. What this means in practice is that the site- and concept-specific information will increase, so affecting the content and the focus of the ESC. This approach is also inherently reflected in the existing RD&D programme and the focus of any new projects.

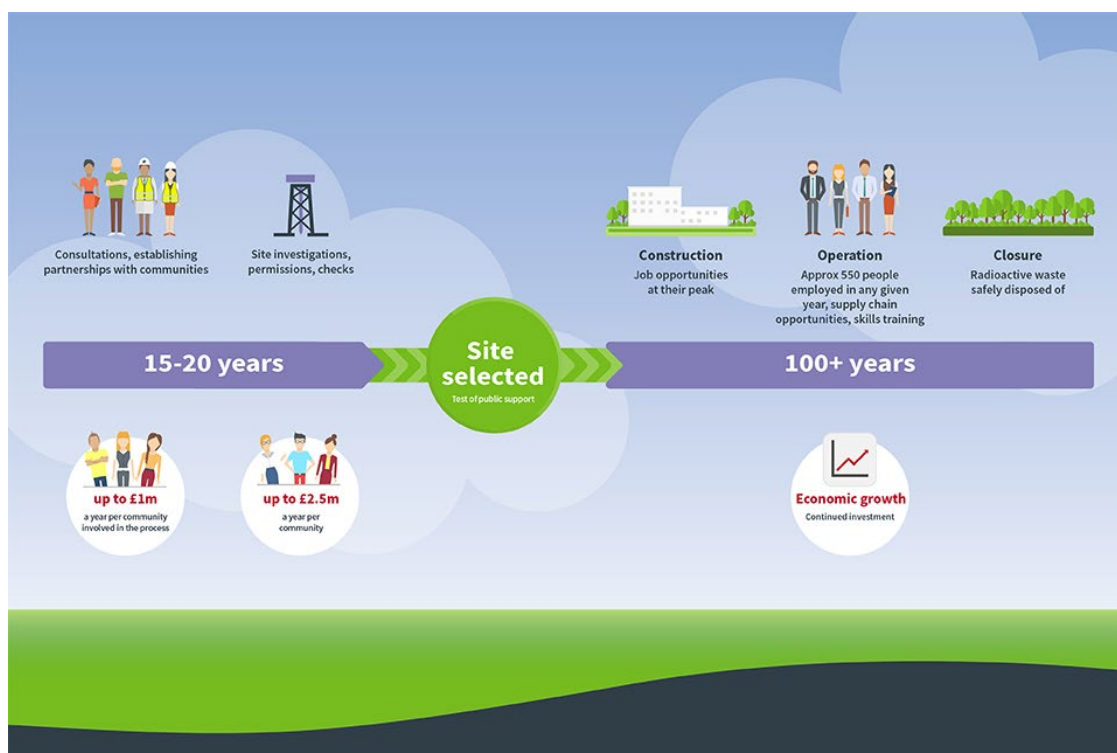


Figure 2-1. The operational timeline of a Geological Disposal Facility (GDF) (source: <https://www.gov.uk/guidance/communities-and-gdf>).

17.4.2023

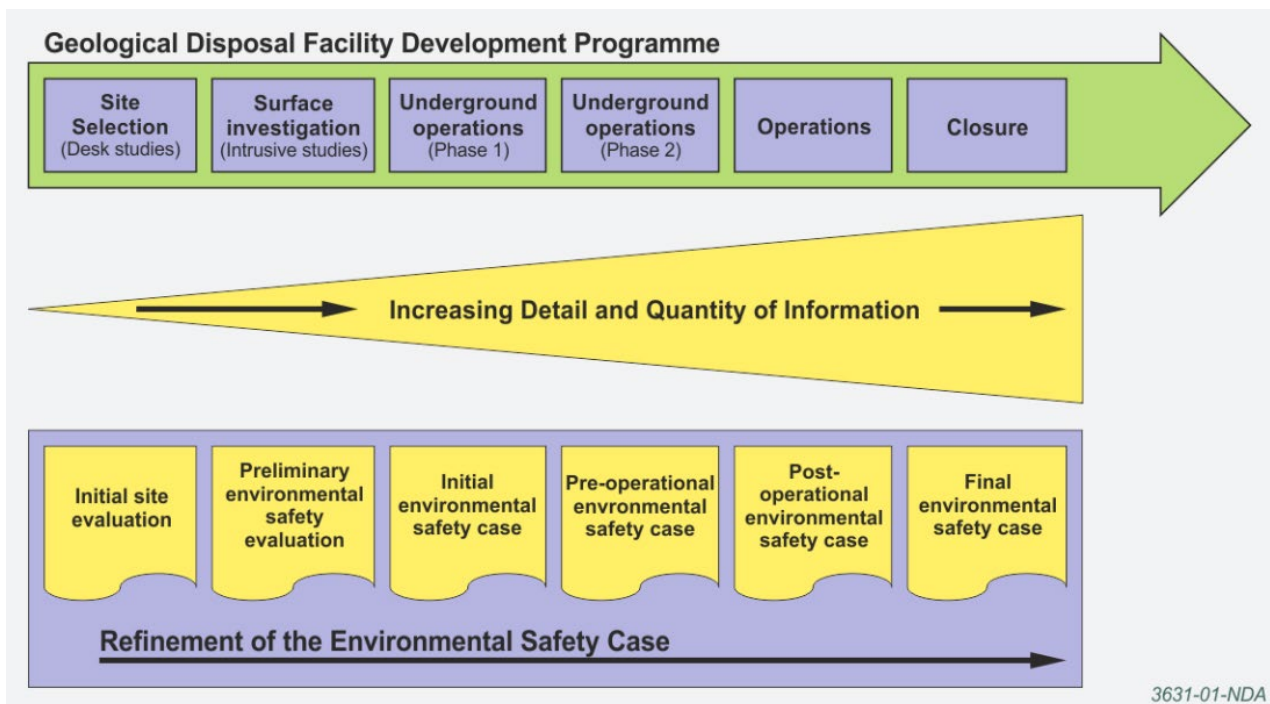


Figure 2-2. Refinement of an ESC as increasing amounts of information in a possible site for a GDF become available as set out in the GRA (GRA 2009, Figure 6.1).

According to Corporate strategy 2019:

- NWS's vision is to provide a safer future by managing radioactive waste effectively, to protect people and the environment.
- NWS's mission is to deliver a Geological Disposal Facility and provide radioactive waste management solutions.

It is further defined in the Corporate strategy that: *"Our vision is aspirational and challenging and is supported by a mission statement which says what we will do to achieve that vision. This strategy describes how we will address this challenge and sets out a number of strategic objectives. Our Business Plan presents a programme of work to meet these objectives."*

In addition, *"Since the previous version of our Corporate Strategy we have reviewed the values and agreed two changes with our Board. One change is to include "Safe" as a specific value to reflect the overriding importance we give to it. The other is to change the previous "Accessible" value to "Engaging". This is to reflect the need for a more proactive style of engagement as we enter the next stage of the programme."*

17.4.2023

NWS Values:

Safe: We are committed to achieving the highest standards of safety, security and environmental protection.

Professional: We are experts in our field, acting with integrity and efficiency to deliver the best solutions.

Engaging: We are open and communicate in a straightforward way that enhances understanding and encourages engagement.

Learning: We continuously learn, share knowledge and build strong mutually beneficial relationships.

The full strategy can be read at:

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/835903/RWM_Corporate_Strategy_2019_a.pdf

The overall strategic framework is used as a basis for this strategy development.

2.4 Safety case and NA

NWS's approach to NA information and its use in the ESC is based on the concept that NAs provide an additional line of reasoning to support the safety assessment. The current requirements explain the use of multiple lines of reasoning *viz*:

“As noted in Section 2.1, it is a requirement of the GRA [Environment Agency and Northern Ireland Environment Agency 2009] that an environmental safety case presents multiple lines of reasoning to support its evaluation of safety. The use of safety arguments based on the understanding of the environmental safety functions of the GDF and their evolution represents an important line of reasoning, which can be developed at this generic stage for the illustrative disposal concepts and can continue to be applied in the context of a site-specific ESC. Insight modelling and more detailed numerical modelling to understand how radionuclides are contained by each component of the GDF's multi-barrier system constitute further lines of reasoning.”

In the ESC (RWM 2016a), NAs are presented as one of the potential lines of reasoning:

“Other lines of reasoning may also be used to support an evaluation of post-closure safety. These include the use of complementary indicators and natural and archaeological analogues. For example, complementary indicators include measurements of groundwater age (by comparisons of oxygen isotope concentrations) that can give confidence in calculated groundwater flow rates. Archaeological analogues include studies of materials proposed for use in the engineered barriers of the GDF to give confidence in calculations of barrier performance. Natural analogues can include comparisons with geological sites that have similarities to one or more components of the GDF. To

17.4.2023

provide a reference source of safety-relevant examples from natural systems that could be used to support a safety case, RWM has produced a catalogue of natural analogues for radioactive waste disposal [Milodowski et al. 2015a].”

In addition to the catalogue, other literature is mentioned:

“Also, in support of the safety case for spent fuel disposal at Olkiluoto in Finland, Posiva produced a report on ‘complementary considerations’ with the objective of enhancing confidence in the safety case [Posiva 2012a]. Posiva’s report includes a compilation of observations from natural and anthropogenic analogues of the disposal facility, its components and the processes that affect safety, and provides a further reference source for consideration in the development of different lines of reasoning to support an evaluation of the safety of a GDF in the UK.”

At the time of writing this report, RWM’s NA catalogue is being updated and this is considered in the development of the strategy presented here.

2.5 NWS content management

NWS has established a novel information platform to aid knowledge management and report production called Visualisation of System Information tool or “ViSI tool” (Figures 2-3 and 2-4). The main objectives of the ViSI tool development have been to (Bailey et al. 2020a):

- aid in the knowledge management process
- make information more accessible
- help needs-driven research planning and
- help to increase the robustness of the safety case

ViSI supports the NWS Business Cycle via a claims-arguments-evidence (CAE) tree structure (Figure 2-3). CAE stands for Claims Arguments Evidence and it is a common framework for reasoning and communicating. The ESC 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.

17.4.2023

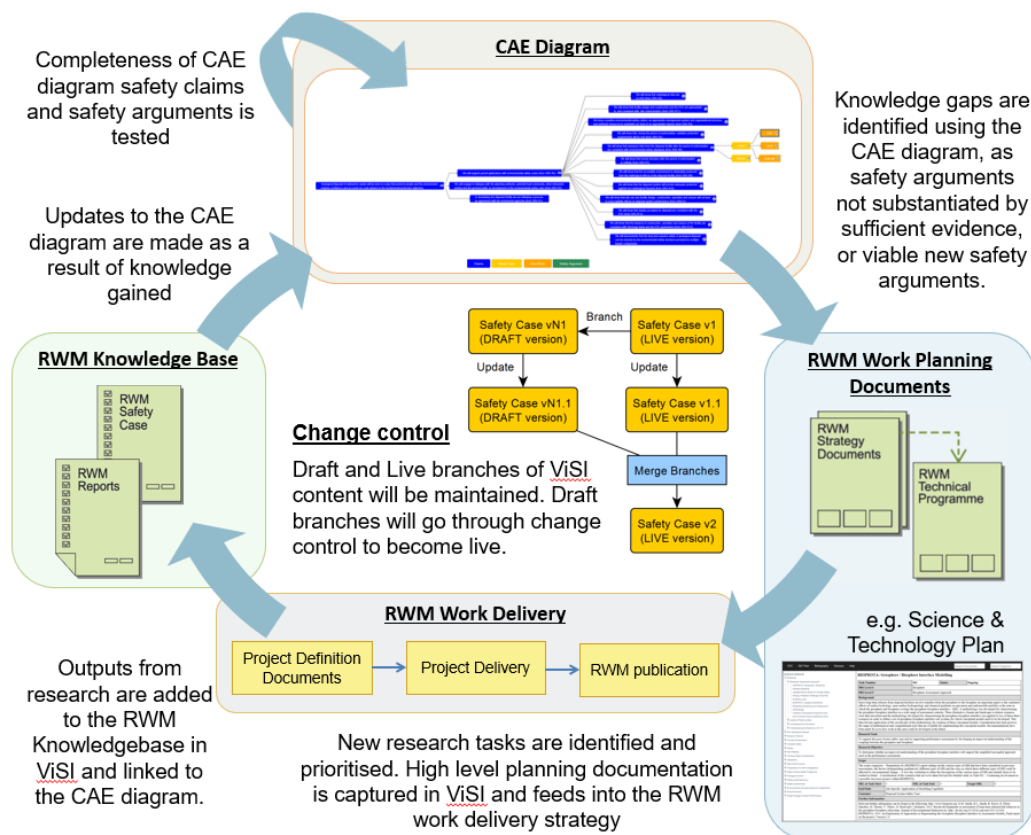


Figure 2-3. ViSI supporting NWS's Business Cycle via CAEs (modified from Bailey et al. 2020a).

Bailey et al. (2020b) also presented an overview on how ViSI is aimed to be used as a digital safety case management system designed to display NWS's GDF ESC in an accessible and traceable manner. In its essence, ViSI is a user interface to access existing information and editing contents to produce new reports and other documentation (Figure 2-5) as (based on Bailey et al. 2020b):

- All safety case documents and diagrams can be loaded via the **home page**.
- Safety case documents are displayed as **navigable**, structured web pages within ViSI. References to other sections, RWM's bibliography and pages displaying metadata are rendered as **hyperlinks**.
- **ViSI can render hierarchical diagrams**, such as the CAE diagram or the Features, Events and Processes (FEP) diagram dynamically. Users can access load underpinning information by clicking on boxes in the diagram.
- **All content is indexed and searchable**. Users can quickly reach sections they need of the safety case and underpinning reports.

17.4.2023

- Content, written in a format that allows **publishing to multiple formats** (web, pdf, ebook), can be produced using a WYSIWYG² editor. A **custom citation system** enables the referencing of sections of the safety case, RWM's bibliography and glossary and tasks on RWM's Science & Technology plan. These references are displayed as hyperlinks in ViSI and their design ensures they are unique, robust and durable.
- ViSI will **incorporate a version control system** for stored documents, which will include the ability to create different 'branches' of versioned content – parallel developments of the same content with a common origin. ViSI will use different branches to help **manage changes to the safety case**, thus enabling the user to manage licencing submissions and facilitate regulatory review.

The screenshot shows the front page of the ViSI content for the 2016 Safety Case. At the top, there is a navigation bar with links for 'ESC', 'S&T Plan', 'Bibliography', and 'Help'. To the right of these links are two search boxes: 'Search Documents' and 'Search Diagrams'. The main heading is '2016 Safety Case' in a large, bold font. To the right of the heading is the 'Radioactive Waste Management' logo. Below the heading, there are two main sections: 'Documents' and 'Diagrams'. Each section contains a list of links to various reports and documents. Below each list is a search box labeled 'Quick Search Documents:' and 'Quick Search the Diagram:', with 'Search Documents' and 'Search Diagram' buttons respectively. The page is clean and professional, with a clear layout and easy navigation.

Figure 2-4. ViSI content 2016 front page (NWS).

² WYSIWYG is an acronym for “What You See Is What You Get”. It denotes the representation of text on-screen in a form exactly corresponding to its appearance on a printout (i.e. the user does not see the underlying code).

17.4.2023

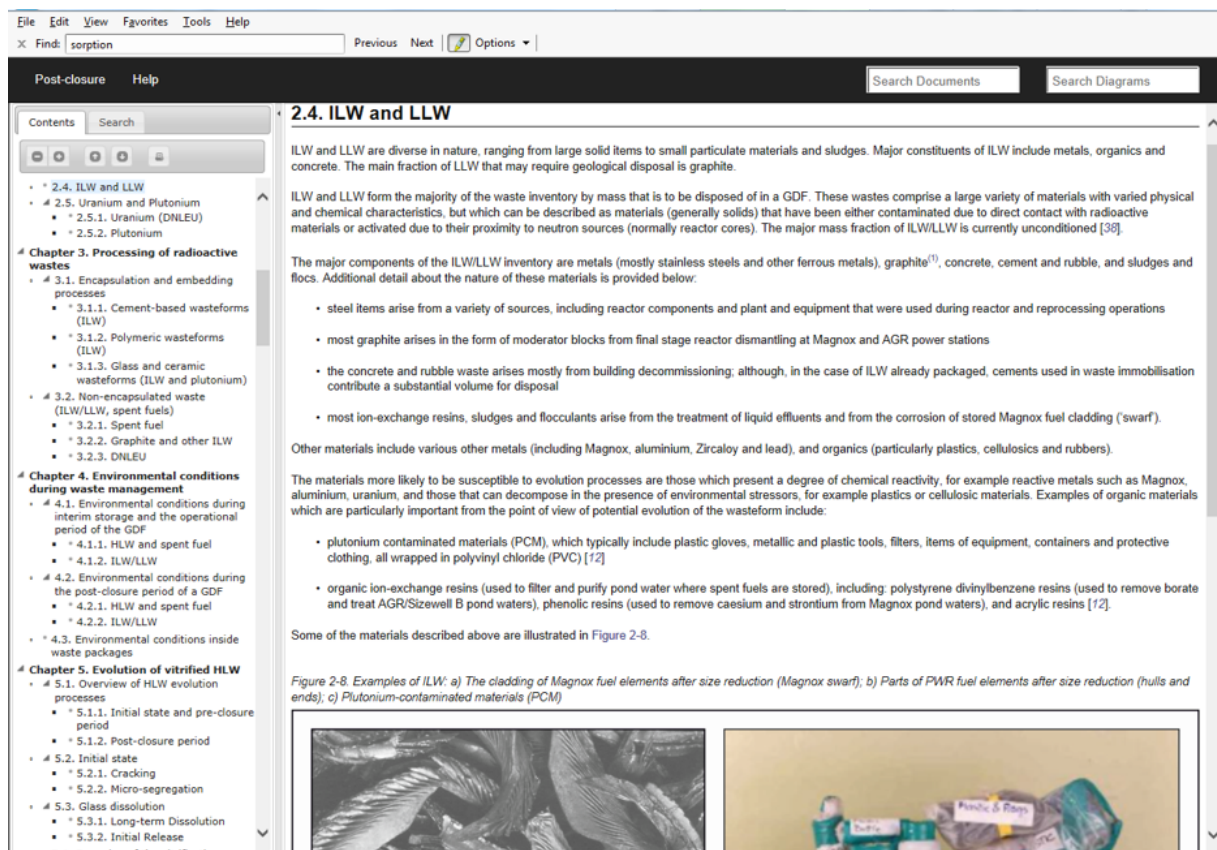


Figure 2-5. Screenshot of the report interface in the ViSI tool (NWS).

The ViSI tool documents and especially diagrams provide a platform for the future knowledge management development at NWS as they allow effective, traceable, and searchable cross linking of information.

2.6 NWS's current and planned involvement in NA projects

All ongoing or currently planned work under science and technology development for geological disposal has been compiled in NWS's planning documentation (RWM 2020a). Below, the main Tasks identified related to NAs have been listed.

Ongoing projects:

- B.5.2.3 Copper Stability Natural Analogues Study (Keweenaw Peninsula, Michigan, USA – "Michigan International Copper Analogue Project")

17.4.2023

- NA on copper stability: the long-term stability of copper is of interest in assessing the long-term performance of high-level radioactive waste repositories, therefore a number of scenarios need to be considered for the post-closure safety case. Copper corrosion is driven by water prevailing in contact with the copper canister, the presence of microbial-induced sulphide, and in the shorter term by contact with air, before saturation. Copper is an important part of many waste packaging concepts, e.g. KBS-3 (Sweden and Finland) and Mark II (Canada). The Keweenaw native copper site provides a natural analogue for examining copper corrosion processes of metallic copper in two important scenarios of HLW disposal. (RWM 2020a)
- B.5.4.4 RWM's Collaboration in Kiruna Natural Analogue Project (KiNa)
 - NA on bentonite stability: A project between Nagra and SKB, ANDRA, NWMO, POSIVA and RWM on collaboration in the Kiruna Natural Analogue Project. The expected outcome of this project will be an important addition to the safety case as it will provide evidence from a bentonite body under repository-like conditions for several hundred million years. More specifically it will provide the following key information: (i) demonstration of sustainable performance of safety relevant aspects of bentonite such as swelling pressure and low hydraulic conductivity; (ii) a validation of the model for iron and bentonite interaction; (iii) insight into the evolution of the mechanical properties of smectite aged several hundred million years. In the north of Sweden, the up to 50 m thick clay alteration zones have been encountered in the Kiruna-type magnetite(- hematite)-apatite deposits, which are hosted in weakly to strongly metamorphosed intermediate to acid volcanic and subvolcanic rocks. Preliminary data indicates that the clay contains a high amount of montmorillonite and that the swelling pressure and hydraulic conductivity are similar to that of commercial bentonites intended for repository use. (RWM 2020a)
- B.5.4.5 Sealing Deep Site Investigation Boreholes: Phase 4: including the International Bentonite Longevity (IBL) project
 - NA on bentonite stability: In the EA Guidance on Requirements for Authorisation for Geological Disposal Facilities on Land for Solid Radioactive Wastes (EA 2009) the regulator recognises the potential for deep boreholes, such as those that could be drilled as part of a site investigation process, to affect the integrity of a site. RWM commenced its "Sealing Deep Site Investigation Boreholes" project in 2013. Phase 1 and 2 are now complete. Phase 4 extends Phase 3 to undertake more field-scale work in pre-existing UK unsealed boreholes in lower strength sedimentary rocks and higher strength rocks, plus overseas work in halite. This task sheet covers Phase 4 of the project. The Scope of Phase 4 activities include: bentonite natural analogue study (International Bentonite Longevity project). (RWM 2020a)

17.4.2023

Future plans including NA aspects have been mentioned at least in the following task descriptions:

- B.5.2.2 Natural Analogue and Modelling Study of the Implications of GDF Operations on Geosphere Host Rock Properties
 - Modelling task utilising industrial analogues: This task may follow the previous review of learning from natural analogues and includes modelling of the information gained from the previous task. This task is of particular significance when considering a possible period of extended retrievability. The scope comprises a desk-based study on the disturbed zone, its evolution and its safety case significance. A modelling component will include analysis of information derived from natural and industrial analogues and will include an investigation of what can be learned from existing underground voids to inform GDF-relevant studies (for example, the evolution of rock-bolting; evolution of the excavation disturbed zone; and the relationship between vault construction methodology, its resulting excavation disturbed zone, and how that excavation disturbed zone has evolved). (RWM 2020a)
- B.4.3.8 Gas Migration in a Tight Fractured Rock and Gas Hold-up by Cap Rocks (HSR)
 - Learning from literature (regional analogues). There is a need to demonstrate an in-depth understanding of gas migration from a GDF, relative to the rate and distribution of gas release and the geometry and properties of fractures in HSR, to support the ESC. The scope of this task could include:
 - The further development of modelling approaches for two-phase flow. A practicable generic approach to *in situ* evidence of processes is to study analogues for gas migration in HSR.
 - Literature review on specific topics (gas dissolution, sorption, saturation-dependent diffusion coefficients, natural gas seeps and case studies of the failure of natural gas storage systems, large-scale onshore CO₂ studies providing further information regarding potential induced seismicity).

17.4.2023

3 BACKGROUND

3.1 Overview on the use of NA information

NAs are considered in international safety case guidance by Nuclear Energy Agency (NEA) (e.g. NEA 2004, 2013) to be a part of the safety assessment:

- *The safety assessment analyses repository performance and provides a quantitative estimate of potential radiological consequences associated with a range of possible analysed evolutions of the system over time, i.e. for a range of scenarios. It also serves to identify uncertainties that affect the assessed level of safety. Other evidence and arguments (in some programmes described as being a qualitative part of the safety assessment) include the intrinsic quality of the site and the design, the use of natural analogues, an account of measures taken to assure the quality of the safety assessment, and a strategy to address residual uncertainties and outstanding issues. (NEA 2013)*
- *Some uncertainties can be reduced by methods including additional site characterisation, design studies, fabrication and other demonstration tests, experiments both in the laboratory and in underground test facilities. As a programme matures, studies will increasingly focus on key safety-relevant uncertainties and the specific data and measurements needed to increase confidence in system safety. For example, in situ experiments of radionuclide migration may improve confidence in the migration models or allow their improvement. In some cases, uncertainty can be managed by seeking multiple lines of evidence for particular assessment assumptions or parameters, including, for example, evidence from natural analogues to support the longevity of engineered materials. (NEA 2013)*
- *The nature of the safety assessment outcome:... The results [of the safety assessment] are also discussed in the context of any independent supporting evidence (e.g. the existence of relevant natural analogues for the repository). This work creates the synthesis of evidence, analyses and arguments that quantify and support the results of the safety evaluation and constitute the safety case. (NEA 2013)*
- *The possible evolutions and performance of a well-chosen geological site and host rock and a well-designed engineered system can be bounded with reasonable confidence over sufficiently long time scales to assure adequate system safety. Supporting evidence of such bounding can be evidence concerning the stability of geologic formations in general, natural analogues, or natural tracer profiles. (NEA 2013)*

NAs are included as qualitative evidence, alternative lines of evidence, independent evidence or bounding information, which all more or less detach them from the quantitative part of the safety case. The emphasis is on the qualitative information, but the use as bounding information, brings the potential use closer to the quantitative part of the safety case.

17.4.2023

Most safety case work is based on the overall NEA's approach with modifications. However, the exact use of the analogue information varies widely between waste management organisations (WMOs).

Overall, it can be stated that NAs form an integral part of considering the long-term relevance of any FEPs identified in the safety case if such information is available. NEA does not explicitly mention NAs as a part of the assessment basis, but naturally they form a part of the scientific basis that underlies the assessment.

One attempt to illustrate the positioning of the analogue information in the prediction process of material behaviour is presented in Figure 3-1, emphasising the importance of understanding the past to be able to start projecting the future. Gin et al. 2017 emphasise the integration of the experimental science (including learning from the past), engineering and predictive modelling to meet the challenges of long-term safety needs. The view of Gin et al. (2017) repeats the overall views of previous works such as Miller et al. (1995), Miller et al. (2000) and Alexander et al. (2015).

In addition to feeding into the prediction of the future (see above), the long-term aspects and the very nature of NAs compared to the experimental evidence can be illustrated via time-space diagram. Several examples of this can be found in the literature, but here, a generic one from Posiva is used, as it captures the essential (Figure 3-2): NA information extends both temporally and spatially beyond the experimental work, but also can overlap them. Depending on the process, not only can very slow long-term processes be observed via analogues, but also the more dynamic ones.

An overview of the role of analogues in GDF development is provided in Figure 3-3, emphasising the integration of NA as a part of a multi-faceted process which supports safe disposal of radioactive wastes.

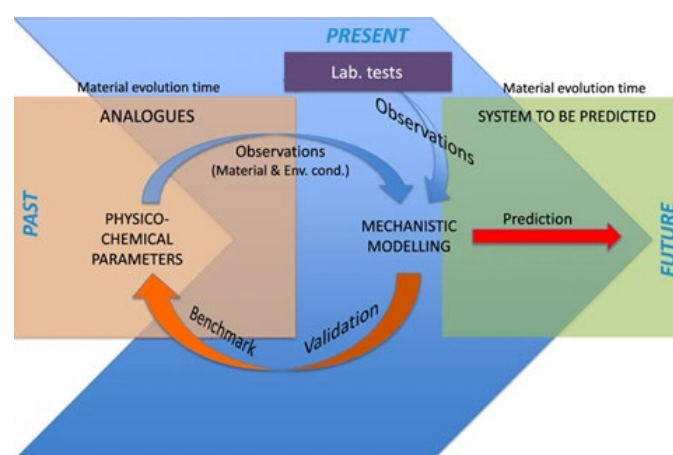


Figure 3-1. Example of positioning of approaches using NAs in the overall prediction process (Gin et al. 2017).

17.4.2023

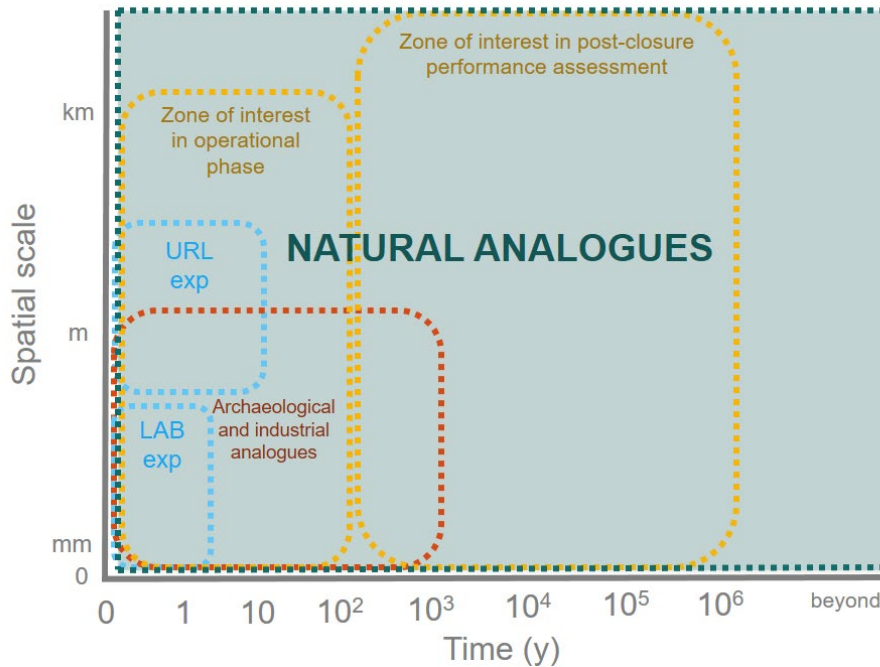
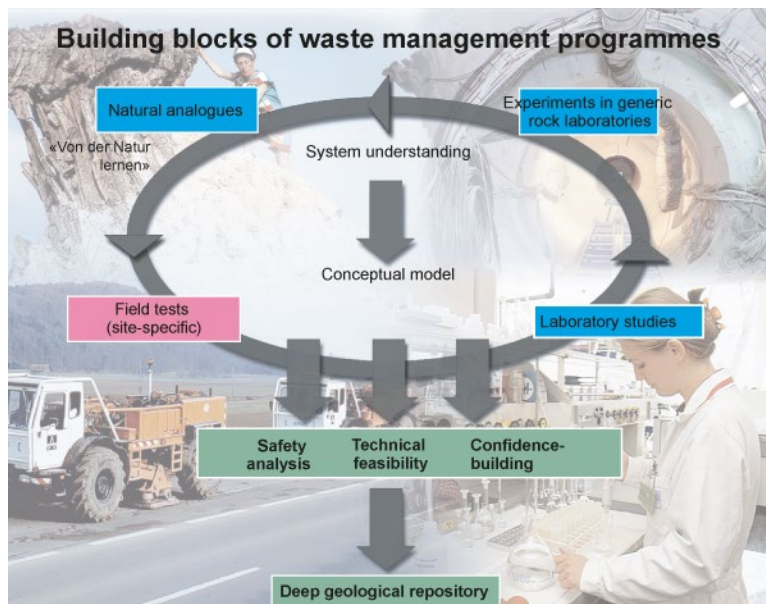


Figure 3-2. Schematic illustration of the spatial and temporal scales for experiments, NA studies and the scope of assessing performance (Reijonen et al. 2022). URL=underground rock laboratory, LAB=laboratory, exp= experiments, 'operational phase'=period of repository construction, waste disposal and repository closure'.



17.4.2023

Figure 3-3. Role of NAs in system understanding and conceptual model development (Alexander et al. 1998).

3.2 Previous work on NA strategy development internationally

3.2.1 EU NAWG

Background

From 1982, the Commission of the European Communities (CEC) had been involved in specific work on NAs in the framework of its activities on radioactive waste management, principally within the MIRAGE project which concerned migration of radionuclides in the geosphere. In parallel with these CEC activities, more consideration was being given to the application of NAs in the field of radioactive waste disposal overall and, in 1984, a report (Chapman et al. 1984) was commissioned by SKB and Nagra on the topic. In October of the same year, SKB and the USDOE organized a workshop at Lake Geneva, USA, to consider NAs of crystalline rock environments. The concept of an international working group on the NA theme emerged in the technical discussions held there (see Smellie 1984 for details).

In April 1985, SKB, the USDOE and Nagra (and subsequently the UKDoE) discussed the launching of an international research programme at the Poços de Caldas site in Brazil and, consequently, the idea of a working group focussed on ongoing NA projects came once more to the foreground. This and other ongoing EU-funded research led the CEC, in June 1985, to enlarge the nucleus of specialists which had been active in NA studies for the CEC project MIRAGE since 1982 (see Chapman & Sargent 1984 for details), to include all those who had developed or were planning projects in the field. The CEC felt that this proposal offered a twofold advantage: in meeting the need for an international discussion forum which would be wider than the CEC nucleus; and by starting from a pre-existing structure.

This was the origin of the EU-Natural Analogue Working Group (NAWG – in which the CEC acted as the NAWG secretariat and published NAWG meeting reports under their EUR system). It was planned from the beginning that, within the group, safety case modellers and the producers of NA data could meet regularly to exchange information and experience.

In the first workshop report (Come & Chapman 1985), the ad hoc group 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:

17.4.2023

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 NA in 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 NA 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. There have been 17 NAWG workshops since the first in 1985 (Table 3-1) and the proceedings are available in the original EU report series or online on the NAWG web site (as noted in the table).

Table 3-1. List of the NAWG workshops since 1985.

NAWG Workshop	Date	Location	Theme and publication
1	5-7 November, 1985	Brussels, Belgium	Interaction between (safety case) modellers and data providers (Come & Chapman 1985)
2	17-19 June, 1986	Interlaken, Switzerland	Anthropogenic analogues and the role of colloids, complexes and microbes were reviewed (Come & Chapman 1987a)
2a	28-30 April, 1987	Brussels, Belgium	<i>The role of NA in radioactive waste disposal (Come & Chapman 1987b)</i>
3	15-17 June, 1988	Snowbird, USA	The application of NAs to GDF performance assessment (Come & Chapman 1989)

17.4.2023

NAWG Workshop	Date	Location	Theme and publication
4	18-22 June, 1990	Pitlochry, Scotland	Review of the first 5 years of NA studies and the final conclusions drawn from the Poças de Caldas study (Come & Chapman 1991)
5	5-9 October, 1992	Toledo, Spain.	General NA discussions and the final workshop of the Alligator Rivers Analogues project (von Maravic & Smellie 1994)
6	12-16 September, 1994	Santa Fe, USA	Review the "state-of-the-art" of several key NA issues in near-field and far-field processes and their importance to PA with the intention to provide a consensus view of the remaining areas requiring further NA research (von Maravic & Smellie 1996)
7	28-30 October, 1996	Stein am Rhein, Switzerland	General NA discussions and the potential application of NAs to toxic waste disposal (EUR 17851 EN)
8	23-25 March, 1999	Strasbourg, France	Overview of three major international NA projects, Oklo (II), Palmottu and Pena Blanca (von Maravic & Alexander 2002)
9	20-21 June, 2002	Aarau, Switzerland	Short meeting on the current status of NA studies worldwide (<i>No report</i>)
10	25-26 August, 2007	Munich, Germany	Discussion on how current and future NA studies could be better focussed on providing appropriate data for the various end-users of NA data. https://www.natural-analogues.com/nawg-workshops/nawg-10-2007-germany
11	11-15 October, 2009	Liverpool, England	Short meeting on the current status of NA studies worldwide (<i>No report</i>)
12	11-13 May, 2011	Larnaca, Cyprus	Overview of the Cyprus NA Project (CNAP) and overview of ongoing NA studies. https://www.natural-analogues.com/nawg-workshops/nawg-12-2011-cyprus
13	13-16 May, 2013	Nagoya, Japan	General overview of ongoing/recent NA studies. https://www.natural-analogues.com/nawg-workshops/nawg-13-2013-japan
14	9-11 June, 2015	Rauma, Finland	General overview of ongoing/recent NA studies. Alexander et al. (2015) https://www.natural-analogues.com/nawg-workshops/nawg-14-2015-finland
15	23-25 May, 2017	Prague, Czech Republic	General overview of ongoing/recent NA studies. Alexander & Havlova (2023) https://www.natural-analogues.com/nawg-workshops/nawg-15-2017-czech-republic
16	15-18 October, 2019	Zao Onsen, Japan	General overview of ongoing/recent NA studies and site visit to the IBL project. Alexander et al. (2023).

17.4.2023

As can be seen in Table 3-1, although NAWG ceased to be a CEC associated body around twenty years ago, it is still operational and currently functions as an *ad hoc* group of individuals who collaborate to promote appropriate use of NA data in national safety case.

Comment: how has NAWG helped in promoting a strategy of using NA in national programmes?

As noted above, this was never an actual aim of the original founders of NAWG and, due to the significant differences between individual national programmes (in waste streams, host rock types, GDF designs and regulatory environments), this is arguably beyond an international group such as this. Nevertheless, the fact that NAWG is now into its fourth decade and that the majority of that time has been without formal funding from any national or international body such as the CEC, shows that there remains a role for NAWG in the overall promotion of the use of NA in waste disposal.

3.2.2 IAEA

Background

Following the initiative of NAWG, the IAEA became actively involved in promoting the use of NA in the safety case and Vovk (1988) introduced an upcoming report (IAEA 1989) on the subject at the third NAWG workshop. However, as noted in the introduction to the work “This report briefly summarizes the state of the art in this field for technical specialists and may also serve as an introduction to the subject for managers.” and so it was produced as more of an overview of existing technical studies (such as Cigar Lake) with some general comments on how to use NA. Confusingly, the contents were a little illogical with chapter 3 (Potential roles of analogues in performance assessments) following on behind chapter 2 (NAs in performance assessment). Following on after this early start by the IAEA, most of their sparse output over the following 15 years was focussed on specific technical studies (e.g. Mazurek et al. 1992, IAEA 2005a), rather than offering any particular form of advice on strategy. When such an attempt was made (e.g. IAEA 1993, 1994a), the discussion of NA tended to be rather superficial and statements on uses of NA in the safety case were invariably tempered by words such as ‘may’ and ‘could’.

IAEA (1989) was followed up by IAEA (1999) and, here, the authors attempted to address more strategic issues, noting that the report would focus on what the authors felt were the most useful aspects of quantitative applications for model development and testing (geochemistry and coupled transport models). And went on to state “*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.*”

17.4.2023

Overall, the report provides both a useful overview (e.g. IAEA, 1989: Table II) of the technical uses of NA in safety case up to that point and a helpful set of guidelines for the overall use of NA in safety case. But concrete strategic recommendations are scarce, although the last point notes:

- *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 repository sites. This is essential for further refinement of models and for the detailed optimization of disposal systems.*

IAEA (2003b) and IAEA (2005) offered some examples of the use of natural safety indicators and natural (radionuclide) concentrations and fluxes in supporting the safety case, but IAEA (2003a) proffered somewhat more concrete statements such as:

“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 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, in effect, the IAEA addressing the less tangible aspects of NA use for the first time and, in section 5.5 (Confidence building in the results of SA/PA) of the report they reported that the key issues in confidence building are:

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

It was further noted that *“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*

17.4.2023

great extent in the support of PA and is only now starting to drive the data gathering specifications of site characterization programmes.”

Within section 5.5.1 (Natural analogues) of IAEA (2003a), there is some discussion of how generic NA information can be employed in a generic safety case, but no attempt is made to propose how to actively encourage the use of NA in national programmes nor how to lay down strategic plans to encourage any such use.

Comment: how has the IAEA helped in promoting a strategy of using NA in national programmes?

While the broad reach of the IAEA waste programme means that any of their documentation on NA has surely helped promote at least awareness of NA issues (if not the actual use of NA information), the generally superficial nature of the material published to (e.g. IAEA 1975, 1989, 1999, 2003a, 2005) date means that the impact has probably been minimal. It could be argued that developing national programme strategies is not in the IAEA’s remit, but this would be naïve considering the above-mentioned broad reach of the organisation. And certainly, they have striven to produce similar ‘how to do it’ documentation for other topical areas of waste disposal (e.g. IAEA 1985, 1993, 2018).

3.2.3 NEA

Background

The NEA did not produce anything on the use of natural system (including geoscientific) data until they participated (along with SKI, the then Swedish regulator) in the HYDROCOIN (1984-1990)³ project (see HYDROCOIN 1992) and both the INTRAVAL (1987-1993) project Phase I (e.g. INTRAVAL 1994) and Phase II (e.g. Rasmussen et al. 1996). All projects focussed on the verification, testing and validation of models of the transport of radionuclides in groundwater through the geosphere. The above projects (summarised in Larsson et al. 1994) indicated a lack of appropriate geoscientific information for input to safety case and this led to 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 focused 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 and actually touched upon the use of NA

³ HYDROCOIN succeeded the INTRACOIN project (1981-1986) which was directed solely by SKI (see, for example, INTRACOIN 1984, for details).

17.4.2023

information for the first time (albeit, only peripherally, with the first project report merely noting that NA data are “underused” in the safety case; NEA 2004, Table 1).

The AMIGO project consisted of three workshops and a widely distributed questionnaire which aimed to collect information on organisation’s experience in using geoscientific data in the safety case. While the project summary report (NEA 2010) claimed that “...considerable progress has been made since 2002 in defining the roles of geoscientific information in safety cases.”, the same cannot be said of the handling of NA input where they noted “of course, not all aspects are fully resolved; practical challenges and debate remain in some areas related to, e.g. the use of natural analogues.....”. Other comments in the project reports suggest that the use of NA data was clearly understood, for example, in Table 2 of NEA (2010), it is stated that “The use of information from NA in a safety cases is often restricted to a specific process, or part of the system, for which the basis of transferability can be demonstrated (e.g. the interaction of hyperalkaline water with the rock matrix – e.g. Maqarin, Jordan)”. Further, it was also stated that “...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” (although this misuses the point that such ‘negative analogues’ were discussed and clarified in 1991⁴)

Interestingly, at the same time as these messages on NA usage were published, 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.

Apart from the above-mentioned AMIGO project, the NEA’s first (and so far, sole) foray into strategic planning (for the use of NA in a national safety case) was in 2013 when the NEA’s Salt Club⁵ held a three day workshop in Braunschweig (Germany) and the proceedings (NEA, 2014)

⁴ As noted in Come & 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 massive degradation of granite by kaolinization, and the formation of uranium ore deposits requiring a massive movement of uranium.”

⁵ 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 GDF 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 SC issues (in the German national programme).

17.4.2023

included many recommendations for both the strategic use of NA in a safety case for an evaporitic host rock, but also included much comment on developing a strategic plan for the German national programme at the time (see comments in section 3.2.8 for further detail). There is little indication in the literature that the report made much impact, but this is probably more a reflection of the limited number of national programmes considering an evaporitic host rock than any intrinsic problem with the report (see also further comments in section 3.2.8).

Comment: how has the NEA helped in promoting a strategy of using NA in national programmes?

In many areas of radioactive waste disposal, the NEA has arguably been very active in pushing strategic planning in national programmes. For example, 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 GDF implementation, the IGSC also provides a platform for international dialogues between safety experts to address strategic and policy aspects of GDF development.

As the above-mentioned Salt Club is a sub-group of the IGSC, it could be argued that the NEA is also lending support to developing a strategy for the use of NA studies and knowledge in national programmes and safety cases. However, the output of the AMIGO project to date has been limited to publications that have mixed messages on the use of NA data. This has probably been more of a hindrance than a help in planning the future strategic use of NA information in a national programme.

3.2.4 EU NAnet project

Background

NAnet (NA network) 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 considered⁶ applications of analogue information in safety assessments of radioactive waste repositories and for communication purposes.” (NAnet 2006a). To fulfil this aim, NAnet undertook a critical review of published NA studies and their previous applications in safety assessments and public communication. Four thematic areas were identified:

- Near-field
- Far-field

⁶ The authors carefully avoided stating ‘more considered than what’.

17.4.2023

- Surface environment⁷
- Communication

In total, some 78 NA studies (from Akrotiri to Zirconolite, see Appendix 1 for details) were considered and, to make intercomparison possible, a framework of headings was used for the review of all studies including:

- Description (usually including at least one figure)
- Relevance
- Positions in the matrix tables (see below)
- Limitations
- Quantitative information (*produced in the study*)
- Uncertainties
- Time-scale
- PA/safety case applications (*i.e. in which safety case was information used?*)
- Communication applications (*i.e. any examples of the information from the study used for communications purposes?*)
- References
- Added value comments (*i.e. reviewers' comments on possible improvements in the study itself or in how the information could be better used*)
- Potential follow-up work (*i.e. what else could be done in the study?*)
- Keywords
- Reviewers and dates (*note, some studies had sole reviewers, others had multiple reviewers*)

In addition to the list of headings to be addressed for each reviewed study, a matrix of relevant processes was developed for the four thematic areas. Table 3-2 shows the matrix developed for the near-field NA review. In addition to providing information on process-material combinations which would be likely and unlikely (or 'invalid' in the report) in the GDF near-field, the matrix identifies relevant NA studies which could provide additional information for the SC (or stakeholder communications)

⁷ The analogues considered therefore relate to studies dealing with, or impacting on, processes occurring at the geosphere-biosphere interface and to the effects of near-surface to surface contaminant transport. Biologically-influenced pathways were specifically excluded.

17.4.2023

Table 3-2. The generic analogue matrix for the near-field (NAnet 2006a, Table 6). The shaded squares represent 'invalid' process-material combinations that would not occur in a GDF. The empty squares represent process-material combinations that can occur in a GDF but which have yet to be investigated in a NA study.

17.4.2023

		Wasteform			
		Glass	SF	Cement	Others
Degradation of the engineered barriers	Mechanical	Glasses: archaeological Glasses: natural	Bangombe Cigar Lake Oklo Shinkolobwe	Hadrian's Wall	Bitumen studies Resin studies Synroc studies
	Chemical (corrosion, alteration and radionuclide release from wasteform)	Glasses: archaeological Glasses: natural	Alligator Rivers Bangombe Cigar Lake El Berrocal Mina Fe Oklo Tono Peña Blanca Shinkolobwe Marysvale	Hadrian's Wall Khushaym Matruk Maqarin Scawt Hill	Bitumen studies Resin studies Synroc studies
Radionuclide transport	Advection (flow)			Beziers Maqarin Khushaym Matruk Hadrian's Wall	
	Diffusion				
	Colloid transport				
	Two-phase flow				
Radionuclide retardation	Sorption, precipitation and physical retardation	Glasses: archaeological Glasses: natural	Bangombe Alligator Rivers Cigar Lake El Berrocal Mina Fe Oklo	Maqarin	

Comment: how has NANet helped in promoting a strategy of using NA in national programmes?

It did not for several reasons:

17.4.2023

- 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
- The ‘critical reviews’ tended to be far from that, possibly because the reviewers knew the report was to be openly published (and therefore were overly polite) and almost certainly because many had little or no experience in a safety case and so had little idea of what was and was not of relevance⁸. Finally, in several cases, the reviewers had been directly involved in the study under review, probably colouring their view of the value of the work somewhat
- 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 – see section 3.2.1). 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.”

 - Looking beyond the comments on the relevance of some of the material and the quality of the reviews of said material, questions have to be asked as to whether having such a list of uncritical reviews (never mind keeping them updated) is of any relevance when developing a strategy for the use of NA studies and knowledge in the UK GDF programme and safety case.

3.2.5 Finland

⁸ Several examples of this are apparent in Table 3.2.4-1. Oklo, Bangombe and Shinkolobwe are poor analogies of both SF and EBS degradation (see discussion in Miller et al. 2000). Khushaym Matruk is a diffusive system (see Pitty & Alexander 2011, for details), so how could it possibly be of relevance to advective radionuclide transport?

17.4.2023

Background

In Finland, the use of NAs in the safety case is required by the regulatory body in relation to requirements to include complementary considerations in the safety case (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. [2018-02-13]

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. [2018-02-13]

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. [2018-02-13]

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 NA 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 concept (Figure 3-4). 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 the Posiva's disposal concept, Olkiluoto site and future scenarios, most recently:

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

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

17.4.2023

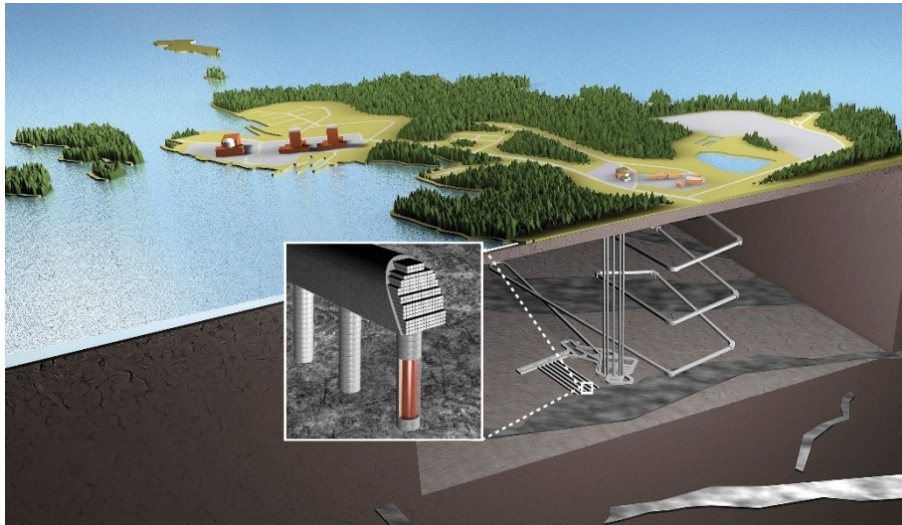


Figure 3-4. Schematic presentation of the KBS-3V GDF at Olkiluoto island. Image courtesy of Posiva (www.posiva.fi).

Comment: how has Posiva’s work helped in promoting a strategy of using NA in national programmes?

Posiva has provided an example of handling NA information as complementary considerations (CC) (Neall et al. 2007; Posiva 2012a; 2023a), mainly focusing on presenting alternative lines of evidence. Strategy has been promoted by STUK, the regulator, by the regulatory framework for safety case (see above).

Posiva presented in their 2012 safety case a state-of-the-art review specific to Olkiluoto site and KBS-3 concept (Posiva 2012a). This was further propagated towards the use for the international programmes in 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 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)*
- *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,*

17.4.2023

- *Additional discussions on process understanding (i.e. FEP descriptions) and screening of FEPs (c.f. Alexander and Neall 2007)."*

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).

3.2.6 Japan

Background

The first generic safety case (generally known as H3; PNC⁹ 1992) in the Japanese national programme included NA data as supporting information regarding bentonite stability and radionuclide migration in the geosphere. The future use in the national safety case was confirmed when AEC (Atomic Energy Commission of Japan) noted in their regulatory guidelines (AEC 1994) the importance of continuing NA studies subsequent to H3, in particular with a view to understanding long-term phenomena. The regulations were followed when JNC (Japan Nuclear Fuel Cycle Development Institute, PNC's successor) produced the second generic safety case (generally known as H12; JNC 2000) which significantly increased their use of NA information, in this case particularly for canister corrosion rate estimates (see the discussion in section 3.3.2.4 and Alexander et al. 2015, for details). This pattern has continued through subsequent safety cases with the most recent generic safety case (NUMO 2021) including a specific supporting report (Alexander 2021) which focussed on providing NA information in support of the safety case findings.

As the Japanese national regulations include guidance to utilise NA information in the safety case, it might be expected that little thought was given to development of a strategic plan to utilise NA data in the safety case, but this is not the case. In 2006, RWMC (Radioactive Waste Management Funding and Research Centre) initiated a project with the aim of producing a step-by-step plan to ensure that NA information became an integral part of future safety cases in the national programme. The work is described in detail in McKinley and Alexander (2007a, b) and Alexander et al. (2007) and a condensed version is presented here.

The process was formally structured by a bottom-up critical assessment of internationally published NA literature (due to their depth of experience in the NA field, this was carried out by RWMC's main contractors), focus was placed on the requirements to provide input to the development of the safety case for the national programme. Due to the direct experience of some of their staff in the above-noted previous safety cases, this was carried out by RWMC, starting from an assessment of the weighting given to the wider aims of the NA programme, taking account

⁹ Power Reactor and Nuclear Fuel Development Corporation (PNC) (in Japan)

17.4.2023

of secondary aims associated with the “safety strategy” and the practical constraints resulting from the likely duration of the NA project when compared to national programme deadlines. This then led to specification of optimised NA project(s) in a top-down manner, representing main goals in terms of individual work packages (WPs), bearing in mind that there can be synergies involved in combining such WPs at a suitable location. This was concluded with a process for site selection, which can also be carried out in a structured way using some form of multi-attribute analysis (MAA – cf. Alexander and Milodowski 2008).

As the national programme safety cases had all been generic to that point, it was decided to focus on a bottom-up development of a preliminary NA ‘wish list’ (something which is probably not necessary in a more mature programme). This process was initiated by a critical review of the NA literature, producing summaries of key publications and producing an archive of all relevant material. This provides input to the process, in terms of identification of areas where required input for the Japanese programme could be obtained from existing published work and other relevant areas where little information was available. This was the knowledge base that forms the core around which the safety case support was built.

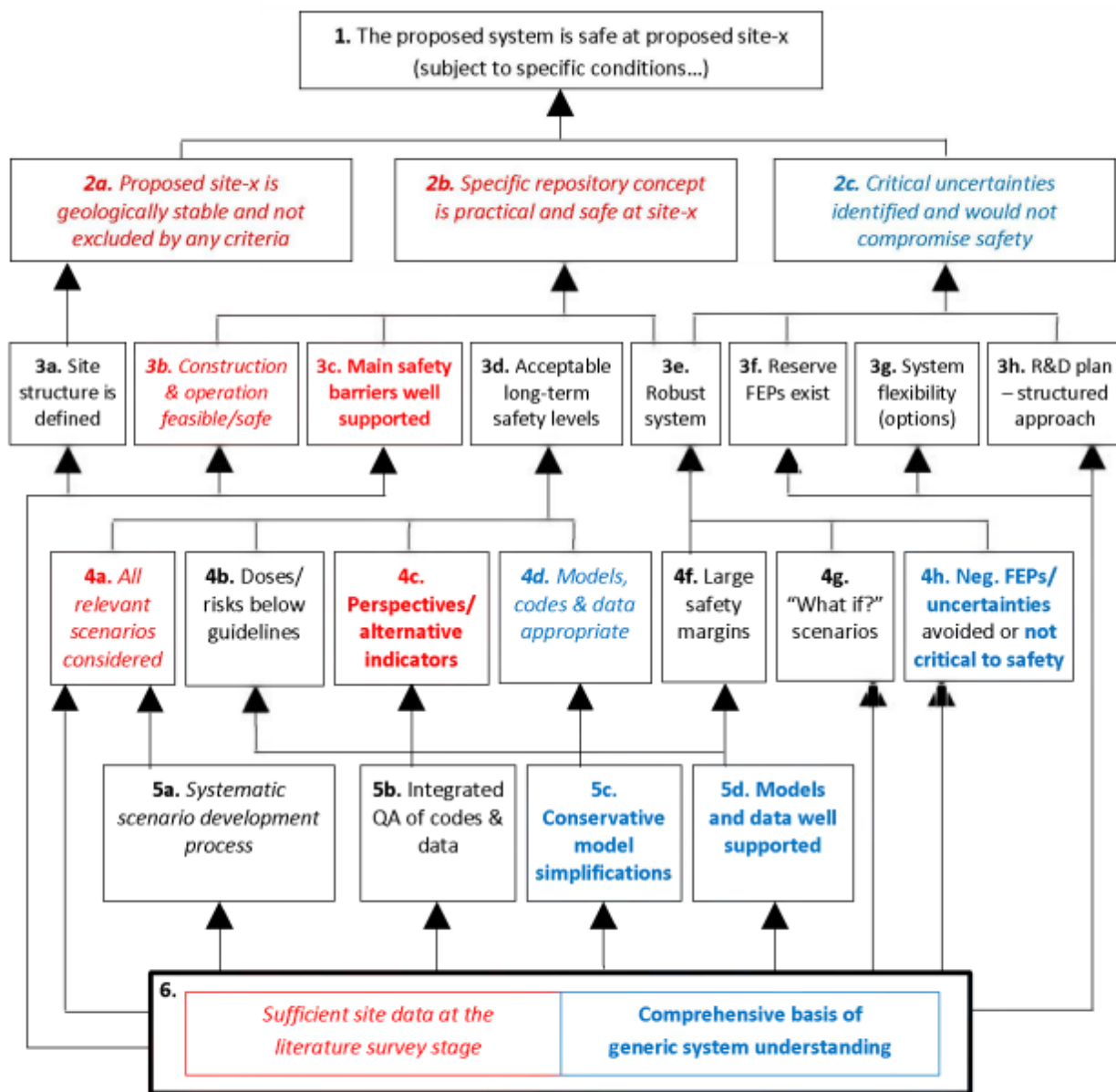
Critical review of everything available in the NA field allowed quality levels to be assigned to projects and publications. This led to more detailed assessment of a few ‘key’ NA projects, allowing further assessment of the relevance of output for the Japanese national programmes and the potential of extensions of such work to fill gaps in available information. This was complemented by a superficial overview of the requirements for a safety case based on the procedure outlined elsewhere - in this case, JNC’s H17 safety case report (JAEA 2005) was used as an example.

The assessment of the requirements for making the safety case is outlined below, based at that time on expert opinion on the likely level of information available at the likely time of site selection in Japan. It should be emphasised that, as implied by the bottom sub-divided box in Figure 3-5, the distinction between generic and site-specific work is often artificial and, indeed, this will tend to become even more blurred with time, as the project moves on to the full site characterisation stage.

The individual areas where it was deemed that NA studies could be used were listed, using the numbering system used in JAEA (2005), and are shown in Figure 3-5. It should be emphasised, however, that this representation of making the safety case does not cover all key applications of NAs, in particular the “higher level” goals included in the safety strategy (e.g. establishment and maintenance of an experienced work force) and also special requirements for presenting the safety case to key stakeholders, which will be considered at the top level of establishing project aims as described below.

It is also important to note that higher level boxes in this flow chart would tend to be supported by system NAs, while lower levels are supported by sub-system or process NAs. It should also be emphasised that, for technical applications, NA studies are most effective when integrated in a combined programme of laboratory, modelling and in situ studies (cf. Alexander et al. 1998).

17.4.2023



Key – Assessment of analogue potential:

Blue – generic, Red – dependent on site selected, Black – none, Bold – important role, *Italic – minor role*

Figure 3-5. Flow of information to make the safety case for the example of a GDF in Japan (H-17) at the PIA stage (Alexander et al. 2007).

For training purposes, complex, integrated NAs - which study systems or sub-systems (e.g. Cigar Lake) - are generally best for accumulation of interdisciplinary experience, which is difficult to

17.4.2023

obtain elsewhere. For stakeholder communication, system NAs are often used (e.g. Oklo), but there is a great danger of over-interpretation of the analogy due to the simplifications that have to be introduced (see discussion in McKinley and Alexander 2007a, Alexander et al. 2007). For unambiguous communication, simple sub-system NAs (e.g. materials longevity) are usually best.

Looking more closely at Figure 3-5, several types of NA study were identified, which could be appropriate in supporting certain aspects of the Japanese safety case (at that time + some updates based on more recent literature).

Generic analogue studies:

2c Critical uncertainties identified and would not compromise safety: system NAs – no additional processes identified which are not included in the analysis (weak use of NAs – absence of evidence rather than evidence of absence – hence should not be over-interpreted: see discussion in von Maravic & Smellie 1996, Miller et al. 2000)

4d Models, codes & data appropriate: this is a generally weak application of NA information in the case of complex systems and tends to show no more than the ability for the models to simulate the reality as represented in the NAs rather than carry out rigorous testing (as in the rare case of blind model prediction; cf. Pate et al. 1994)

4h Negative FEPs/uncertainties avoided or not critical to safety: sub-system analogues focused on potential problem areas – e.g. gas, colloids, microbes, organics (e.g. McKinley and Grogan 1988)

5c Conservative model simplifications: all models involve simplifications of the real system; focused NA studies can determine if these are truly conservative for relevant systems – e.g. assumed conservatism of Kd sorption model (Alexander & McKinley 1994)

5d Models and data well supported: key role of specifically testing PA-relevant models and databases in relevant environments/over relevant timescales – e.g. material degradation, radionuclide release and transport (e.g. Milodowski et al. 2016)

6 Comprehensive basis of generic system understanding: especially critical for extending understanding over long time periods but also includes generic understanding of the properties of undisturbed geological systems (especially relevant to radionuclide transport; e.g. Noseck et al. 2012)

Site-specific (siting environment type) NAs:

2a For the purpose of the exercise, the proposed site-X was assumed to be geologically stable and not excluded by any criteria: studies carried out in environments analogous to that of the site (NB a self or regional NA cf. Nagra's use of the Mont Terri site data in the Opalinus Clay Safety Case – Nagra 2002a)

17.4.2023

2b Specific GDF concept is practical and safe at site-X: complete system NAs – e.g. ore body in coastal location for a coastal site (cf. Smellie and Karlsson 1996)

3b Construction and operation feasible/safe: anthropogenic analogues (mining, underground civil engineering) – generally not included in usual NA definition, but see examples of their use in Posiva (2012a, 2023a)

3c Main safety barriers well supported: arguments from NAs to support assumed performance of barriers at the proposed site – e.g. support for assumed bentonite properties under conditions with varying groundwater chemistry (fresh <-> marine; Reijonen & Alexander 2015).

4a All relevant scenarios considered: NAs of safety barriers in relevant siting environments, with special consideration of time-varying processes – e.g. marine transgressions/regressions in coastal areas (e.g. Smellie and Karlsson, 1996).

4c Perspectives/alternative indicators: natural fluxes of radionuclides etc; could include biosphere NAs (cf. Neall and Smith 2001, Posiva 2012a, 2023a,)

6 Sufficient site data at the literature survey stage: cf. Nagra (2002b) and discussions in von Maravic & Smellie (1996)

Synthesis

The special areas identified as potential topics for future NA studies were grouped as:

1. Settings or host rocks which are of relevance to the Japanese programme, but little studied elsewhere
 - Active tectonic situations
 - Accretionary wedges
 - Small islands

2. Special areas of study
 - Palaeohydrogeology
 - Radionuclide (solute) transport processes (from geochemical anomaly or ore body)
 - Processes of fault reactivation and self-sealing
 - Effects of perturbations - colloids, organics, microbes, gas
 - Construction/operation (engineering; expected evolution, perturbations)

3. Process Understanding
 - Bentonite - host-rock interaction
 - Radionuclide migration within the EBS
 - Model/database testing

17.4.2023

- Radionuclide solubility/speciation within overpack
 - Realistic steel corrosion model (rate/gas production)
 - Retardation of radionuclides on anaerobic corrosion products
 - Retardation of radionuclides on concrete alteration products
 - Long-term behaviour of the host rock at higher GDF temperature
4. Uncertainties and perturbations
- Rheology of the host rock (long-term waste tunnel movement)
 - Long-term performance of shaft and tunnel seals
 - Role of microbes in the near-field

The input of such literature surveys was integrated with the identified needs above to derive a preliminary 'wish list' of possible NA projects to support the safety case. This list of potential projects also included a very rough, subjective assessment of a wide range of issues of relevance to any national programme overall and the safety case in particular:

- Technical complexity
- Potential for model testing
- Possibility of production of GDF relevant data
- Risk of failure (i.e. desired output not achievable within budget and time constraints)
- Cost
- Potential for staff training
- Extent of application for stakeholder communication purposes
- Potential international interest in collaboration in the project
- Minimum duration (under ideal conditions)

In summary, the flow of information to produce this "NAs Wish List (1)" is presented in the bottom half of Figure 3-6. It should be noted that, in addition to the documented reviews, some general messages on the applicability of NA literature were produced as a form of spin-off from the work.

17.4.2023

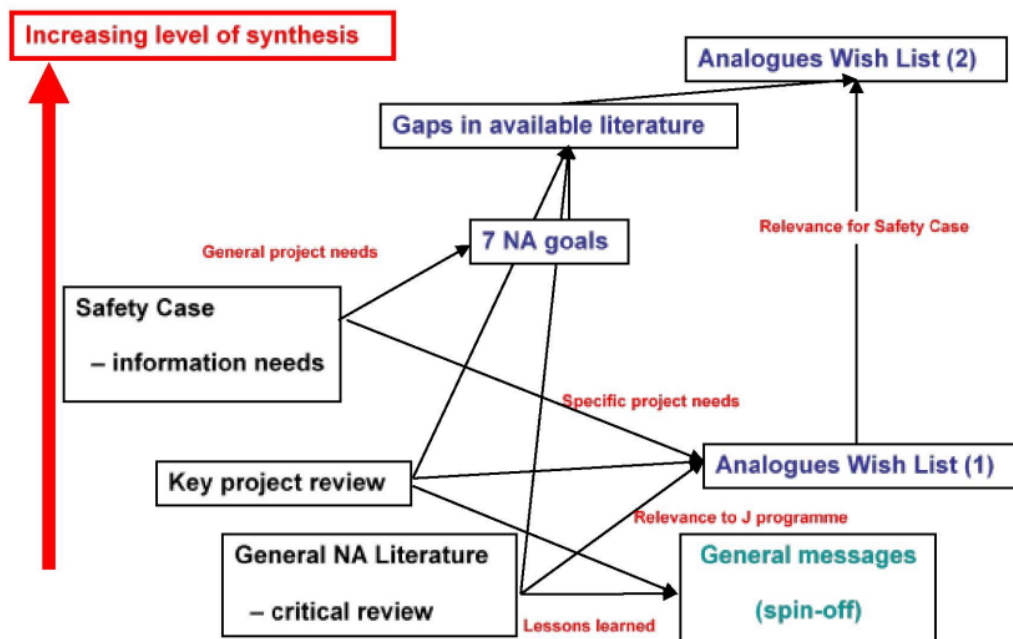


Figure 3-6. Summary of information flow in the bottom-up assessment of requirements (Alexander et al. 2007).

Derivation of Safety Goals

In addition to the specific project requirements listed above, the general areas of the safety case where NAs could contribute can be reformulated as a series of goals – as also indicated in Figure 3-6. These are considered top-down in terms of a safety case hierarchy, with sub-divisions in terms of aspects which are either waste- or site- specific.

Goal 1 Demonstration of geological Stability

The assurance of geological stability is *sine qua non* for a deep disposal project and the site-specific database may be rather limited and hence it may be useful to complement this work by studies of similar rocks in similar geological settings, where the ability to access appropriate information may be greater. As noted above, such studies are usually classified as a self or regional analogue.

The type of NA study which was envisioned was further subdivided as involving assessment of the:

1. Stability of host rock
2. Stability of setting

17.4.2023

3. Robustness to perturbations

These topics are closely related and result from the fact that the present characteristics of any potential host rock result from its original properties at the time of its formation, modified by the perturbations accumulated during its history. In the case where the host rock/setting has been disturbed, there may be processes which minimise the effects on key geological characteristics – e.g. plastic deformation or self-healing of a salt or soft clay host rock. In general, the less a host rock has been altered over geological time and the more stable its geological setting has been, then the easier it will be to characterise¹⁰ and to predict its future evolution. Examples of the type of work that could be carried at NA sites would be:

- Assessment of stability of overlying sediment in the case of deep burial and subsequent uplift by examining mineral transformations
- Assessment of the effects of local folding on rock mechanical and hydrogeological properties
- Quantification of self-healing of fractures and faults

Such information could, for example, be obtained from tunnels or other underground constructions outwith the actual site (cf. Nagra 2002a,b). Note that this work is generally considered part of site characterisation in most national programmes and hence terminology should be clarified before initiating such work in any national programme.

Goal 2 Demonstration of deep groundwater stability

As groundwater release scenarios are a major concern in most post-closure SA, the stability of the hydrogeological environment is also a key concern. This is subdivided into:

1. Flow stability
2. Chemical stability

It is generally desirable that the groundwater in the host rock and surrounding formations should be characterised by both low fluxes and low velocities. As these parameters are often difficult to measure directly, a useful surrogate measure is groundwater age – very old groundwater being an indirect indication that both fluxes and velocities are low (see discussion in Alexander et al. 2021, for example). The determination of the history of site hydrology – palaeohydrogeology – is an established discipline and part of normal site characterisation (e.g. Ota et al. 2010). The particular interest here would be studying hydrogeology at self-analogue sites (as considered above) when these would provide better access than the proposed GDF site (cf. Niizato et al. 2010).

In addition to the stability of hydrogeology, hydrochemical stability is also important in determining the performance of both the engineered and the natural barriers. Preferred hydrochemistry would include intermediate salinity, chemically reducing conditions in the host

¹⁰ Although this comment overlooks the accretionary wedges which are common along the coast of Japan.

17.4.2023

rock and neutral – mildly alkaline pH – and chemically reducing conditions in the surrounding formations. NA studies could examine the extent to which such conditions were buffered by the host rock – particularly under any major perturbations that may occur in the site of interest over relevant time periods (e.g. marine transgression/regression, flushing with oxidising water as a result of de-glaciation: e.g. Noseck et al. 2009, Alexander et al. 2021).

As noted above, in most national programmes, such work is considered part of site characterisation and not classified as being within the remit of NAs, but excluding this from such a holistic assessment risks missing the potential support to the safety case that such studies can offer.

Goal 3 Demonstration of EBS robustness

Particularly at early stages of the siting process, GDF relevant geological databases are likely to be rather uncertain and hence the Safety Case is likely to focus on the behaviour of the EBS. Particularly important in this case is the robustness of EBS performance, even in the case of minor perturbations or degradation of the natural barrier.

The robust performance of the EBS results from the accumulated barrier roles of materials and processes, including:

1. Steel (in this case the only metal considered)
2. Bentonite/clay
3. Cementitious materials
4. Redox buffering (including microbes)
5. Radionuclide solubility
6. Radionuclide transport (including colloids, ...)
7. Gas (production, release, ...)

Study of such materials and processes has been a past focus for NA studies and a significant volume of relevant information exists in the international literature. Although it is important to assess the relevance of individual studies to the GDF project conditions in any specific country, much of the EBS work is fairly generic and so could be profitably data mined. A good recent example of this is the work on potential grout leachate reaction with bentonite in the Swedish programme (Sidborn et al. 2012)

Goal 4 Demonstration of natural barrier performance

The natural barrier role is a key aspect of any site and hence information on this may help to support decisions associated with preliminary site selection. The aim would be to look for evidence, at either the proposed site or one which can be considered analogous, which would allow conclusions to be drawn about key processes such as:

1. Radionuclide sorption
2. Matrix diffusion
3. Dilution and dispersion

17.4.2023

4. Radionuclide immobilisation (trapping)
5. Colloid effects (including organics)
6. Microbes
7. Gas

As considered above, such studies have been a past focus of NA studies and a considerable literature exists of potentially relevant work. In this case, however, applicability is very much dependent on the host-rock and siting environment.

Goal 5 Demonstration of robustness to engineering

In the many national GDF concept development processes, the impact of construction, operation and closure of a GDF on its long-term performance is identified as an issue to be considered at early stages. This would be particularly important in any case when long-term access for institutional control is considered. The aspects of interest are associated with the response of a rock in a particular setting to construction and operation, especially:

1. Recovery of hydrology
2. Recovery of geochemistry
3. Recovery of rock mechanics

Such processes could be studied at construction sites, mines etc., either in the proposed siting region or somewhere similar. Again, such studies are not generally termed NAs when carried out in most national programmes (often part of engineering geology site characterisation), but their great potential should not be ignored (see Posiva 2012a, for examples).

Goal 6 Demonstration of robustness to site evolution

The robustness of particular sites to the perturbations which may be expected to occur as part of long-term evolution is clearly an attribute which is important to consider when making a site selection. This has recently been receiving more interest for coastal locations in particular (e.g. Milodowski et al. 2005, Salas et al. 2010, Posiva 2012a, 2022), due to concerns about the effects of sea level change, but the approach is completely valid for any potential site (cf. Alexander 2010). A few examples of the topics which could be relevant would be:

1. Glacial transitions
2. Climatic biosphere cycles
3. Coastal sea-level changes
4. GBI alteration (erosion/sedimentation, transgression/regression etc)

Although little studied directly in the past, NA methods would be applicable to interpret the consequences of past processes of this type at a proposed site (or a similar location as noted above) in order to bound what might be likely to occur in the future. Indeed, it has been noted that concerns about site robustness in the broadest sense are often raised by non-technical stakeholders (see, for example, West et al. 2002, NDA 2012).

17.4.2023

Goal 7 Demonstration of insensitivity to EBS component interactions

Past generation of SA models have tended to simplify the treatment of EBS components, treating them as effectively independent of each other. In order to develop a safety case, however, such assumptions need to be shown to be valid. The interactions which may be important include:

1. Steel – waste
2. Bentonite – steel
3. Bentonite – cementitious materials

As with goal 3 above, these reflect the types of study which have been included in past analogue projects (e.g. Mitsui et al. 1996a, b) – although interactions have certainly been looked at less rigorously than the behaviour of materials in isolation (but see Milodowski et al. 2002 for a good example).

Comment: how has the RWMC NA programme helped in promoting a strategy of using NA in national programmes?

The example here illustrates a top-down approach to defining and developing relevant NA studies applied to the Japanese national programme. Of note is the fact that this method led to the establishment of a novel study: the Philippines Natural Analogue Study (PNAS), where the potential reaction of industrial bentonite with alkaline leachates from low-alkali cements was studied at the Zambales ophiolite in Luzon and the Palawan ophiolite in Palawan (see Alexander et al. 2008; Arcilla et al. 2009; Fujita et al. 2010, Fujii et al. 2015 for details). In principle, however, the same structured approach can be applied for the boundary conditions of any national programme.

However, due to the role of RWMC in the national programme as an R&D/Disposal Fund manager (and not as an implementer or regulator), the overall programme has had little lasting impact on the use of NAs in the safety case. This is not to say that NAs are not used the safety case, rather that (as noted in the introductory comments), the main producers of safety cases to date, NUMO and JAEA (and its predecessors, JNC and PNC), have tended to focus on process-specific NAs. Recently, NUMO initiated a self-analogue project in support of the future site characterisation programme (see Yamada 2021), but this has been paused due to personnel changes within NUMO. Indeed, if anything, this constant flux of personnel in the Japanese national programme (something which characterises industry in general in Japan – see Meyer-Ohle 2009, for discussion) has been the biggest hindrance to strategic planning on the use of NA in the safety case – that and the lack of a functional knowledge management system within the national programme.

Nevertheless, the methodology could still be of relevance, if it is appropriately altered to better reflect the UK national programme and to produce a 'living document' which can be updated as the programme matures and moves through the GDF development cycle.

17.4.2023

3.2.7 Germany

Background

Until recently, the German national programme had many parallels to the Japanese programme insofar that many different organisations¹¹ were involved and the overall programme was generic with neither GDF design nor host rock being fixed. Nevertheless, a programme (Wissenschaftliche Grundlagen zum Nachweis der Langzeitsicherheit von Endlagern or Scientific basis for evidence for the long-term safety of repositories) was launched in 1996 and one of the six (plus one overview) reports produced under this theme was an examination of evidence for far-field radionuclide retardation based on NA studies (Noseck 2000). This looked at existing studies such as Alligator Rivers, Broubster etc. to ascertain what, if anything, could be used from the studies in future safety case in the German programme.

In parallel with this review, work on specific NA studies had already been initiated with sites such as Heselbach in Germany (e.g. Schönweise et al. 2006) and Ruprechthov in the Czech Republic (e.g. Brasser et al. 1999) were assessed as potential areas to further study far-field radionuclide retardation in sediments. After due deliberation, work continued only at Ruprechthov (see, for example, Noseck & Brasser 2006, Noseck & Havlova 2014, for details).

As these process-specific NA studies were under development, a wider study of the potential to dispose heat-producing radioactive wastes in three host rock types (evaporites, claystones and hard rocks) was carried out. As part of this wide-ranging study, a review (Brasser et al. 2008) of the potential role of NAs was conducted and published as an appendix to the main report. The review focussed on three key areas:

- The long-term stability and isolation potential of the three host rock types of interest
- Potential disruption effects and the capability to self-seal of the three host rock types of interest
- The long-term behaviour of the waste and EBS materials

Overall, the review produced few, if any, new insights and tended towards bland, qualitative statements (and produced no conclusions nor provided guidance for future strategic uses of NAs

¹¹ Those included, in October, 2019, the Bundesministerium für Umwelt, Naturschutz und Nukleare Sicherheit, BMU (the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety), with the participation of the Gesellschaft für Zwischenlagerung mbH, BGZ (the Federal Company for Radioactive Waste Storage), the Bundesgesellschaft für Endlagerung mbH, BGE (the Federal Company for Radioactive Waste Disposal), the Bundesamt für kerntechnische Entsorgungssicherheit, BfE (the Federal Office for the Safety of Nuclear Waste Management), the Ministerium für Umwelt, Klima und Energiewirtschaft des Landes Baden-Württemberg, UMBW (the Ministry of the Environment, Climate Protection and the Energy Sector Baden-Württemberg), the Niedersächsisches Ministerium für Umwelt, Energie und Klimaschutz (the Lower Saxony Ministry of the Environment, Energy and Climate Protection), EWN Entsorgungswerk für Nuklearanlagen GmbH and its subsidiary KTE (publicly owned organisations for the decommissioning of nuclear facilities), Brenk Systemplanung GmbH, and the Gesellschaft für Anlagen und Reaktorsicherheit GmbH, GRS (limited liability Technical Support Organization, TSO, for plant and reactor safety).

17.4.2023

in the safety case). For example, in the wrap-up discussion (role of (NA) investigations on evaporites) of section 3.1, it was stated:

- NA studies 'complete' lab-based studies by examining real systems
- Support safety case statements through general knowledge (of the studied system)
- NA studies increase confidence that the relevant processes and characteristics (of evaporites) are well known
- Understanding of current examples of evaporite NA studies increase confidence that long-term forecasts of GDF development (over the required time space of a million years) can be reliably established

However, a point was made insofar that NA studies were being seen as an important factor when developing future safety cases in the German national programme.

Later, in parallel with the ongoing study at Ruprechthov, a decision was taken to focus ongoing safety case studies on a GDF in an evaporitic host rock and, as part of this process, a much broader review (Brasser et al. 2014) of evaporite-focussed NA studies was conducted. This review also benefited from the fact that the more general Part 1 (completed in 2011) was followed by a Part 2 review (conducted over 2012-2013) which focussed on those features and processes identified in the safety case as being of most import for the GDF design and foreseen host rock, producing a much more valuable review than that of 2008.

The conclusions of Part 1 were simply that existing evaporite NA studies have significantly improved understanding of the long-term processes expected to take place in a GDF. Part 2 focussed on the processes identified in the safety case to be of potential relevance, which included:

- Sealing of anhydrite formations in a salt dome in the post-diapir stage
- Compaction of the salt backfill
- Chemical composition of fluid inclusions
- Thermal stability of evaporites
- Mechanical stability of evaporites
- Potential impact of earthquakes on the integrity of evaporites and the GDF
- Quality assuring final closure of the GDF
- Metal corrosion
- Microbial processes

Comment: how has the German NA programme helped in promoting a strategy of using NA in national programmes?

17.4.2023

The last review¹² (Brasser et al. 2014) discussed here is a helpful model to follow when a GDF waste stream, design and host rock have been chosen and Part 2 provides a good, step-by-step plan to follow, providing sections within each identified process (e.g. metal corrosion) on:

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

Unfortunately, as with Brasser et al. (2008), there is no overall conclusion offered nor is there any attempt to offer a strategic roadmap on how to initiate and maintain the use of NA in future safety cases. However, this has much to do with the multi-organisational structure of the German national programme (cf. section 3.2.7): GRS, a research institute, has produced the reviews to date and are therefore not ordinarily expected to offer strategic advice to either the new German implementer, BGE¹³, nor the new regulator, BASE¹⁴.

3.2.8 Canada

The current conceptual design (NWMO 2016a) in Canada consists of a GDF constructed at a nominal depth of 500 m below the surface containing a network of placement rooms for the projected inventory of 5,224,000 used fuel bundles, encapsulated in about 108,800 long-lived used fuel containers which are placed in buffer boxes and then stacked in the GDF emplacement tunnels (Figure 3-7 and 3-8). With respect to the overall use of NAs in the national programme, NWMO's view is that long-term GDF performance cannot be verified by laboratory and URL experiments over relevant time scales. NAs can illustrate long-term behaviour and can assist in understanding how a GDF may behave over time scales ranging up to many millions of years, including the underlying principles relevant to the long-term isolation and containment of SF. They provide support for key model assumptions and for the identification of processes that need to be represented and those that can be excluded.

¹² Note that GRS has also reviewed NAs for GDFs in clay and crystalline host rocks, with a connection between NA studies and both the safety principles and the key FEPs of the respective FEP catalogues (but, again, without any discussion on strategic planning). These reviews will be published in 2021 (U.Noseck, pers. comm., January 2021).

¹³ Bundesgesellschaft für Endlagerung mbH (the Federal Company for Radioactive Waste Disposal).

¹⁴ Bundesamt für die Sicherheit der nuklearen Entsorgung (Federal Office for the Safety of Nuclear Waste Management).

17.4.2023

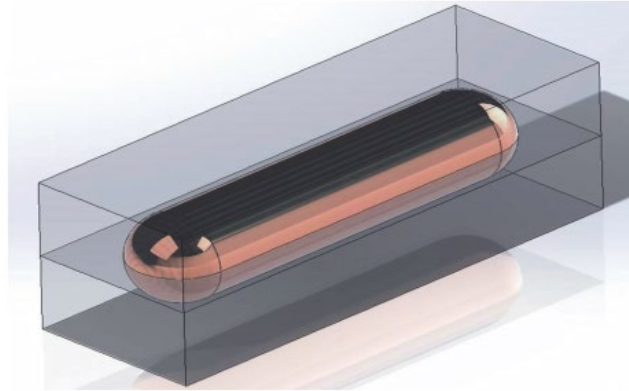


Figure 3-7. Proposed NWMO EBS design: SF in a copper-coated, steel container is emplaced in a 1x1x2.8 m rectangular buffer box consisting of highly compacted bentonite (Noronha 2016).

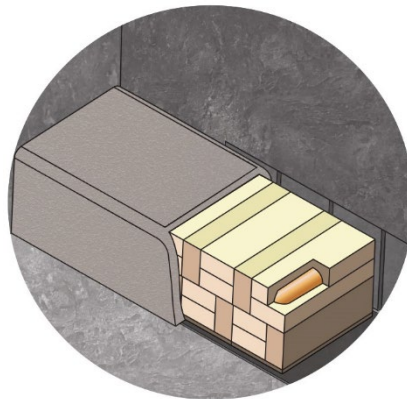


Figure 3-8. The buffer boxes are stacked in the emplacement tunnels (Blyth & Kremer, 2023).

NAs exist for most features of the GDF system (see section 3.3), including the SF, EBS and host rock and key processes such as transport of hypothetical contaminants. Indeed, 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) which states: “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 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 desire to learn from local, traditional knowledge at potential GDF sites. Indigenous knowledge places an emphasis on interrelationships within the environment and, as such, can offer insight into the overall GDF system. For example, Indigenous societies have explored the

17.4.2023

copper deposits around the Great Lakes since before 3000 BC (Emerson et al. 2000) and these deposits may be thought of as a NA for the long-term durability of copper containers within the GDF (e.g. Aaltonen et al. 2022). As noted in Blyth & Kremer (2023) *“NWMO developed its Indigenous Knowledge Policy (NWMO 2016b) 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.”*

3.3 Use of NAs in a waste disposal programmes

3.3.1 Use in siting

In the past, much effort was expended into examining the mutually beneficial cross-pollination between NA studies and GDF site characterisation programmes (cf. discussions in von Maravic & Smellie 1994, 1996)¹⁵. Here, a few different approaches are examined via selected examples. The list is not exhaustive (more detailed listing is in the NA Catalogue update, Alexander & Reijonen 2023).

3.3.1.1 Regional analogues for site characterisation

There is a direct form of NA which has been used in site characterisation (both directly and indirectly). The essence of this work is that the setting of the NA study should be as similar as possible to expected GDF sites and, most appropriately, would be like the ‘Regional (or Self) Analogue’ of Nagra’s Wellenberg site in Switzerland (Nagra 1997). Here, the term was coined to cover data from similar settings to the GDF site (e.g. the same formation as the GDF host rock or a similar formation with the same tectonic setting) which could be used to extend the information base on the site. The NA should tie evidence for stability (e.g. information focussed on hydrochemistry/isotope hydrology in the form of a palaeohydrogeological study) with other indicators that may exist in the existing literature of a potential GDF site (such as data on groundwater chemistry related to regional tectonic history).

In addition to Nagra’s self-analogue study for the Wellenberg site, they also utilised the approach when characterising a potential GDF site at Benken, in NE Switzerland. Here, data for the potential GDF host rock, the Opalinus Clay, are shown in Figure 3-9 and it is worth noting that the data presented are a mix of site-specific data from the Benken deep borehole which was drilled at the

¹⁵ And almost equally as much effort has been invested in debating the differences between site characterisation and NA studies. In Miller et al. (2000), for example, a significant amount of text was dedicated to pulling apart the minute differences between the two ‘disciplines’ and trying to justify the view that they should not be considered under the same umbrella.

17.4.2023

site and 'non-site' data from the Mont Terri URL, which is found some 150 km west of Benken. Of interest is that this led to no perceptible weakening of the message of GDF host rock stability and was deemed acceptable by the Swiss regulator.

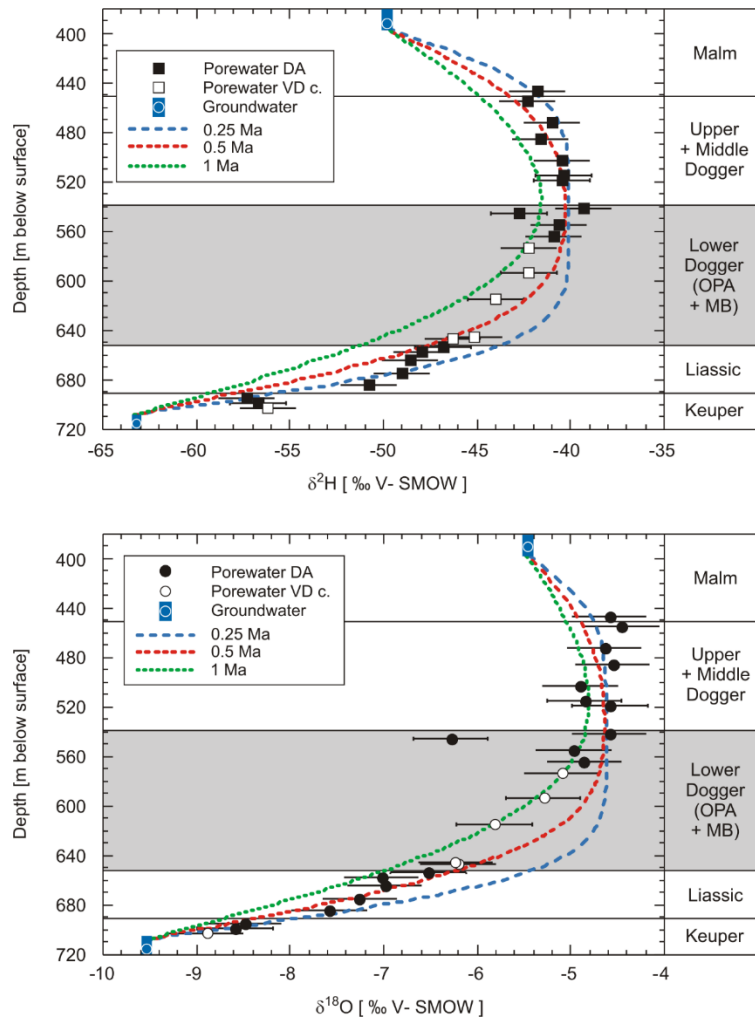


Figure 3-9. Natural tracers in porewaters of the Opalinus Clay (grey) and surrounding formations. Dotted lines are the best fit simulations of data for pure diffusion across the five formations with assumed constant concentrations in the Keuper (lowermost formation) and Malm (topmost formation) aquifers. In the key, "groundwater" means groundwater compositions in under- and over-lying formations (from Nagra 2002)

17.4.2023

3.3.1.2 Regional analogues for process understanding

In addition to site-scale regional (or self-) analogues mentioned above, the focus can also be set to more specific process wise considerations.

One regional analogue that has been recently brought forward in the waste management community is the use of smectites occurring at disposal sites and relevant analogous sites as a regional analogue for bentonite longevity in variable groundwater conditions. The idea of using natural host rock smectites to assess the likely longevity of industrial EBS bentonite was initially raised by Arthur and Savage (2012) when reviewing information on the Forsmark site for the Swedish regulator. At Forsmark, smectite occurs at most depths in bedrock fractures (see Figure 3-10). Reijonen & Alexander (2015) took the discussion forward compiling information available from candidate GDF sites in Finland, Sweden and Canada (e.g. Gehör 2007, Sandström et al. 2008, Drake et al. 2006, Koroleva et al. 2009). Dating of the fracture systems at Forsmark suggests that the smectites have been present since at least the Palaeozoic (i.e. 540 to 250 Ma BP) with the deep brines in contact with the smectites having been stable for at least several million years, if not longer (Smellie et al. 2008). This observation alone is already a powerful argument for the longevity of bentonite at the site, although further data would be needed for detailed evaluation (cf. discussion in Reijonen & Alexander 2015, Reijonen & Marcos 2016).

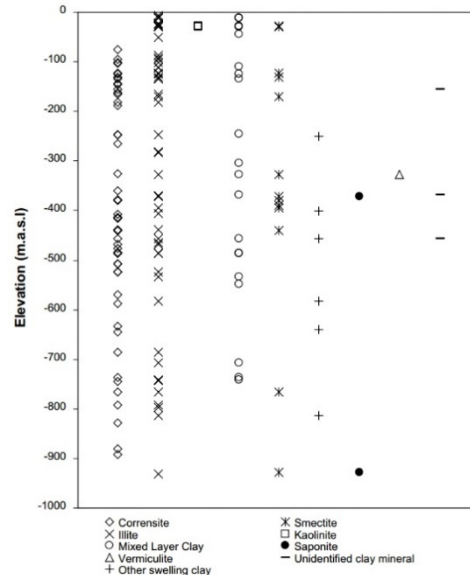


Figure 3-10. depth distribution of different clay minerals in Forsmark Sweden (Sandström et al. 2008).

17.4.2023

In Canada, at the Bruce site in the Michigan Basin of North America, (Figure 3-11) mixed layer illite/smectites occur (e.g. Koroleva et al. 2009) in the Ordovician Shales above the potential GDF host rock. Based on the literature, the lower members of the shale (Blue Mountain and Collingwood) have gone through the oil window (e.g. Béland Otis 2012) which is assumed to have converted any smectite originally present to illite (Jackson 2009). However, a potential regional analogue could be found in the stratigraphically higher formations (Queenston, Georgian Bay) where mixed layer illite/smectite has been reported and where the groundwater/porewater TDS (total dissolved solids) reach as high as 300 gL^{-1} , somewhat higher than in the GDF horizon (cf. Raven et al. 2010).

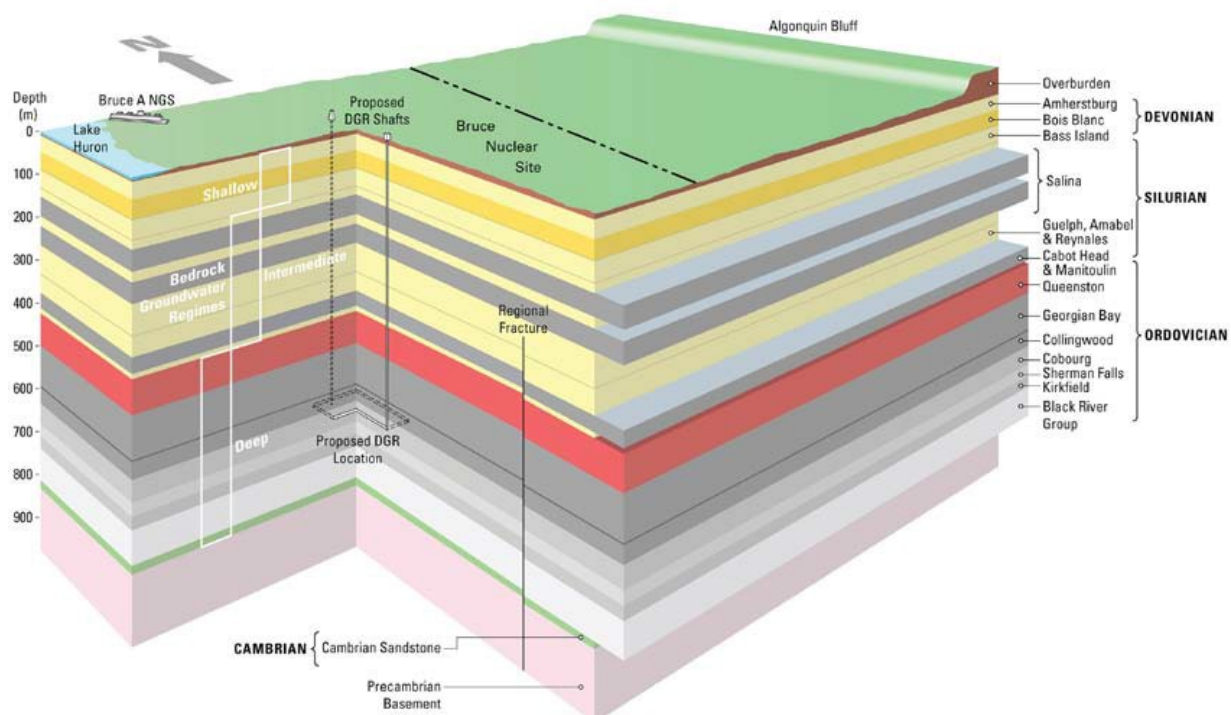


Figure 3-11. descriptive Geosphere Model of the Bruce site (Jensen et al. 2009). NB DGR (deep geological repository) = GDF.

Clark et al. (2013) have suggested that the brines in the Bruce GDF host rock are Palaeozoic in age (i.e. 540 to 250 Ma BP), indicating long-term isolation of this groundwater system.

Smectites present in sedimentary rocks and as alteration products in fracture fillings provide potential to study a regional analogue for the bentonite buffer considering a large range of hydrogeochemical conditions.

17.4.2023

Other examples of regional analogues for process understanding exist (see Reijonen & Alexander 2023 for more details), such as the study of uranium ore alteration in an unsaturated host rock at the Peña Blanca uranium orebody in Mexico (Pearcy et al. 1994). This was undertaken to examine the long-term behaviour of UO_2 in unsaturated volcanic tuffs, a system which is analogous to the SF in the tuff host rock at the proposed Yucca Mountain GDF site.

3.3.1.3 Regional analogues for site understanding

In addition to site geology, regional analogue concept has been used for example by Posiva to describe the future biospheres by utilizing regional data. Short overview of the work is mentioned in Posiva 2012a, and the whole concept is thoroughly discussed in the latest biosphere description report by Posiva (2013a). The regional analogue approach is based on the need to assess changes in the surface environment due to the continuous land uplift process taking place in Finland (and elsewhere in formerly glaciated terrains). Hence, in addition to biosphere studies on Olkiluoto Island and in its surroundings, a so-called Reference Area was delineated (Figure 3-12), allowing objects that are poorly represented on Olkiluoto (e.g. lakes, mires) to be studied at other locations to provide analogues to the future objects that will develop in the area due to the land uplift (Haapanen et al. 2010). Posiva (2013a) also points out that: *“the age of the present objects [Olkiluoto Island] is young, and the 9 000 – 10 000 years of development covered by the Reference Area can be used as an analogue for future development at the Olkiluoto site (discussed further in sections 2.1 – 2.3 in [Posiva 2013a])”*. Olkiluoto Island started to emerge from the sea around 3000 years ago (Mäkiäho 2005). The analogue data collected has been used in the future modelling of the site.

17.4.2023

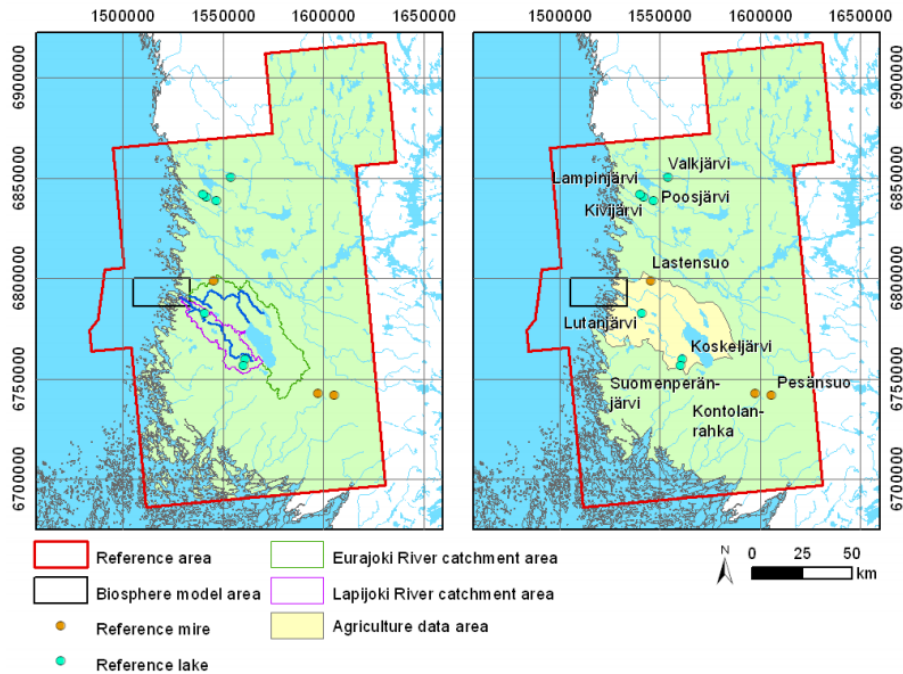


Figure 3-12. Schematic presentation of the Reference Area, the selected reference lakes and mires and the catchments of Eurajoki and Lapijoki Rivers (left), the main area of the agricultural data (right). Map layout by Jani Helin, Posiva Oy. (Posiva 2013a)

3.3.2 Use in Safety Case

NAs can be used in the safety case in several ways with varying the input from qualitative to quantitative. Some examples of the coverage of the NA data have been listed in the previous NA Catalogue (Milodowski et al. 2015a), which is currently being updated. Milodowski et al. (2015a) listed a few examples on the different ways NAs can contribute to the safety case:

- Analogues can increase our confidence in the safety case by identifying mechanisms or processes that could be relevant to the GDF and its long-term evolution.
- Analogues provide qualitative understanding of the impact of processes that may occur over long (geological) time scales but which cannot be readily studied under laboratory conditions or within laboratory experimental timescales.
- Analogues can be used to test model predictions or extrapolations from laboratory experiments, regarding the performance of the GDF host rock and engineered barrier materials over long timescales.

17.4.2023

In general, most safety cases prepared over the last 30 years have included analogues in some form or another, whether to support conceptual model development, to test models or with direct input of quantitative data.

Some examples of the use of analogues in a safety case (after Milodowski et al. 2015 and references therein + updates in this report) are provided in Table 3-3.

Table 3-3. Examples of the use of NAs in safety cases during the past 40 years.

Safety case / safety assessment (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 GDF 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 GDF 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 GDF	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

17.4.2023

Safety case / safety assessment (reference)	Conceptual model development	Model testing / development	Direct data input
TILA-99 (Vieno & Nordman 1999)	Support for the assumed conservatism 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)	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 ¹⁶ report (Posiva 2012b).		Copper canister corrosion rates Support for conservative dissolution rates of SF
SR-Site (SKB 2011)	Complementary considerations approach + use in specific process discussion		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	Integration of information from NA studies with laboratory, URL and modelling studies	

¹⁶ Features, events and processes

17.4.2023

Safety case / safety assessment (reference)	Conceptual model development	Model testing / development	Direct data input
	disturbed zone in the host rock for a GDF Development of conceptual models to evaluate the impact of climate change.		
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 & Kuusisto 2021), aquatic environment (Kirkkala & Mikkilä, 2021), forests and mires (Aro 2021), agriculture (Salo 2021) and fauna (Haavisto & 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.

Unfortunately, not all safety cases note where analogue input has been used and much material is only utilised implicitly, with some relevant reports remaining as unpublished supporting documentation.

Analogues are also heavily used to build confidence in the output of any safety case. Analogues also provide clear examples of GDF processes and mechanisms which can be used to communicate complex issues, or geological processes that operate over long timescales, in a simple manner.

17.4.2023

3.3.2.1 Examples from national programmes

Finland

Complementary considerations approach has been incorporated in the safety case work both in safety cases for the KBS-3H and KBS-3V GDF repository designs since early 2000's. The first complementary evaluations report (Neill et al. 2007) focused on wider range of complementary discussion in support of the KBS-3H safety case and has relatively narrow discussion on the NAs. During the next update for KBS-3V concept, the name was changed to complementary considerations and the NA review was extended significantly (Posiva 2012a). Posiva (2012a) report was written with the KBS-3V concept in mind, but it was considered applicable also for 3H concept. Hence, in the interim safety evaluation of the KBS-3H (see. e.g. Posiva 2018) no new update was produced. For the interim safety case, some concept relevant updates were made for the NA discussion, especially in relation to chemical erosion (Smith et al. 2017). Later, for the operation license safety case (see safety case plan in Posiva 2017) new update was included to support the reference concept only (KBS-3V). Whilst having dedicated reports, Posiva has used NA information to support process understanding, see section 3.3.2.2. In addition, Posiva has used some explicit examples also in their performance assessments, for example Posiva (2013b).

Posiva's development work in discussing NAs is a journey from high-level listing of a few examples for the generic safety cases (e.g. TILA-99 by Vieno & Nordman 1999, see also Table 3-3) to increasingly more concept specific reviews as the GDF repository designs details and site understanding has increased (Figure 3-13).

Feedback from STUK for the safety case 2012 commented on CC report being not connected to other parts of the safety case. This was accounted for in the Safety Case Plan (Posiva 2017) where aiming towards parallel production of CC along with the whole safety case was emphasised.

Most recently, the role of CC has been defined in Reijonen et al. (2022) as follows: *“The main emphasis of the CC report is on the evidence and understanding that can be gained from observations at the site, including its regional geological environment as well as from natural and anthropogenic analogues for the repository components and the processes that affect safety. In particular, the report addresses diverse and less quantifiable types of evidence and arguments. In addition, the purpose of the CC report is to enhance confidence (or provide further insights) in the conceptualisation and modelling results provided by the performance and safety assessment. These considerations, described as evaluations, evidence and qualitative supporting arguments, complement the more quantitative analyses presented in the performance and safety assessment reports of the safety case. “*

17.4.2023



Figure 3-13. Overview on the main developments of complementary consideration approach during Posiva’s safety case evolution towards operational licensing. Reports from left to right: Vieno & Nordman (1999), Neall et al. (2007); Posiva (2012a, 2023a).

Sweden

Regarding SKB’s programme, the multibarrier concept has been initially justified partly based on the use of natural materials, e.g. in Andersson et al. (2000) it is stated:

“Another principle is to make the repository “nature-like”, i.e. to use natural materials such as copper for the outer shell of the canister and bentonite clay for the buffer”

Overall, NA input has been in the safety case process throughout the years, see Table 3-3 for an overview of the main NA inputs.

SKB’s latest safety case for the construction licensing was published in 2011 (SR-Site). In SR-Site main report (SKB 2011) on post-closure safety, an overview is provided on the NAs providing input for additional argumentation along with assessing future human actions, best practices, verification of omitted FEPs and a brief assessment over 1 Ma (see chapter 14 in SKB 2011). Figure 3-14 illustrates the whole assessment methodology, including NAs as step 11 (additional analyses). This is similar to Posiva’s CC approach.

17.4.2023

Overall, by SKB (2011) Use of NAs is summarized as follows:

- *“An account of natural analogues as a support for a safety assessment of a KBS-3 repository is given in Section 14.6. [SKB 2011] Both the role of natural analogues in safety assessments and the actual supporting arguments for specific repository materials and processes affecting them are discussed.*
- *In Section 14.6.5 [SKB 2011] it is concluded that the outcome of the natural analogue studies has been of a more qualitative than quantitative nature. The gathering of scientists and modellers in the international projects studying natural analogues has focussed the research efforts and method development, so that enough information is available for identifying processes and scenarios relevant to safety assessments. Also, many natural analogues provide support to long-term safety analyses by improving general perception and understanding of the concept of a deep repository.*
- *Furthermore, in cases where natural analogues provide useful information for the understanding of specific processes, this information is given in the Process reports, under a dedicated heading.”*

Similarly to Posiva’s case, NAs are a part of the process understanding (see also section 3.3.2.2).

17.4.2023

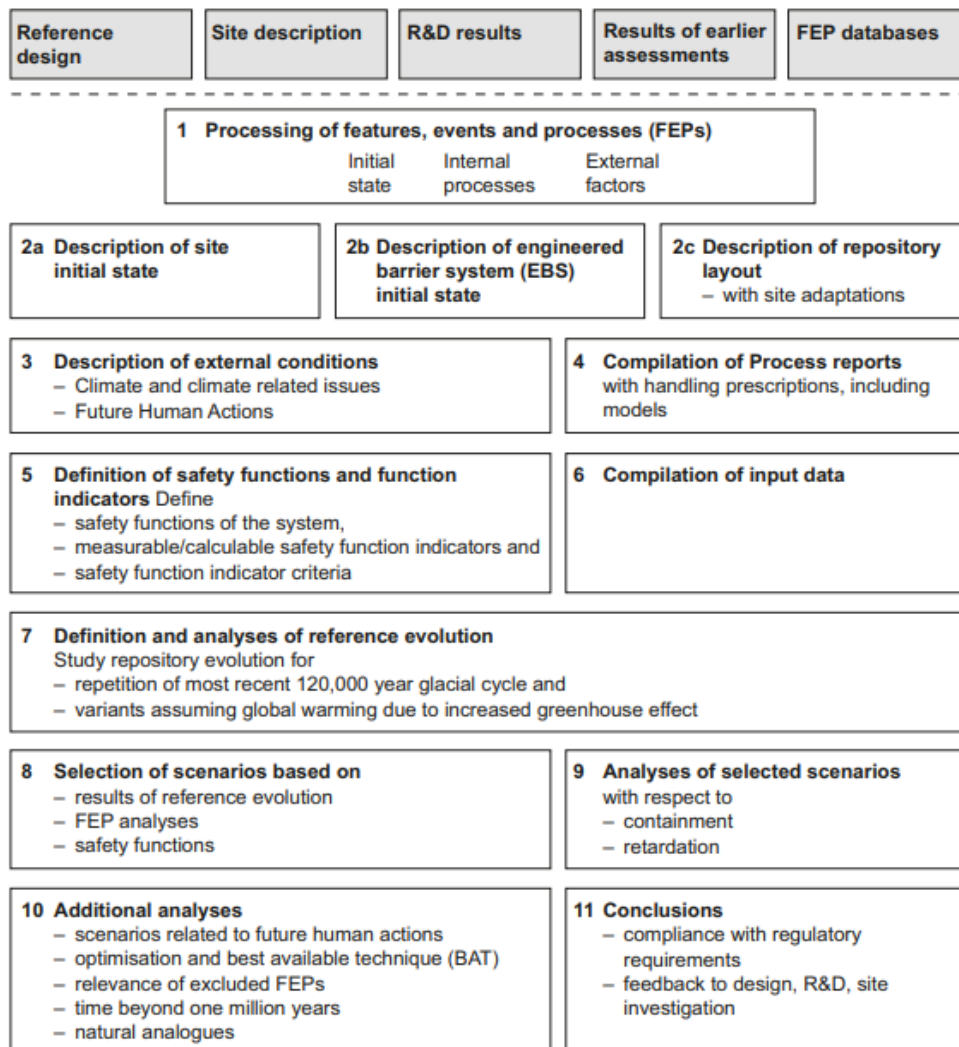


Figure 3-14. An outline of the eleven main steps of the SR-Site safety assessment. The boxes above the dashed line are inputs to the assessment. Natural analogues are input for the step 10 in the additional analyses (SKB 2010a).

Japan

Use of NA in the various safety cases previously published in the Japanese national programme is discussed in some detail in section 3.2.7. For the most recent generic safety case (NUMO 2021), despite the existence of a dedicated supporting report on NA evidence (Alexander 2021), the use of NA has been patchy. For example, there is information (including the use of ‘natural evidence’) included in the areas on GDF design, but almost nothing in the safety assessment itself. Nevertheless, one of the top-level statements in NUMO (2021) points out that “....selecting a

17.4.2023

suitable GDF site in Japan where the favourable thermal, hydrological, mechanical and chemical (THMC) conditions will persist in the host rock environment for a long period of time would be feasible". As noted in Ota (2023), this key statement is underpinned by the multiple lines of arguments and evidence that potentially significant impacts of natural disruptive events/processes on the geosphere can be precluded. Then the temporal and spatial (or 4D) evolution of the host rock environment can be characterised with considering gradual natural processes that develop rather slowly with time over a large spatial scale. In other words, by NA (including regional analogue) evidence.

That more has not been included in NUMO (2021) is likely down to personnel changes something which, as noted in section 3.2.7, is a constant feature of Japanese industry (cf. Meyer-Ohle 2009).

Switzerland

The Swiss national programme was among the first to both support the production of and utilise NA information in the safety case. Appendix 2 is an incomplete (i.e from 1984 to January 2003) list of Nagra-supported publications on NA themes and, as can be seen, it covers a wide range from process-specific NAs to regional analogues to reviews of NA studies, reviews of NA support of the safety case and safety case reports (up to 2002) which include specific mention of NA information (Nagra 1994, 1997, 2002).

Nagra has produced in the past CC type reports called "results in perspective", but these are no longer produced in this format (see Neall et al. 1994; 1995).

This involvement in the production and use of NA information continues to the present, with ongoing NA projects (e.g. KINA, the Kiruna Natural Analogue study, see Gilg et al. 2017, for example) and safety case.

3.3.2.2 Process understanding

NAs have been a part of the knowledge base in many FEP compilations in various waste disposal projects and safety cases. Here a few more recent ones are described.

Posiva has utilized NAs as part of FEP descriptions providing context to the process in specified safety case (e.g. Miller & Marcos 2007, Posiva 2012b and Posiva 2016). The overall framework for presenting FEPs and relevant information was established by Miller & Marcos (2007), where each of the processes were described using a common tabular format. The key components of this format were: category, general description, Olkiluoto specific issues, uncertainties, time frames of relevance, scenarios of relevance, significance, treatment in performance assessment, key references. Of the key components listed above, the 'general description' considered also NA information, as by definition, it: *"provides a concise explanation of the process and current understanding of how it operates in the repository and affects performance – reference is made to evidence for the process from field and natural analogue observations, laboratory studies and modelling studies. Where possible, summary quantitative data for the process are provided"*. This same overall approach to include NAs in the FEP descriptions was followed in the subsequent

17.4.2023

update of Posiva's FEP report (Posiva 2012b). Overall, as the main focus of NAs has been set to complementary considerations, the process specific analogue discussion has been more secondary in nature. Sometimes, drawing the line between performance assessment and complementary considerations is not clear, as it is often difficult to define if NA input is direct or complementary. It may depend on how the same analogue study is used in different parts of the safety case.

As mentioned above, SKB has also used the NA information in their SR-Site safety case in a process specific manner (e.g. SKB 2010b). NAs are included in the FEP methodology (Figure 3-15). This has increased the systematic discussion as all processes identified are documented following the same structure. In some cases, it is evident that the overall assessment of the existence of NAs has been limited to literature that explicitly discusses topics under geological disposal framework. The significance of NA data varies from non-existent to cases where NA data is the only source of information regarding process understanding. A good example of the latter is chemical alteration of the SF matrix, i.e. coffinitisation, which is almost solely based on observations from nature, see e.g. SKB (2010c, section 2.5.9).

17.4.2023

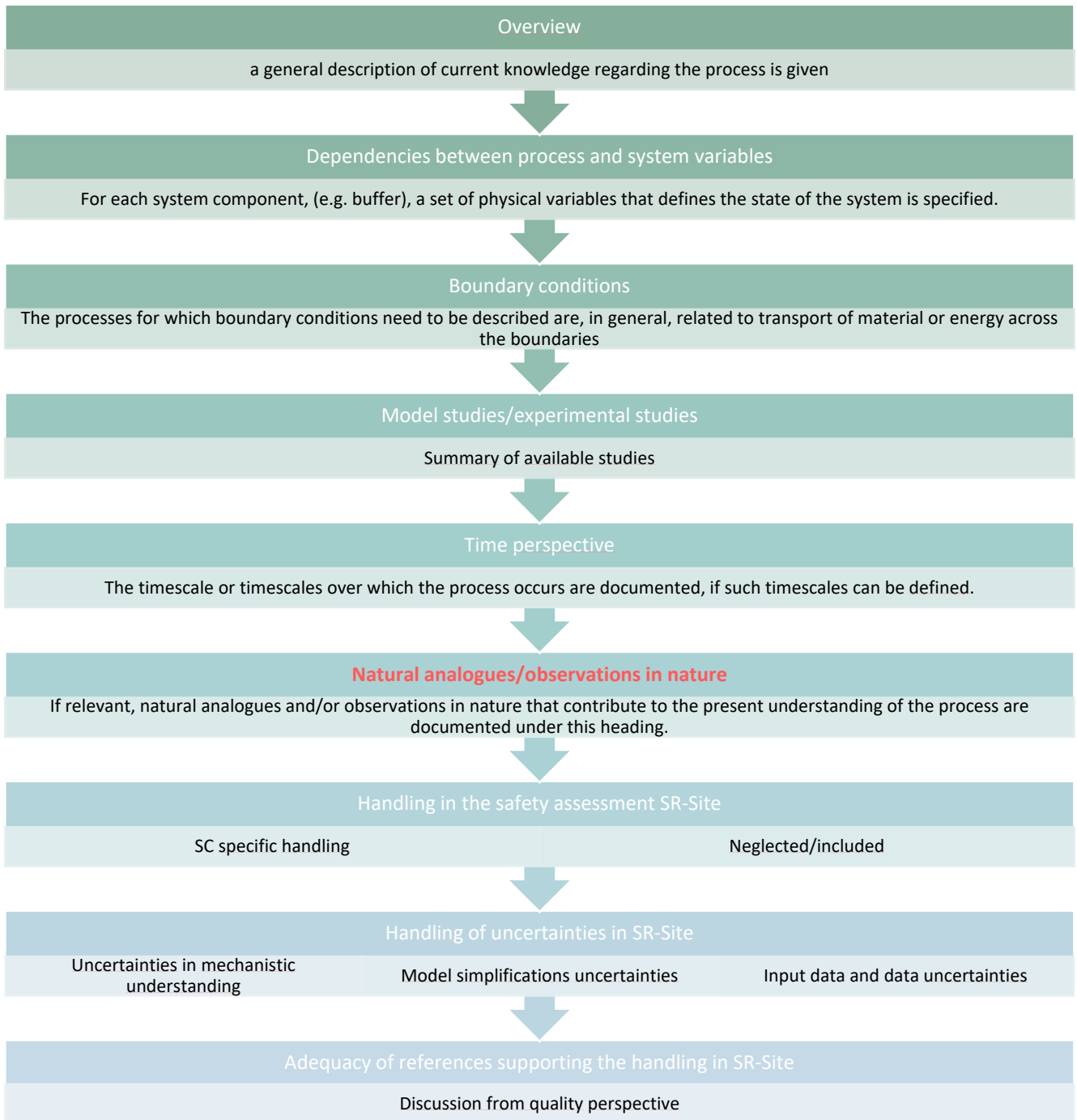


Figure 3-15. FEP description methodology according to SKB (2010b). NAs in the process highlighted in red.

17.4.2023

Below, a few examples of the use of NA information for specific process understanding are discussed to highlight the meaning of NA input.

3.3.2.3 Example of use of NA in safety case: Cement leachate-host rock interaction

As noted in Alexander (2012), the quantitative implications of cement leachate/host rock interaction on the long-term performance of a GDF on the host rock have barely been examined. Nevertheless, four examples exist where preliminary assessments of the implications of the alkaline cement leachates on specific GDF sites have been carried out. In the first, Alexander & Mazurek (1996) considered the likely impact on the fractured marls of the potential GDF site in Wellenberg, Switzerland. Focus was on application of the data collected in the Jordan NA study (see Pitty & Alexander 2011, for details) and the main conclusion was that it was necessary to conduct a detailed assessment of the likely long-term impact (e.g. on the overall site hydrogeology) of gradual fracture sealing at the site due to the host rock reacting with the alkaline fluids.

In the second, data from the Jordan NA were once again considered (Alexander 2003) as part of a wide-ranging (i.e. using NA, laboratory, URL and modelling study output) examination of the likely impact of cement leachates from a GDF on the Opalinus Clay host rock. Due to the diffusive nature of groundwater transport in the host rock, the implications are that the leachates will have no significant impact on the long-term barrier capabilities of the host rock (Mäder 2003).

In the third case, a modelling study by Vieno et al. (2003) assessed the likely impact on the EBS of alkaline leachates (predominantly from cement grouts in water-conducting fractures) at the Olkiluoto site in Finland. The results suggested that little impact would be expected, but subsequent investigation utilizing NA information (Alexander & Neall, 2007) suggested a more cautious approach. Consequently, Arenius et al. (2008) recommended the use of low-alkali cement grouts at the site during development of the ONKALO facility (mainly in relation to bentonite performance, see also the CNAP discussion in section 3.3.3). The fourth example also examined the Olkiluoto site, but here Höglund et al. (2018)¹⁷ looked at the potential impact on the SF GDF from cement leachates from the nearby L/ILW GDF. Based on a reassessment of existing NA information from the Jordan NA study¹⁸, it was concluded that a mixture of dilution along flow paths combined with leachate/host rock reaction would ensure that any leachates from the L/ILW GDF would have no significant impact on the SF GDF.

Several NA, laboratory and URL studies have indicated that the reaction of cement leachates on a GDF host rock is likely to impact the site hydrogeology and hydrochemistry. Depending on the

¹⁷ Employing models and methods developed for SKB's SFR GDF (cf. Höglund et al. 2014).

¹⁸ Although not explained in detail in Höglund et al. (2018), this constituted a reassessment of the 'standard' concrete degradation models based on the fact that the natural concretes of Jordan, Syria, Israel and Saudi Arabia have survived almost unchanged for several million years. As such, based on discussions with the junior author of this report, the degree of degradation of concrete in the models was addressed in a more realistic (i.e. less conservative) manner, leading to the production of lower volumes of alkali leachate which could interact with the host rock and the SF GDF.

17.4.2023

scenario under consideration, the impact could be positive (e.g. reducing groundwater flow at GDF depth) or negative (degrading the GDF buffer and backfill) but, for the Olkiluoto site, the scoping calculations carried out to date led to a change in GDF management (i.e. the use of low-alkali cement grout below a depth of 200 m in the ONKALO facility) which should minimise any potential negative impacts on the GDF and host rock. Further, more realistic treatment of concrete degradation based on NA information suggest that most cement leaching model output is over-conservative (in the safety case sense).

3.3.2.4 Example of use of NA in safety case: Steel corrosion

As noted in Posiva (2012a), the main perturbations associated with a steel canister are canister failure through corrosion, hydrogen gas production due to anaerobic corrosion and redox changes around the canister following canister failure. As a check on the long-term performance of the canister, both Nagra and JNC (now JAEA) carried out natural and archaeological analogue studies of iron artefacts from a range of environments. Despite the fact that most material studied came from oxic to sub-oxic environments and would therefore be expected to corrode to a much greater extent than in the anaerobic setting of a GDF, a maximum corrosion depth of 10 mm in 1 ka was calculated for Nagra (Figure 3-16), so increasing confidence in the results from the short-term experimental data and the Base Case assumption of 29 mm (Table 3-4).

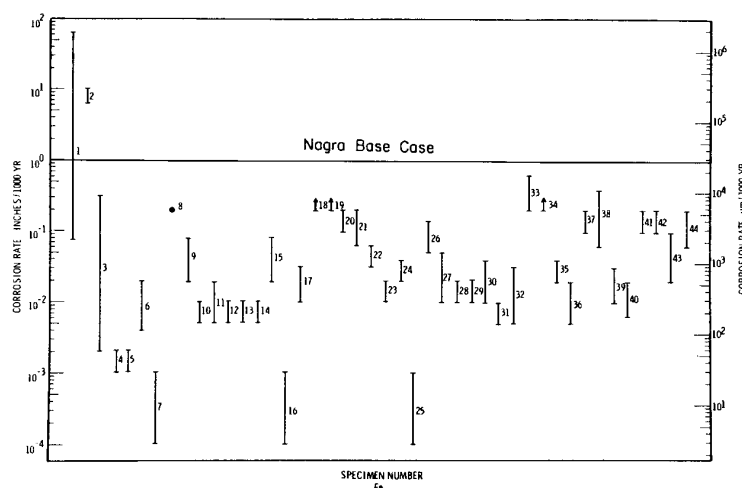


Figure 3-16. Iron corrosion rate data from natural and archaeological analogue studies (adapted from Miller et al 2000). The corrosion rates for the archaeological artefacts range from 0.1 to 10 $\mu\text{m a}^{-1}$ (note that samples 1 and 2 are from oxidising marine conditions; details of all other samples included in Johnson & Francis 1980). The Nagra base case corrosion rate for steel canisters from Projekt Gewähr (Nagra 1985) is also shown for comparison.

17.4.2023

For JNC, a maximum corrosion depth of 15 mm in 1 ka was calculated, again comparing well with the Base Case assumption of 31.8 mm in H12 (Table 3-4). The maximum corrosion depth was dropped to <10 mm in JNC (2005), even though this included data from aerobic environments (Figure 3-17), see also section 3.2.2 in Alexander & Reijonen (2023).

Table 3-4. Comparison of steel corrosion depths cited in the H12 (JNC, 2000), Kristallin-1 (Nagra 1994) and H17 (JNC 2005) safety cases with a range of archaeological analogue data for steel/iron artefacts (Posiva 2012a).

Form of data	Corrosion depth (per 1000 a)	Reference	Comments
Short-term lab	31.8 mm	JNC (2000)	Uniform corrosion of carbon steel. Base Case value
Short-term lab	29 mm	Nagra (1984)	Conservative corrosion rate, including an allowance for pitting. Base Case value
Natural analogue	0.09x10 ⁻³ mm	Hellmuth (1991a, b)	Weathering of native iron in basalt (Disko Island)
Archaeological analogue	10 mm	Range of studies cited in Nagra (1994)	Uniform corrosion of iron and steel
Archaeological analogue	<15 mm	Range of studies cited in JNC (2000)	Uniform corrosion of iron and steel
Archaeological analogue	0.1 - 10	David (2001)	Literature review of corrosion of archaeological samples
Archaeological analogue	<10 mm	Range of studies cited in JNC (2005)	Uniform corrosion of iron and steel

17.4.2023

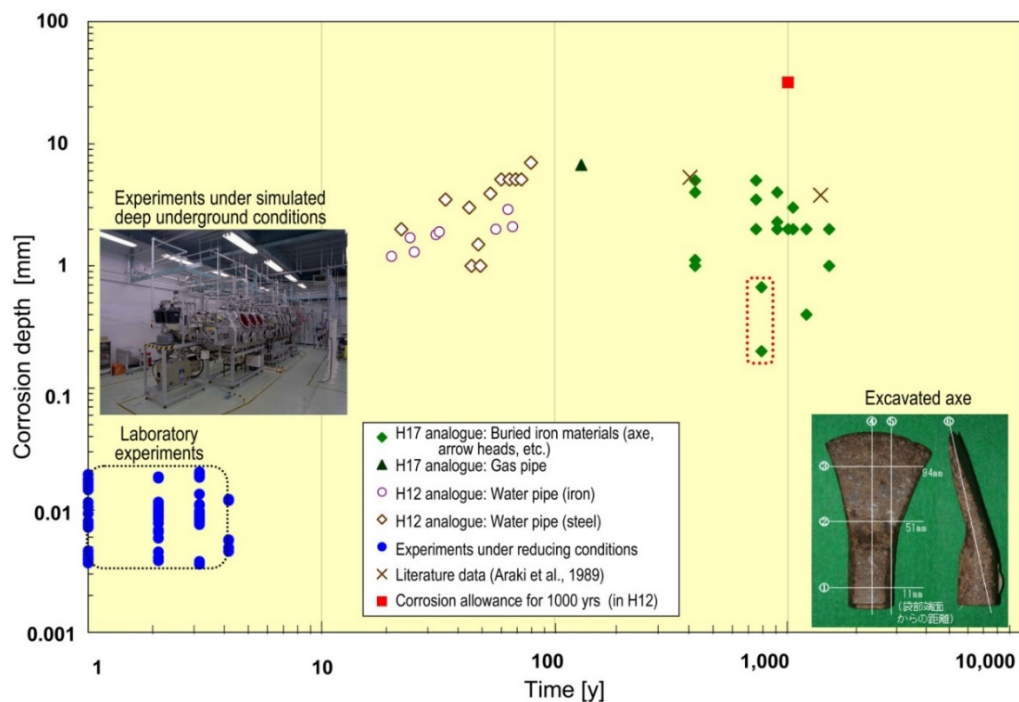


Figure 3-17. Integration of iron/steel corrosion data from laboratory experiments and several NA sources (details in JNC, 2005). Note that the H17 analogues surrounded by the red dots come from an aerobic environment.

3.3.2.5 Example of use of NA in safety case: Copper corrosion

In both JAEA’s H12 and H17 safety cases in Japan (JNC 2000, 2005 respectively), corrosion data from archaeological analogues were used to increase confidence in the data produced in short-term laboratory corrosion tests for copper canisters (see Table 3-5). To these data, additional information which was either not included in the H12 assessments or which did not exist at the time have been added from other NA studies. The newer data from the IAEA (for example) suggest that the assumptions made in H12 and H17 are certainly conservative.

Table 3-5. Comparison of copper corrosion depths cited in H12 with existing and new archaeological analogue data for copper/bronze artefacts.

Form of data	Corrosion depth (per 1000a)	Reference	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

17.4.2023

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

3.3.2.6 Example of use of NA in safety case: Matrix diffusion

Matrix diffusion as a far-field radionuclide retardation process has long been included in both generic (e.g. IAEA, 2005; NUMO, 2020) and site specific (e.g. Nagra 1994) safety cases with NA information supporting both the conceptual models and the actual reaction depths cited in the safety cases. Numerous reviews (e.g. Heath 1995, Havlova et al. 2020) of matrix diffusion NA studies already exist, as do several (e.g. Alexander 1993, Miller et al. 2000) assessing the NA input to the safety case, so they will not be discussed further here. NWS's recent work (Wogelius et al. 2020, Metcalfe et al. 2021) on matrix diffusion is discussed in detail in Posiva (2022).

3.3.3 Use in design development

The earliest mention of natural systems in GDF design goes right back to 1955 and a seminal conference held in Princeton on radioactive waste disposal by the US Atomic Energy Commission (see USNRC 1957, for details). Here the discussion noted that working with natural materials, such as bentonite, copper and iron, was a sensible path to pursue as we have so much experience with them and have used them for a very long time. Despite this, material-specific NA studies to date have tended to focus on EBS materials (e.g. see Reijonen & Alexander 2015, for a review of bentonite NA studies), mainly because few GDF designs have progressed to the point that information on the long-term behaviour of specific materials has been required. However, this is changing and a few examples of the focussed use of NA information in support of various aspects of GDF design are presented here.

3.3.3.1 GDF seals

Overview

The shaft of the proposed OPG (Ontario Power Generation Inc.) GDF for L/ILW at the Bruce NPP (nuclear power plant) site in Ontario, Canada, will be sealed with several hundred metres of a combination of bentonite-, concrete- and asphalt-based seals. As part of the development of the

17.4.2023

safety case for the GDF, NWMO felt that appropriate NA-based indications of the likely long-term durability of the materials would be useful (Kremer & Alexander, 2015¹⁹). In particular, it was felt that NAs that are more specific to the materials and conditions currently specified in the reference design concept would be of most use and so NWMO were interested in:

- NAs for durability of the specified GDF seal materials, namely bentonite-sand material, low-heat concrete and asphalt-sand-lime material (rather than bentonite, cement and asphalt in general – see comment in section 3.3.3.1) under highly saline conditions.
- NAs for the durability of either the combined seal materials (preferred) or, if this proved impossible, the main materials (i.e. bentonite, cement and asphalt) under long-term reaction with highly saline waters. At the Bruce site, the pore water chemistry is essentially Na-Ca-Cl brine at 260-370 gL⁻¹ and near-neutral pH at 10-25°C.

While NAs can provide information on the long-term (10⁴-10⁷ a) behaviour of GDF seals, industrial and archaeological analogues can also provide valuable information. Industrial analogues have the potential to identify processes that are relevant to borehole sealing on the timescale of 10¹-10³ a. Examples would include coring of engineered structures where different materials relevant to GDF sealing are in contact, or over-coring of sealed shafts to recover and test shaft seals. Archaeological analogues can look at timescales of 10²-10⁴ a, so closing the gap between industrial and NAs. Examples here include examination of the longevity of Roman cements, many of which are still capable of fulfilling their original functions at least 2 ka after construction (e.g. Vola et al. 2011).

This study was slightly unusual insofar that no attempt had previously been made to examine NAs of such mixed materials and, as such, where no information on the mixtures was available, two approaches were taken, namely:

- the most appropriate studies of the main materials were presented
- the most appropriate alternative materials or material combinations were identified for future study if deemed necessary

As an example, the result of the study for a mixed bentonite/silica sand seal are summarised in Table 3-6.

Table 3-6. summary of the results of the study for a 70% MX-80 bentonite/30% silica sand seal (courtesy NWMO).

Bentonite Material	Smectite %	Quartz %	Other %	Temp C	Age Ma	Salinity gL ⁻¹	pH	Status	Comments
70 MX-80, 30 silica sand	60	32		10-25	0.1-1	300 NaCl	neutral	stable	

¹⁹ This short paper provides an overview of an unpublished NWMO internal report.

17.4.2023

Bentonite Material	Smectite %	Quartz %	Other %	Temp C	Age Ma	Salinity gL ⁻¹	pH	Status	Comments
USA/Canada: Wyoming bentonite	80-90	3	Feldspar, mica, trace	10-50?	100 ?	0-50?	neutral	stable	May have been protected by self-sealing
Cyprus: Perapedhi bentonite	25-50	10-13	Amorphous silica 18 - 32	10-50?	90	0-30?	neutral	stable	Ca. 90 Ma in marine environment, no discernible degradation
Sweden: Forsmark, Laxemar fractures	unknown	unknown	unknown	Formation temperature of 80 – 145, long-term at 25 - 30	250-500	15-45	neutral to alkali	stable	No detailed analyses available
Sardinia: Busachi bentonite	60 - 90	unknown	Calcite 2	800 on day 1, 200 after 2 months	20 - 25	30?	Assumed neutral	Altered in places	No detailed analyses available
Libya: Ishrini bentonite	90	unknown	unknown	30 - 90	5	Unknown, but 'hypersaline' inclusions in places	unknown	minimal	T>190°C for cementation
Spain: Cortijo de Archidona bentonite	unknown	unknown	unknown	10-50?	1-10?	0-30 ?	neutral	stable	Too poorly described to be of use

Conclusions

Appropriate NAs of GDF seal materials under the salinity conditions present at the Bruce site are rare. And this is even more so when the mixed seal materials are considered. Nevertheless, several examples of the durability of the mixed seal materials were reported and here, little or no degradation has been observed. Overall, however, should more precise NA evidence of seal durability under the proposed GDF-relevant conditions at Bruce be required, then novel, focussed studies would need to be initiated. However, it must be emphasised that these would be studies of materials which are analogous to the GDF seal materials, full copies of the materials simply do not exist.

3.3.3.2 GDF exploratory borehole seals

In a similar vein, NWS has been conducting a study of potential materials to provide long-term seals for GDF exploratory boreholes. The Borehole Sealing (BS) project developed principles and requirements for selecting post-closure seals and these were implemented in a flowchart and

17.4.2023

decision support tree (see Jefferies et al. 2016 for details). Candidate materials for post-closure seals in HSR (higher strength rocks) and LSSR (lower strength sedimentary rocks) were identified, and a preliminary assessment of their applicability in different settings was undertaken.

Potential sealing materials for boreholes in HSR and LSSR were grouped into the following categories:

- high density sealing elements, such as bentonite blocks;
- granular materials, such as bentonite pellets and sand/bentonite mixtures;
- pumpable materials, such as SANDABAND²⁰, cement (OPC or low-alkali) and various bentonite-based mixtures;
- graded sand/crushed rock.

Jefferies et al. (2016) identified two principal Safety Functions of post-closure borehole seals:

1. to ensure that groundwater and/or gas flow through the sealed borehole is sufficiently reduced that the borehole does not compromise the geological containment objective of the geosphere (achieved through 'low permeability').
2. to reduce groundwater and/or gas flow through the sealed borehole for as long as is required to ensure that the borehole does not compromise the geological containment objective of the geosphere (achieved through 'longevity').

The principal Safety Function of the support elements for post-closure seals was identified as:

3. to provide mechanical support to overlying post-closure seals, in order to prevent the post-closure seals being damaged by movement within the boreholes.

In the context of these three safety functions, NA information was used as one of the lines of approach to build understanding of the likely long-term performance of materials used for seals (and support elements) in boreholes.

Conclusions

As with GDF seals (section 3.3.3.1), the main conclusion from this work was that specific NA information on borehole sealing *per se* is all but missing. Nevertheless, existing NA studies provided qualitative input to many of the areas of concern within the BS project (see Alexander, 2017, for details). Further, numerous examples where more information can be supplied at the qualitative level were noted, but also where truly quantitative support could be available through

²⁰

SANDABAND™ is composed of about 70-80% by volume of solids, and approximately 20-30% of water and other additives to control its fluid properties. The solids are quartz grains of different dimensions; essentially the material is a mixture of sand grains and micro-silica. The material is used for plugging and permanent abandonment of oil and gas wells

17.4.2023

novel NA studies (e.g. in Italy and Jordan) or extending existing work (e.g. at sites in Cyprus) through re-analysis of existing raw data or samples or acquiring new material.

3.3.3.3 Exploring design limits for cementitious waste packages

The potential for waste canister sinking/settling in bentonite (or a bentonite-sand mixture) buffer over long timescales has been little studied. Modelling suggests that it is unlikely, but this needs to be checked against data and the most appropriate method to do so is to utilise data from natural systems as a 'reality check' on model predictions of long-term processes. To date, most modelling effort has been focussed on the settlement of HLW or SF canisters where the load on the bentonite is of the order of 0.1 to 0.2 MPa (e.g. Börgesson & Hernelind 2006, Åkesson et al. 2010). However, as various L/ILW GDF worldwide move towards realisation (e.g. SKB 2014), there is a requirement to assess the potential settlement of cementitious waste packages and other structures and here the expected loads on the bentonite are greater, being in the order of 0.3 to 0.4 MPa (see Figure 3-18 for example design).

At the Kato Moni site in Cyprus, as an analogy of cementitious L/ILW containers emplaced in bentonite, three cores in natural bentonite underlying the limestone overburden at the site were collected (Alexander et al. 2017). The limestone was deposited slowly, without exerting sudden impacts on the bentonite thus producing a system of direct relevance to the GDF environment (bentonite under load). Some bentonite samples displayed evidence of natural fracturing, associated with shear displacement (note that shear is the response of a rock to deformation, usually by compressive stress and forms particular textures).

In addition, bentonite pellets/micro-pellets at the site were observed to react to confining pressure in a different manner to the massive bentonite shown above. The pellet texture appears to encourage creep of the bentonite, suggesting this form of emplacing the bentonite buffer should be avoided in this case²¹.

²¹ However, this could be advantageous when trying to ensure filling of borehole voids under potentially stringent QA conditions. This could prove especially useful where the borehole space to be filled is irregular in shape and ensuring a homogenous density of the bentonite plug is critical to seal performance (see also section 3.3.3.3).

17.4.2023

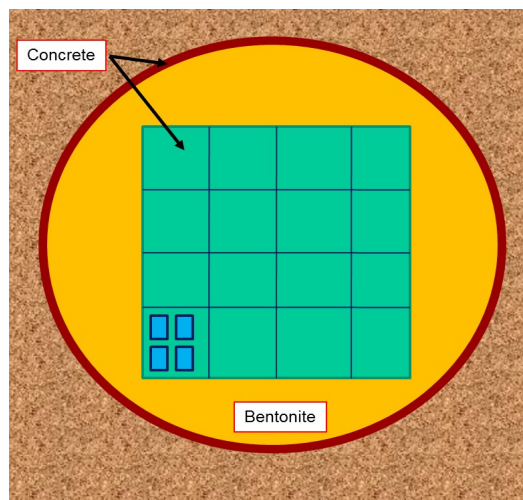


Figure 3-18. A generic waste cavern design for a cementitious L/ILW GDF. Waste containers (blue, typically 200 L metal drums filled with waste and a cement grout) are encased in concrete boxes (green) which are usually backfilled with more cement grout. The boxes are then protected by bentonite to minimise groundwater interaction with the waste. The tunnel walls may also be supported by concrete tunnel liners (Alexander et al. 2017).

The work at the Kato Moni site (Alexander et al. 2017) in Cyprus has shown that both natural and industrial bentonites are intrinsically susceptible to shear, but it would appear that it may be possible to design around this susceptibility in certain GDF designs for SF which may not be applicable to repositories for cementitious (L/ILW) wastes. For example, the high bentonite swelling pressures assumed in SF designs (e.g. Börgesson & Hernelind 2006, Börgesson et al. 2010) are unreasonable in a cementitious waste GDF as current waste package designs do not take this into account. In addition, this SF design assumes full saturation of the bentonite to attain the high swelling pressures and evidence from natural bentonites (e.g. Reijonen & Alexander 2015) suggest that this may not happen in all cases.

Conclusions

The NA information from the Kato Moni site in Cyprus suggests that current L/ILW GDF designs which assume emplacing packages of cementitious wastes in a bentonite buffer may need to be re-examined with a view to avoiding potential package sinking due to bentonite shear. In addition, due to the propensity for pellet bentonite to shear more than massive bentonite, the use of pellet bentonite in such designs should probably be avoided.

17.4.2023

However, simply employing the SF design parameters would appear not to be an option as the current waste package designs do not take the very high bentonite swelling pressures into account (and would likely be crushed *in situ*).

3.3.3.4 Why use low alkali cements?

Bentonite makes an important contribution to the performance of the EBS for the disposal concepts developed for many types of GDF. The choice of bentonite results from its favourable properties for isolation and containment of the waste and its stability in relevant geological environments. However, bentonite, especially the swelling clay component that contributes to its essential barrier functions, is unstable under the high pH (initial pH >13) conditions expected when OPC Ordinary Portland Cement) concrete leaches following reaction with groundwater.

There have, therefore, been extensive efforts to better understand the interactions of alkaline fluids with bentonite (e.g. Ahn et al. 2017, Xiang et al. 2019), coupled with studies aimed at reducing the potential risk by development (e.g. Bodén & Sievänen 2012) and testing (e.g. Nakayama et al. 2016) of low alkali cement formulations which typically have leachates with a pH of 9-11. Attempts to examine the potential reaction of bentonite experimentally at these lower pH values have been complicated by the inherently slow kinetics of such reactions (e.g. Heikola et al. 2013). Clearly, this is an area where studying natural systems could play a valuable role – bridging the disparity in realism in temporal and spatial scales between laboratory studies and the systems represented in GDF performance assessment. Indeed, in this case, the particularly slow kinetics of bentonite reaction in low alkali cement porewaters suggests natural system studies would appear to be the only viable method of assessing bentonite reaction within a timescale which would allow input to current GDF safety cases.

As part of this design process, NWS (along with SKB and Posiva), were involved in the assessment of long-term natural bentonite reaction with natural alkaline (pH 9-11) groundwaters at the Parsata site in Cyprus (see Milodowski et al. 2016 for an overview of the Cyprus Natural Analogue Project, CNAP). The results suggest that there has been very limited alkaline groundwater reaction with the natural bentonite over a period of 10^5 - 10^6 years, tending to indicate that any long-term reaction of industrial bentonite with low alkali cement leachates in a GDF environment will be minimal. Perhaps of equal importance is the fact that, when compared with most existing NA, laboratory and URL studies of bentonite reaction in alkali solutes, this is the first to approach GDF conditions (see also comments in Reijonen & Alexander 2015) insofar that the field conditions closely simulate what would be expected in a GDF:

- an appropriately large mass of bentonite is 'in place' (as in a GDF), rather than a small plug within laboratory apparatus
- an appropriate alkali leachate can react with the surface of the bentonite in a manner similar to what would be expected in the GDF, rather than in the unrealistic conditions (e.g.

17.4.2023

inappropriate bentonite:leachate ratio) common in laboratory and previous natural system studies

- reaction between the leachate and the bentonite appears to be generally driven by diffusive transport of solutes (especially Ca) into the body of the bentonite from the bentonite/alkali leachate contact zone, again as would be expected in a GDF
- the temperatures of reaction are also GDF-relevant
- the reaction timescales are of much more relevance to a GDF than accelerated laboratory and URL studies

Conclusions

Although it is arguably too early in the UK and Swedish national programmes for NWS and SKB to have utilised the results in their GDF design, this is not the case for Posiva. Indeed, to avoid future potential problems with the EBS of the (at that time) proposed GDF, Posiva decided (Sievänen et al. 2012) to use only low alkali cement below -200 m²² when grouting the ONKALO facility. Although the planned (and ongoing) procedures for the expansion of the ONKALO facility are laid out in detail (e.g. Arenius et al. 2008), the impact of specific projects such as CNAP (and, for example, the work presented in Bodén & Sievänen 2006) on the decision to restrict the use of OPC cement at depth are difficult to ascertain as such internal discussions are not generally published openly.

3.3.4 Examples for stakeholder communication

The complexities of safety cases (scenario-, consequence- and uncertainty-analysis, FEPs etc.) are difficult to communicate - even to technical audiences. These communication failures stem from a number of issues. Some of these are technical - the multi-disciplinary nature of the work with each scientific group talking in its own vocabulary, the very long timescales over which safety must be demonstrated etc. Others are psychological and social - many scientists may lack stakeholder communication skills making it challenging to communicate their work to wider audiences, many also feel uncomfortable talking outside their field or giving definitive answers (see West 2000, for example). Some progress on the discussing the long geological timescales with wider audiences than geosciences has recently been made.

As a result of these issues, it can be difficult for the scientists involved to provide clear answers to concerns raised by wider stakeholder groups in any country. However, if scientists cannot communicate their work then it is unlikely that the confidence of the stakeholders (including the local communities in particular) in their ability to dispose of radioactive waste safely will improve.

²² Planned GDF depth of -420 m.

17.4.2023

Without this confidence, radioactive waste disposal programmes in democratic societies will fail. In recognition of this situation, new ways have been sought to try to communicate radioactive waste concepts and to improve confidence in the safe disposal of waste. The use of nature's own laboratories as the key vehicle for such communication has long been recognised as an important approach, but just how successful has it proven to be?

As noted in NEA (2017) *“The basis for the safety cases for both operational and long-term safety of a proposed or a working repository needs to use illustrations of principles and processes based on analogous situations or processes that are likely to be familiar to the public. This analogue approach would involve both human and natural analogues. Learning and insight are developed when analogies are used to promote questioning on the part of the public stakeholder.”*

Here, some examples from international and national programmes are shown to give a flavour of what has been achieved in the past.

3.3.4.1 International effort

A video entitled 'Traces of the Future. Lessons from nature for waste disposal', sponsored by various national radioactive waste disposal organisations²³ was produced in 1994. Despite winning international acclaim²⁴, use of the video has been patchy. Nirex, for example, only used the video for 'internal induction courses' whereas Nagra issued numerous copies to interested scientists and engineers worldwide and to schools in Switzerland. The video was issued in two forms, 52 and 26 minutes long, and the resulting experience suggests that such material should be kept to the optimum attention span of 10 to 15 minutes, unless a documentary is produced specifically for television broadcast.

Although a good first attempt, the video was less successful than was originally hoped, partly because of resistance to the idea from the various PR departments (many of which were not involved in the production) in the funding organisations. Indeed, SKB, whose PR department was involved from the beginning, have probably used the video most extensively. In addition, television companies worldwide have been less than keen to use the video because it was produced by a group of implementing organisations and they did not wish to be seen to be promoting radioactive waste disposal.

The concept clearly has great promise but involvement of professional PR staff from the beginning is important if these groups are to be convinced to use the final product. It is also critical to discuss co-production with television companies if the aim is to produce material for national television broadcast, but less so if the main audience will be schools, universities, sports clubs etc.

²³ The project was initiated by NAWG and was managed by Nagra and funded by JNC, Nagra, Nirex, SKB, US DoE, the EU, AECL, ENRESA and ONDRAF. INER later bought the rights to use the video in Taiwan.

²⁴ The Czech-language version of the video was awarded 1st prize in its category at the 34th International Festival of Films and Videos, Kradec Kralove, Czech Republic 19 October 1996

17.4.2023

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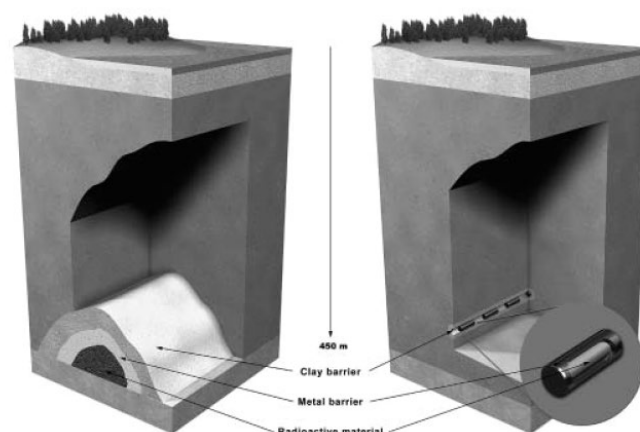
The IAEA has sponsored several technical projects (see section 3.2.2), workshops and expert reviews on NAs, but little with a direct communications component. An exception was the "Media Communication" workshops of the 1990s which focussed on providing information on a wide range of nuclear topics to media and educators in many countries. The radioactive waste presentations often made considerable use of NAs – which was often picked-up in resultant newspaper, radio, and TV articles. Otherwise, although numerous IAEA publications (e.g. IAEA 1994b, 1997, 2003b, 2017) over the last three decades mention the use of NA information in communication of radioactive waste issues, none offer any significant examples nor guidelines for appropriate use in stakeholder communications.

NEA

As with the IAEA, the NEA has sponsored several technical projects (see section 3.2.3), workshops and expert reviews on NAs, but little with a direct communications component. Indeed, the NEA appears to falter between two opinions with Brans et al. (2015), in a report which offers a review of the major works developed in the past fifteen years by the Forum on Stakeholder Confidence (FSC) of the OECD Nuclear Energy Agency (NEA), including no mention at all of either NAs or natural systems. NEA (2017), however, noted that NA are part of a group of areas which are 'Selected safety case topics with high relevance for communication'.

Canada

When the Canadian SF disposal programme was managed by AECL, they made regular use of the Cigar Lake NA as a simple comparison to the Canadian disposal concept. For the Canadian concept of direct disposal of CANDU (non-enriched) UO₂ fuel, the analogy is quite striking for wider stakeholder groups²⁵ (Figure 3-19).



²⁵ In addition, the same example (Figure 3-19) has been used to explain disposal concepts to technical audiences (e.g. Alexander et al. 2006).

17.4.2023

Figure 3-19. Comparison of the Cigar Lake uranium ore body (left) with the engineered barrier system (right) for a GDF for high-level radioactive waste (HLW). In Cigar Lake, the radioactive waste is represented by the natural uraninite ore (dark grey core), the metal barrier by an iron oxide/hydroxide rich zone (light grey middle layer) and the clay barrier by a clay-rich, hydrothermal halo (mid-grey outer layer). Alexander et al. (2006).

Since NWMO took on responsibility for the national disposal programme in 2002, NAs have been an important part in discussions with local stakeholders (see e.g. Blyth & Kremer 2023).

Finland

Although early PR materials were produced in Finnish only, there tend to be significant use of NAs in making a safety case (e.g. 2 out of 14 pages in a TVO brochure, focused on Cigar Lake and natural copper deposits).

Recently, TVO/Posiva produced leaflet on safe disposal in Finnish²⁶, that uses copper and clay analogues as examples.

The Finnish programme has been recently in focus of an external observer. Vincent Ialenti did anthropological field work in the Finnish safety case community during the years 2012-2014. He captured in his latest book that the ‘deep time reckoning’ might be the most important output from the work done in the Finnish safety case programme. His book (Ialenti 2020) has been reviewed by e.g. Science magazine (Hamblin 2020) and received attention in the social media, but the message has hardly reached wider stakeholder groups. However, his approach to address wider scientific group has been significant²⁷ and the need for it acknowledged:

“Because of the myriad challenges of the Anthropocene deep time reckoning is no longer the province solely of geologists, evolutionary biologists, or astrophysicists. It is now our collective responsibility, and we need the tools to do it” (Ialenti 2020)

Japan

Although the NAs video described below was co-funded by PNC and a Japanese-language version exists, it appears to have been little used for stakeholder communications purposes (and it seems that few of those in the Japanese waste management field even know of its existence). In the past, a range of information brochures were produced by Japanese organisations with waste management responsibilities – several of which were translated into English (e.g. brochures from JNFL, RWMC, JAERI, CRIEPI, JNC and NUMO). Examination of these shows a definite emphasis on engineering hardware and technical flow charts with little (if any) use of NAs.

²⁶ https://www.tvo.fi/uploads/julkaisut/tiedostot/Turvallinen_loppusijoitus.pdf

²⁷ Similar attempts to explain geological timescales to other peer groups have been made e.g. by Björnelund (2018) on ‘Timefulness – How thinking like a geologist can help save the world’ and Irvine (2020) on ‘An anthropology of deep time – Geological temporality and social life’.

17.4.2023

On assuming responsibility for the national HLW/SF disposal programme, NUMO produced a range of calendars which used striking NA-based images but made no attempt to explain the link with waste disposal, the safety case or a GDF. More recently, they produced a Japanese translation (Milodowski et al. 2015b) of RWMs original catalogue of NAs (Milodowski et al. 2015a). It is currently unclear as to how NUMO are using this publication nor which audience they hope to reach.

Sweden

SKB was one of the early users of NAs as a vehicle for communicating radioactive waste concepts. In the 1990s, in addition to printed material (e.g. Figure 3-20), short videos were produced with titles such as 'Nature's own technology' (longevity of materials using natural and archaeological analogues), 'Nature's own nuclear waste' (based on the Oklo study) and 'Nature's own GDF (based on the Cigar Lake study). These videos were used to communicate specific, focussed points and appear to have been successful although no formal assessment of the effect of the work was attempted by SKB. None of these videos are currently available on SKB's web site (the oldest video currently available is from 2011)²⁸.

Den svenska metoden för förvaring av använt kärnbränsle är inte ny.



Den har funnits i Kanada i 1300 miljoner år.

Naturen har fört oss med ett flertal bevis på att det går att åstadkomma säkra underjordiska förvaringsplatser för radioaktiva ämnen.

En sådan finns i Cigar Lake i Kanada. Där upptäcktes i början på 80-talet en två kilometer lång malmkropp med extremt hög uranhalt. Fyndet gjordes på 430 meters djup och sats mynnar ihop vid ett förskärningsstadium. Det som förvånade experterna var att fogligheten inte gick att iaktta från markytan.

Vattnet drickbart 5 meter från uranmalmen.

Det visade sig att malmen iakttagits mellan sandsten och underliggande urberg. Runt malmkroppen ligger ett 5-30 meter tjockt lager av kera som hindrade grundvattenflödet. För det omgivande berget var naturligtvis hade. Sedan tillförs de radioaktiva ämnena på plats i 1300 miljoner år.

Många tror att redan fem meter från yttill uranmalmen innehåller grundvattnet 20 gånger mindre uran än det konventionella gruvsvärdet för dricksvatten.

Detta exempel har stora likheter med den metod för förvaring av använt kärnbränsle som vi tänker använda oss av i Sverige.

500 meter ner i urberget. Använt kärnbränsle, som är en bit keramik, avger strålning under mycket lång tid och måste hållas isolerat från till eller nästa led av jordens baser för Örens svenska metodens grund ut på att ianvända bränslet i kopparkapslar som bildas i cirka 500 meter ner i urberget. Detta djup har valts för att åstadkomma en stabil miljö, där kemiska och mekaniska förändringar skryts överst i lagarna, men också för att framtida generationer inte ska riskera att bryta ett bränslell rikt ned i förvaret. Ur strålspunkt hade det räckit med två meter.


Kopparkapslarna effektiva barriärer. Det enda som skulle kunna transportera radioaktiva ämnen från förvaret är grundvatten.

Vill du veta mer om Sveriges radioaktiva avfall? Fyll i namnet och skicka det till adressen: **SKB** 10333 Stockholm

Namn: _____
 Adress: _____
 Postadress: _____

SKB
 Vi tar hand om Sveriges radioaktiva avfall.

HOW HADRIAN'S WALL IS HELPING NIREX TO CONTAIN RADIOACTIVE WASTE SAFELY.



Concrete and other cement-based materials are known to survive for millennia in the right conditions. They were used in ancient China, Egypt and Greece. In fact the condition of concrete recently excavated from the foundations of Hadrian's Wall shows how well it can withstand the centuries.

It is this quality which makes cement-based grout and concrete so suitable for use in the proposed Sellafield Repository.

Even when they break down they form an efficient chemical barrier which prevents many of the wastes dissolving in water. In fact, this is one of their main purposes in the repository.

The Sellafield Repository, if built, will be an impressive feat of engineering, dedicated to the safe and permanent disposal of medium and low-level radioactive waste. As far as the eye is concerned it will barely be noticeable.

But what the eye won't see is the very high degree of care which will be in evidence underground.

Half a mile below ground, in solid rock, a series of huge caverns will be excavated where low and intermediate-level waste can be emplaced.

Low-level waste, items such as overalls, gloves and shoes, will be packed into steel drums or concrete boxes and intermediate-level waste will be grouted into stainless steel drums.

This project will meet the country's disposal needs for 50 years and it will safeguard the environment for tens of thousands of years after that.

For further information write to The Information Officer, UK Nirex Ltd., Curie Avenue, Harwell, Didcot, Oxfordshire, OX11 0RH, or telephone Peter Curd on 0235 825 500, and quote reference 'W'.

United Kingdom Nirex Limited
 SAFE FOR THE FUTURE

²⁸ Other videos are, however, available on YouTube – see https://www.youtube.com/results?search_query=skb%2C+sweden

17.4.2023

Figure 3-20. Examples of older printed material from the Swedish (left) and UK (right) national programmes. On the left, SKB used the long-term (1.3 Ga) stability of the Cigar Lake uranium ore body to make a point about GDF safety. On the right, UK Nirex used Roman grouts to support the long-term stability of GDF concrete.

Of particular note was the extensive use of the SKB radioactive waste transport ship MS Sigyn²⁹ which doubled as a travelling exhibition during the summer months visiting seaports around Sweden and Finland. This brought information to communities which are some distance from the main population centres. NAs were used as a central focus of the exhibitions which were manned by SKB staff. Brochures and fliers were also produced for distribution at the exhibitions.

SKB has also had a successful programme of collaboration with a variety of Swedish universities in their technical NA programme, producing a large body of scientific papers and reports.

Currently, two short NA examples are shown on SKB's Swedish-language web site (e.g. Figures 3-21 and 3-22), but there appears to be little other use of NA information in current stakeholder communication by SKB.



Figure 3-21. Image from SKB's Swedish-language web site showing a 700 year old copper helmet from York, England, as part of a discussion of copper corrosion.

²⁹ Replaced in 2014 by the MS Sigrid.

17.4.2023



Figure 3-22. Image from SKB's Swedish-language web site showing high pH natural groundwaters at the Maqarin site in northern Jordan as part of a discussion on the reaction of cement leachates with a GDF host rock.

Switzerland

Nagra, as with SKB, was one of the first organisations to use NAs as a tool for building public confidence in waste disposal and built this work on the back of a significant programme of technical NAs (see Appendix 2 for examples). Due to the relatively small size of the Swiss programme, Nagra very quickly adopted an intensive approach using international support to generate books and reports on NAs (cf. Appendix 2) and was the lead organisation for the production of the NA video mentioned below.

As with SKB, Nagra has also encouraged several universities in Switzerland and internationally to participate in its technical NA programme, leading so far to three doctorates (which were directly funded by the NA programme) and a large body of scientific papers. Some of this work has also been repackaged for technical magazines and newspapers in Switzerland (see examples in Appendix 2).

In addition to using NAs to inform the general public, Nagra has released several reports (e.g. the two NA books listed in Appendix 2) aimed more at Swiss and international opinion formers and technical peer groups. Although primarily focussed on the technical use of NAs, Nagra went to considerable lengths to make the information both accessible and enjoyable to read by producing the reports in a 'glossy' magazine format. For example, Appendix 3 shows an example of a 2007 brochure (in German) which uses NA information to explain long-term safety of a GDF. Similarly, Appendix 4 shows a more recent (2018) example from Nagra which tries to explain why they are confident about the long-term safety of the GDF. Here, various examples are shown, but one section 'What can nature teach us about waste disposal?' discusses natural systems and NA information. More recently, Nagra has also moved onto YouTube (see <https://www.youtube.com/user/NagraFilme> for example and they have produced a new interactive

17.4.2023

portal for schools and young people that presents a wide range of materials for teachers and students <https://www.nagra.ch/en/interactve-portal-for-schools-young-people>).

Nagra also proposed and edited a series of reports in an international nuclear industry magazine where NAs were used to explain complex safety case issues to an audience which, although technically literate, did not necessarily understand some of the more obscure safety case reasoning or methods. In a step aimed at a similar audience, in the Kristelin-1 safety case, Nagra included a report (Neall et al. 1994) which laid out the reasons why Nagra was confident that it could safely dispose of HLW. This included information provided by technical NAs to increase peer group confidence in the disposal approach. Nagra later produced a similar report (Neall & Smith 2004) on behalf of JAEA to support their H12 safety case.

The organisation has also had considerable success with its educational packages that are loaned to schools across Switzerland (see <https://www.nagra.ch/en/news/newsdetailen/interaktives-portal-schule-und-jugend-alles-auf-einen-blick-en.htm>). These packages have focussed on a wide range of aspects related to GDF development, including explaining (natural) radiation to students and provide teachers with all necessary materials and details of experiments to assist in lesson planning. These are supported by occasional symposia where Nagra staff discuss the educational packages with teachers before they are introduced to the schools. In addition, Nagra has made samples from several NA studies available to both universities and to museums for displaying to the public (more information below).

GNW (The Cooperative for Radioactive Waste Disposal at Wellenberg) was responsible for the proposed L/ILW GDF at Wellenberg in the central Swiss Alps and were involved in an extensive confidence building programme focussed on the public in the area around Wellenberg along with local, regional and national opinion formers and politicians. A part of this programme included the use of NAs to explain some of the more complex issues involved and utilized several 'hands-on' exhibits, including 15 ka old wood from Switzerland which had been preserved in glacial clay and a piece of the 2 Ma old (non-fossilised) wood (Figure 3-23) from the Dunarobba site in Italy (which was the undoubted star attraction at that particular exhibition).

17.4.2023



Figure 3-23. Two views across the clay quarry at Dunarobba, Italy, showing the non-fossilised wood stumps (Martinetto et al. 2014). A piece of the wood (ca. 30x30x30 cm) was cut from a stump and loaned to GNW by the Dunarobba town council for the 4 months of the exhibition in the Wellenberg area of Switzerland.

17.4.2023

3.3.4.2 Older work in the UK

The UK nuclear industry has long been involved in the study of NAs for technical reasons (see, for example Hooker et al. 1985) and Nirex used NAs in its publicity material. For example, adverts have been used to present archaeological analogues, such as the well-known Hadrian's Wall to the general public (Figure 3-20). In this case (using a line drawing, interestingly), the longevity of the mortar between the wall's building blocks was compared to the cement in the GDF. A report commissioned by Nirex also emphasised the potential use of NAs as communication tools but cautions that 'despite their potential input to non-technical demonstrations of safety, the use of analogues has often been unimaginative and, worse still, sometimes misleading'. Indeed, Miller (2002) noted the totally inappropriate use of data from the Oklo reactors by the UK nuclear industry pressure group, the British Nuclear Forum, stating that "Such statements challenge belief at all levels, apart from leaving themselves open to scientific ridicule if ever they have to be defended".

The UK media have also picked up on NAs as good stories for coverage:

- In 1990 'New Scientist', a highly regarded British popular science magazine with wide international circulation, published an article on NAs entitled 'Radioactive waste: back to the future?' written by Neil Chapman (BGS) and Ian McKinley (Nagra). NAs were also used in another article in New Scientist about the microbiology of radioactive waste disposal ('Some bugs like it hot' by Julia West, BGS, and Ian McKinley, Nagra). Feedback from these articles was very positive and resulted in radioactive waste presentations in the IAEA "Media Communication" workshops (see above) and a lecture tour of Australia sponsored by the Uranium Information Centre.
- The BBC has also used NA information in the past. They produced two radio programmes, which were broadcast on both their domestic and international outputs, and outlines of the programmes are given in Appendix 5.

These examples highlight some of the historical attempts made in the UK to use NAs for communicating radioactive waste issues and that they have met with success. They also show that misuse of NAs can happen if the communications staff involved lack any scientific understanding of the topics (and vice versa) or if appropriate reviews are not undertaken by the technical staff on the materials presented via communications.

3.3.4.3 Conclusions

There are a number of characteristics of NAs that should make them invaluable for communication purposes (IAEA 2017):

- *"Natural analogues are directly observable in the environment. They are part of mankind's environment and history and there is also an inherent attractiveness of nature to most individuals, i.e. most people have some interest in the natural environment. Therefore,*

17.4.2023

nature is an effective vehicle for dialogue (as it is, for example, frequently used in commercial advertisements).

- *Natural analogues can help make the timescales of interest to radioactive waste management meaningful. The notion that we are concerned about times far in excess of that for which the sphinx has been in existence has more meaning than a four, six or eight digit number.*
- *Natural analogues are inherently qualitative. This has often been seen as a weakness since it can make them difficult to use for modelling and quantitative prediction. However, for communication purposes it can be a strength since for most people, life is qualitative and intuitive.*
- *The fact that natural analogues are the result of a range of environmental processes, operating together on some artefact or material is a direct reflection of “what will happen” and provides a means of observing the integrated consequences.*

“However, a general impression from the past use of natural analogues in public communication is the lack of impact that they have had. This may be due to the emphasis on the use of written media, namely too static, one-way forms of communication with the objective to convince. The typical mode of presentation of analogues in communication materials has been in the form of brochures and leaflets. Audiences are very sensitive to underlying motivations. Any suggestion of propaganda can undermine the value of the information transfer. Further, too much simplification of an analogue in order to make it easy to grasp by a layman may end up with overstating its significance. Therefore it is important to mention the conditions and limitations of an analogue.”

This statement is somewhat complicated insofar that it contains numerous, mixed messages. These will be teased apart here:

Natural analogues are directly observable in the environment: agreed, but is the problem perhaps that past use has focussed on the dramatic images (e.g. Cigar Lake, Oklo) at the expense of the more ‘normal’ type of natural environment with which most people interact? For example, NWMO make the point that their Indigenous knowledge approach works well as they utilise examples of relevance to the local communities (e.g. *“Indigenous societies (in Canada) have explored the copper deposits around the Great Lakes since before 3000 BC”*). Similarly with GNW’s success in Wellenberg, mixing the ‘normal’ (15 ka old pieces of wood from Switzerland) with the somewhat more exotic (2 Ma old wood from Italy) – but these are still lumps of wood, not uranium ore³⁰. The take-home message here is that more normal, more approachable, examples are better.

NAs can make timescales of interest more meaningful: partially agreed. As above, perhaps the focus should be on slightly more mundane examples than the 1.3 Ga old Cigar Lake uranium ore. Certainly GNW’s audience at Wellenberg were comfortable with the 15 ka old wood from Swiss

³⁰ The junior author once presented a lump of uranium ore to a class of 50 employees of WMOs and asked how many had ever seen such a thing (never mind actually knew what it was)? The answer – zero.

17.4.2023

glacial deposits (the likes of which abound in Switzerland) and this appeared to make them less dubious about the 2 Ma old Sequoia wood from Dunarobba.

Natural analogues are inherently qualitative: Not true. This statement in IAEA (2017), although based on comments in NANet (2006c), is worrying insofar that it is typical of the current views of scientists and engineers working in radioactive waste disposal. Perhaps the message here is that it is first necessary to communicate the strengths of NA to peer groups before trying to work with the wider stakeholder spectrum.

NA are the result of a range of environmental processes: true, but surely this is only meaningful to scientists and the scientifically literate? Are we (as an industry) not guilty of over-complicating the message we try to squeeze out of every example, rather than just living with one small step forward (as is arguably the case for NWMO)?

Lack of impact of NA information on stakeholder communication: there is no denying that this is true (albeit with the rare successes as noted above).

3.3.5 Overview on NA use during GDF process

Reijonen et al. (2023) attempted to compile the overall framework for using analogues at different stages of geological disposal project (Table 3-7). This view relies on the FEP approach for systematic treatment of NAs. Reijonen et al. (2023) list a few main tasks related to knowledge development:

- Systematic approach
- Screening exercises
- Gap analysis

This list is not exhaustive, for example internal communication is not mentioned in this work, and hence the topic is taken forward in chapter 4, see especially section 4.2 on knowledge management and 4.3 on change management (see also Table 4-1).

Table 3.7. Using NA information at different stages of the disposal project (Reijonen et al. 2017).

Objectives of CC	Generic stage	Site & GDF design selected	Advanced stage
Site considerations	e.g. FEP NA analyses: Ranges of conditions (regional analogues ¹)	Screening of FEPs, update FEP-NA analysis. Regional considerations ² for site evolution to enhance predictability. Regional analogues to examine detailed site properties.	Screening of FEPs, update FEP-NA analysis. Site / scenario specific regional analogues /considerations ¹ (e.g. glaciation, tectonic evolution etc.).
Design considerations	e.g. FEP NA analyses:	Screening of FEPs, update FEP-NA analysis.	Update by process specific analogue information based on

17.4.2023

	Material performance in generic range of conditions.	Examination of the long-term stability of the same materials as will be present in the GDF (e.g. bentonite)	the uncertainties/gaps in the overall safety case.
Waste considerations	Description of the waste inventory and mapping the relevant NA information (FEP NA analysis).	Examination of the long-term stability of materials which mimic the waste matrices (e.g. uranium ore for SF) considering site specific conditions.	Transport considerations in site specific geosphere and biosphere.
Stakeholder communications	Basis for geological disposal via examples. Considerations of disposal options. Consideration of GDF design options.	Use of clear examples which mimic aspects of the GDF design (e.g. the Dunarobba fossil forest encapsulated in clays as an example of the role of bentonite in the EBS). Preferably examples used in the generic stage can be elaborated here.	Explaining the safety concept and support for the robustness of design and suitability of the site. Preferably examples used in the generic stage can be elaborated here. Confidence for the safety assessment results.
<p>¹ Regional analogue, which refers to more direct type of analogue to site.</p> <p>² Regional consideration refers to studying scenario related processes and gaining broader understanding of processes through regional geology. This can be e.g. overall understanding on the deep groundwater evolution and characteristics that affect it.</p>			

3.4 Lessons learned

From the discussions in the previous sections the following points are considered specifically important for the NWS strategy development:

Research

- What is defined as a NA study? This seems to be occasionally confusing and literature reviews should ideally cover all relevant publications on the topic
- Many NA studies are highly flawed, so care must be taken about what data to use. Critical reviews are called for in SC application
- In many programmes, NA screening has been done via FEP analyses, but the results may not always produce a state-of-the-art product (see safety culture below)
 - Both relevance and significance screening are needed
- Other literature: a significant amount of information can be obtained from general scientific literature → should avoid focussing only on 'official' NA literature
 - See below comments on the qualitative nature of NAs

17.4.2023

- NA studies are most effective when integrated in a combined programme of laboratory, modelling and in situ studies (cf. Alexander et al. 1998)
 - Comment: this also enables traceability from examples used in the stakeholder communication to safety case details

Safety case ‘culture’

- There is a lack of scrutinized screening and strategic planning in most programmes discussed in this report. This might be due to inherited/predefined complementary/alternative status of NA information
 - This is also related to statements where the emphasis is set on the uncertainties and qualitative nature of NA → uncertainties are present in experimental work and modelling as well, only in different places (NA uncertainties are related to boundary conditions, while short term experiments have uncertainties in extrapolation of the results into the far future)
 - The repeated emphasising the NA uncertainties leads to thinking that the overall uncertainties are somehow bigger than in experimental or modelling work. → it should be acknowledged that NAs provide the only source of data that has relevant time frames (In addition, experimental and modelling work may be taken too often as the ‘right’ answer, despite the uncertainties)
 - Predefined meaning of NAs also creates a culture where significant information might be omitted only because it comes from the field of NA
 - When NAs are used only as “alternative” line of evidence, there is a risk that the information is detached from the other evidence (experimental lab and URL). This creates a risk of over or underestimating processes if extrapolated
- NAs should be intimately included in the safety case process via FEPs and overall approach to assessing performance. There have been attempts to do this, but how to assure systematic handling within the organization, is one of the key questions

Programme level use

17.4.2023

- NAs provide a lot of potential to be used in design development in addition to more traditional uses (siting, safety case and communication)
- There are differences in degree of success of using analogues depending if they have been directed to communication, siting, design, or safety case etc

Communication

- There are good examples of using NAs in local audience communication
- Less has been achieved in communicating between scientific disciplines
- Communication aspects utilising the NAs have potential to be developed further

4 STRATEGY DEVELOPMENT

The main driver for the strategy development work is the need for a more structured way of including NA information within RWM's (now NWS) ESC and attempting to predict how the UK GDF programme will evolve in the future and how NAs and related projects can best be used to support it. The development work includes consideration of the ViSI tool. In addition, the importance of ensuring that NAs are intimately included in the knowledge base is acknowledged.

Initial aims for the strategy development work were defined as:

- *Scrutinization of the utilisation of existing NA-derived information to enhance the robustness of the RWM DSSC (including the constituent ESC and other constituents, e.g. the Operational Safety Case), in consideration of an evolving UK GDF programme*
- *Identification of when the commissioning and undertaking of new NA studies could provide needs-driven, cost effective benefit to an evolving UK GDF programme, via the provision of new information to support e.g. the enhancement of safety argumentation on a site- or sites-specific basis. Consideration should be given to the potential for international collaboration to progress such activities, and the associated pros and cons*
- *How RWM engagement by networking, stakeholder engagement, etc., could identify ongoing or planned national and international work that could*

17.4.2023

provide NA information that could be of use / relevance to the UK GDF programme

4.1 Feedback from NWS personnel

To obtain feedback on the previous NA catalogue (Milodowski et al. 2015a) and how NAs are perceived in general within NWS, a survey was undertaken during late 2020 to early 2021. The results of the survey was used as background for strategy development. In addition, a workshop was organised for NWS staff to discuss the strategy development prior to finalising this report. In addition, the ongoing development work on ViSI tool was discussed from the overall strategic point of view and in the proposed strategy the current features of the ViSI (at the time of writing) and potential features to be developed are included.

4.2 Knowledge management

NA information is part of the knowledge base. Assuming that the ViSI tool will be fully implemented in the near future, it should provide a natural platform for the storage, use and updates of NA information for NWS. However, it makes a difference how the information is presented, how easy it is to access and understand and how easy it is to see connections between disciplines. The knowledge base is only a storage, while managing knowledge is a dynamic process and usually follows the overall scheme presented in Figure 4-1. In the following, the main aspects of the steps (Figure 4-1) in knowledge management are discussed here from the NA information point of view:

1. Collect

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

2. Use

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, and, through requirements for the GDF 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 coherent approach for utilising the data. In the optimal case, the natural analogue providing the data directly to the safety case can be used

17.4.2023

for PR purposes as well providing solid tracking from the communications to hard data (assuring transparency and consistency)

3. Enrich the knowledge base

Updates of the information should be based on a gap analysis and effort/gain assessment (see section 4.6). 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 GDF 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
 - The post-glacial fault studies (Ojala et al. 2019) by Posiva, became only possible when the Lidar³¹ data became available
 - Revisiting previous work: the final remarks in the Cigar Lake revisit (Smellie & 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)

³¹ "laser imaging, detection, and ranging"

17.4.2023

4. Share

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 3.2.1. 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 EURAD³², IGD-TP³³, EURAD-SCIENCE³⁴ and similar, where impact can be made proactively).

5. Assess

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

- Relevance screening against
 - Iteration process, needs arising from design changes, site or safety case (e.g. FEP screening)
 - Scientific relevance
- Significance screening against readiness levels (see section 4.6)
- 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

³² European Joint Programme on Radioactive Waste Management

³³ Implementing Geological Disposal of radioactive waste Technology Platform (IGD-TP)

³⁴ "EURADSCIENCE", a network of research organisations for radioactive waste management science within Europe (Bruggeman et al. 2019)

17.4.2023

clearly recorded in the system). The ViSI³⁵ tool 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 can be obtained via external review process.

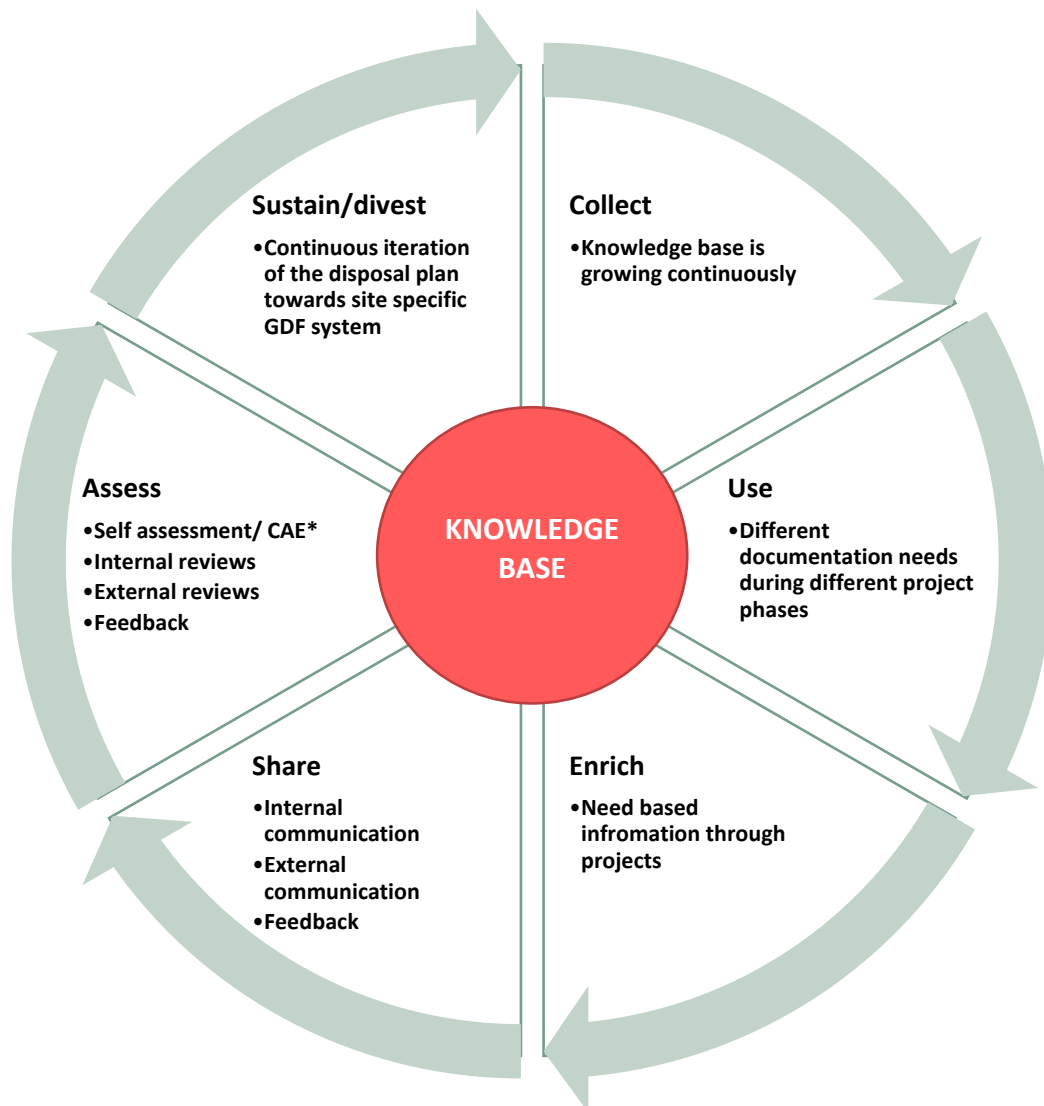
6. Sustain/divest

For this last point, three main sub-points can be made:

1. 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.
2. Further, the QA status of data may be drawn into question, something could guide further work (e.g. re-analysing already available samples, as well as potentially collecting new data).
3. 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.

³⁵ 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”.

17.4.2023



*for CAE, see section 2.4.

Figure 4-1. General knowledge management continuous cycle and main GDF programme related aspects.

The ViSI framework should support an integrated workflow, where consideration of different aspects of evidence comes into the work process of all disciplines more or less automatically. Specifically the CAE framework can help in identification of gaps (Figure 4-2).

17.4.2023

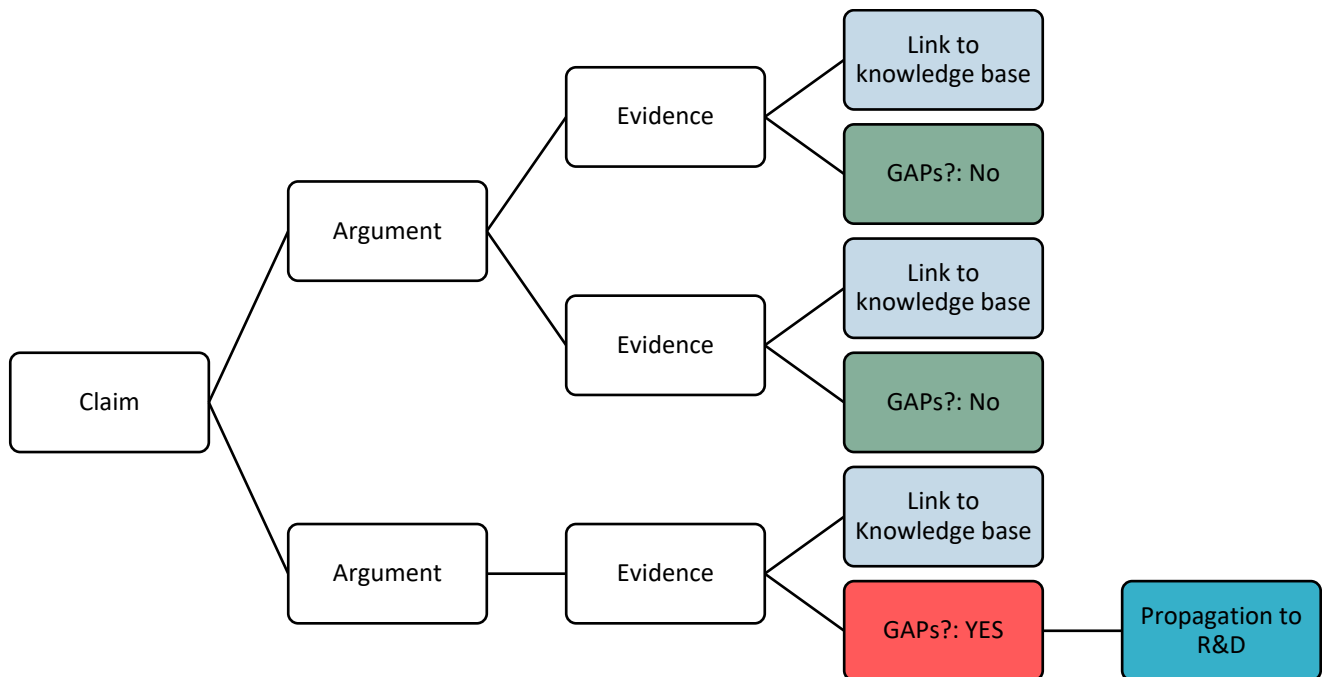


Figure 4-2. Simplified schematic illustration of the NWS CAE process guiding the R&D.

To achieve an integrated workflow, the content management system should provide enough internal links that connect the different users of information. There are many ways of doing this, but starting from the FEP list is good, since it forms the integral basis for system understanding. It should be periodically reviewed and screened to fit the project phase.

Metadata is suggested to be assigned for the NA information to allow flexible use of the knowledge in intended manner. The metadata for each NA item presented in the catalogue should contain at least:

- Name
- Locality
- GDF component and relevant FEPs
- NA description and related uncertainties and relevance considerations (including references)

A set of metadata is included in the catalogue update (Alexander & Reijonen 2023), but it is most likely to be elaborated during the course of the work in the future. Foreseen updates for further mapping the NA data can be related to for example:

17.4.2023

- Technical Readiness Level (TRL)
- Scientific Readiness Level (ARL)
- CAE
- Restrictions (marking obsolete)
- Relevance notifications (generic, site specific etc.or considering time scales)

4.3 Change management and increasing information

During the R&D work and when moving from a generic design to the detailed design and subsequently adjusting the design for the operations, change is more or less a permanent state. During this phase, change management is crucial. Knowledge management is a part of it, but in change management, it becomes important that the changes made are discussed through the organisation at an appropriate level.

In the case of working through databases for knowledge management, change management is relatively straightforward to implement. This report is not dedicated for the change management, but is mentioned here, especially since the needs-derived planning of new projects require to be based on up-to-date information.

NWS's overall change management for ViSI tool should be applied also for NA information.

4.4 Practical implementation of NA screening and gap analysis

In practice, linking information in an ESC and GDF process level can effectively be done only via databases. Without database structure it is difficult to maintain connections. One option to initiate new NA strategy would be integrating the NA catalogue in database format to other NWS databases (such as FEPs, CAE or requirements) and overall contents in the ESC. Figure 4-3 provides one option for the workflow towards NA integration in the ESC. The ViSI tool as a content management system should be the ideal platform to conduct such transformation.

17.4.2023

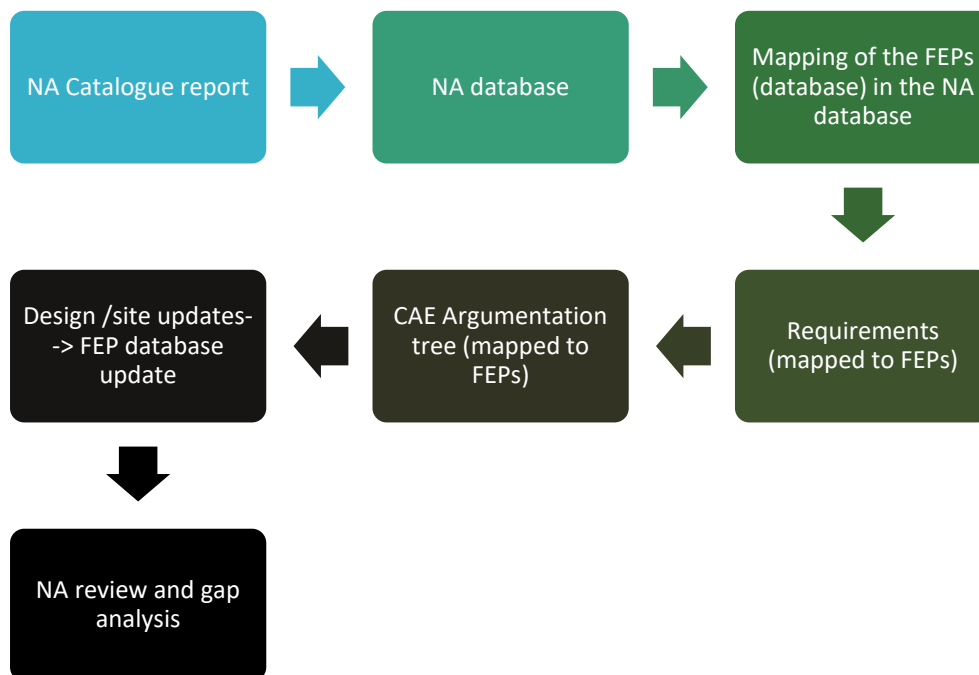


Figure 4-3. From reporting NAs to integrated system where NAs are just one part of the overall knowledge base and the data are connected in the overall ESC framework via other databases such as FEP database.

During the NA review phase, not only is identification of obvious gaps is needed, but it should also include scientific review, for example:

- Has the information been useful for the NWS and UK GDF programme?
- Has NA information been used correctly (requires internal cross checks)?
- Are ESC assumptions still ok in the light of NA information?
- Are some NA data concluded to be unsuitable or erroneous → system should provide tools for omitting data and marking it as “non-usable”. It is equally important to record this, as otherwise old studies keep popping up when new people come along to do the reviews. Note: previously omitted data may become re-admitted if ESC/design changes.
- Regarding gaps identified, what are the most promising new ideas, can they be executed? In collaboration or as internal project? (see section 4.6)
- What new information has become available in the scientific community?

Reflecting the lessons learned, it would seem important that NAs are not treated separately as an additional set of data in the knowledge base, but rather as a part of overall scientific basis for the ESC (i.e. in connection to laboratory and URL data, or even modelling results). This does not mean that assessments of alternative lines of evidence cannot be made. It is to assure, that relevant information is available at process level for all activities and the discussion of the GDF-relevant

17.4.2023

time frames is always supported by long-term information when it is available. One good example of the incorporation of the time aspect at the process level is illustrated in Figure 4-4 below.

The take home message of Figure 4-4 is:

- Different processes work at different time scales
- Most of the safety case discussion that is focussed on the area of longer-term timescales (Performance Assessment (PA in the figure) can only be covered by NAs

These issues are usually clear for geoscientists, but it is often the case that working in separate groups for NAs, experiments and modelling, lead to problems in transferring relevant information. It would be good to take this into account in working group planning to avoid silos³⁶ in the organisation.

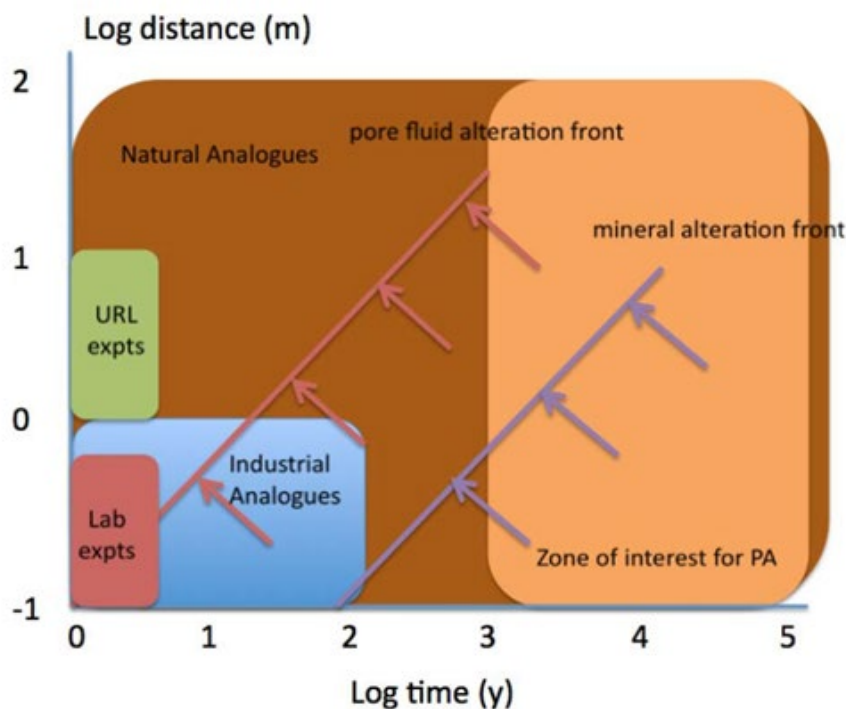


Figure 4-4. Schematic illustration of the differing spatial and temporal scales associated with different data sources in relation to two GDF-relevant bentonite processes (from Savage 2011). PA= Performance Assessment, URL=Underground Rock Laboratories.

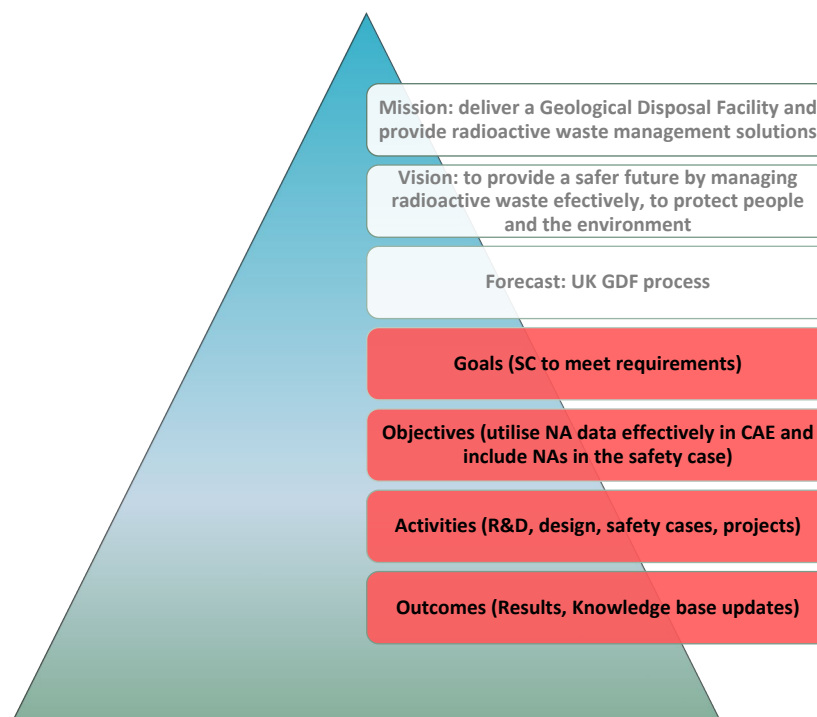
³⁶ situation when there is no communication between different units or working groups.

17.4.2023

4.5 Including NAs in different phases of the national programme

It is foreseen that, during different phases in the UK GDF process (see section 2.3), the strategic thinking behind NA projects will also shift according to the increasingly better-defined site and system.

The NA Catalogue report is being updated to provide analogue screening for the current generic phase of the UK GDF process. In that report, in addition to reviewing the existing literature at a general level, existing international projects of interest are also discussed from the NWS perspective. In the coming years, it is likely that international NA projects will continue and some of these will also produce information of relevance to NWS. In addition, selection of the site (or candidate sites) may create new, UK-specific needs for regional analogue studies. How to assess the need for new information, however, should come through the iterative process of R&D in siting and design, as well as in the safety case. The high-level strategic mission, vision and forecast are assumed to remain relatively stable. But, as NWS moves forward in the GDF process, the goals and objectives of NA related work will at least partially change, which is reflected in the activities and needed outcomes shown in Figure 4-5.



17.4.2023

Figure 4-5. NWSs mission, vision and forecast are assumed to stay the same. Goals, objectives, activities and outcomes needed to reach them will change. These are included in the Figure from the NA point of view, not at NWS level including all activities.

An overview of the changes in strategic needs in relation to NA studies are listed for different GDF process phases in Table 4-1. Note that the objectives may change also due to regulatory requirement updates.

Table 4-1. 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.

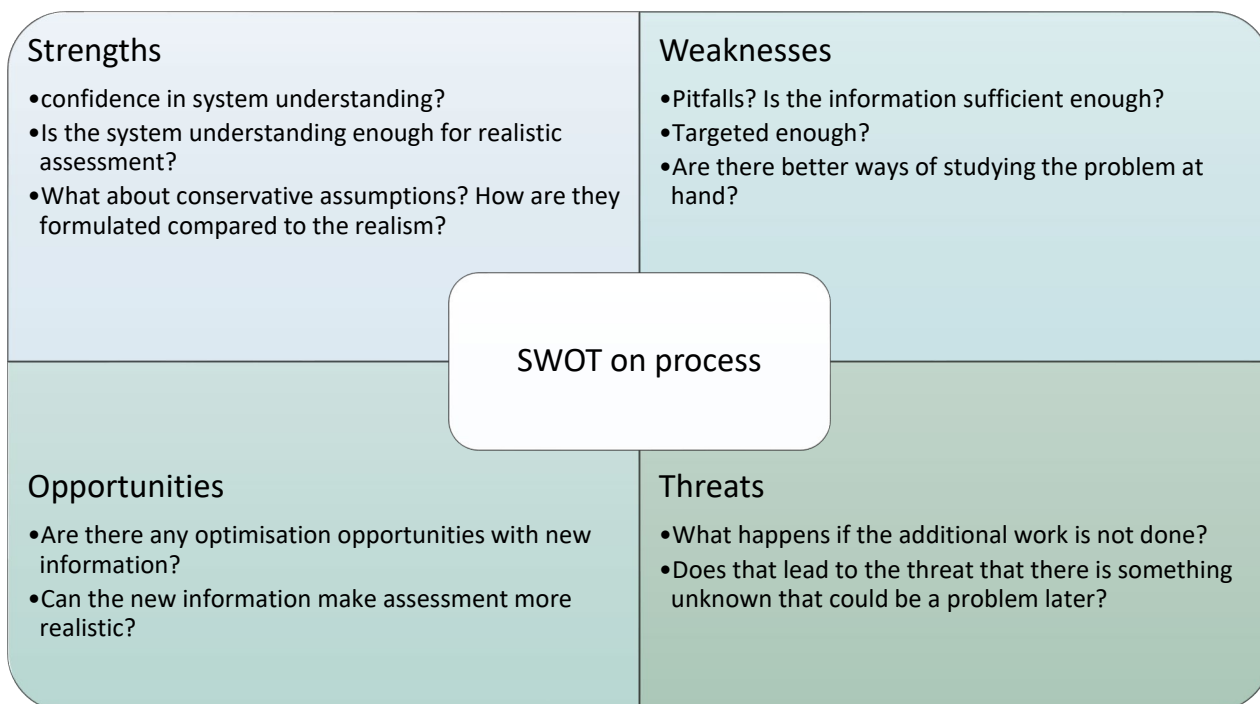
NWS's evolving programme	Safety Case stage	Objectives (of safety case)	Activities in NA knowledge base	NWS NA research needs	NA research outcomes
Consultation– establishing partnerships with communities (ongoing in 2023)	Generic ESC	Statement of confidence for long-term safety Stakeholder communication 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 See Section 4.8 for elaboration	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 2. site selection 3. selected site 4. design 5. Operational safety 6. Communication with the local community via NAs See Section 4.8.2 for elaboration	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	Statement of confidence for long-term safety	Final FEP list, new additions if new	As above See Section 4.8.3 for elaboration	As above

17.4.2023

	detail and monitoring data Potential optimisation of the design	Stakeholder communication Feedback to design Screening of FEPs complete	processes are encountered State-of-the-art NA update Use of NAs in stakeholder communications		
Operation and closure	Periodical ESC including potential optimisation	Checking the robustness of the system Stakeholder communication	As above	As above See Section 4.8.3 for elaboration	As above

4.6 Needs-driven and cost-effective approach in commissioning new NA work

New NA research projects need to serve NWSs goals and objectives. They need to be scientifically/technically relevant, but also communication and collaboration aspects can be driving decisions. One way of assessing the status of gaps identified, and related new project ideas for NAs, is a SWOT (Strength, Weakness, Opportunity, Threat) analysis (see Figure 4-6). There are of course many other ways to assess the risk/benefit aspects of a planned projects.



17.4.2023

Figure 4-6. Strength, weakness, opportunity, threat (SWOT) thinking on a specific scientific issue.

NWS utilises technical (Figure 4-7) and scientific (Figure 4-8) readiness levels in the GDF development programme (RWM 2020a) and in the ideal scenario NA information would be connected to data feeding into the readiness assessment and could be then used to guide the research needs also for NA projects. The concept of Technology Readiness Levels (TRLs) is widely used across the NDA estate (NDA 2012) and they have been seen useful in evaluating technical activities, including NA projects. SRLs are similar to the TRLs and *“complement their assessment of the ‘deployability’ of technology with their assessment of the scientific robustness of understanding of the underlying science” (RWM 2020a).*

17.4.2023

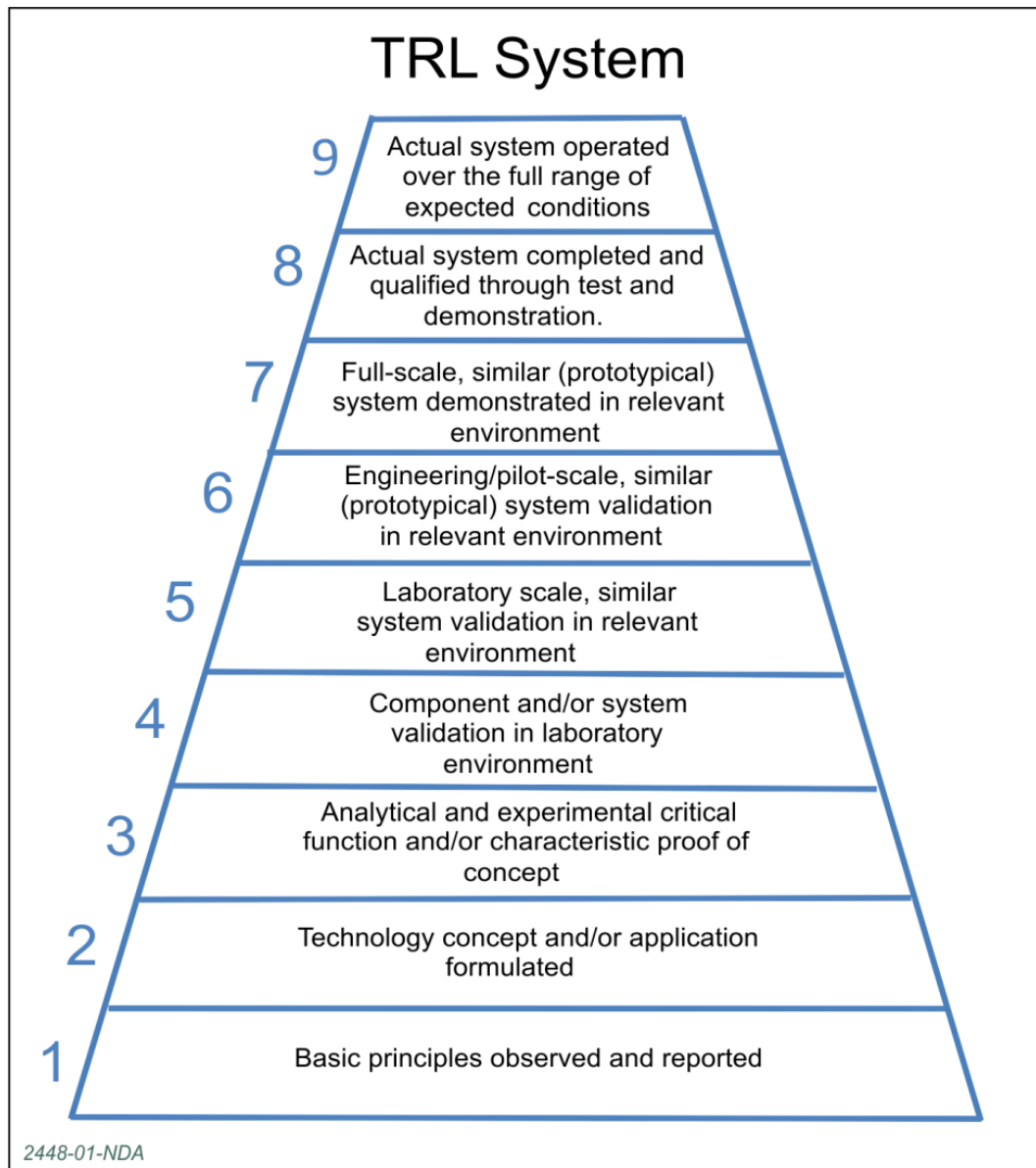


Figure 4-7. Technical readiness levels (RWM 2020a).

17.4.2023

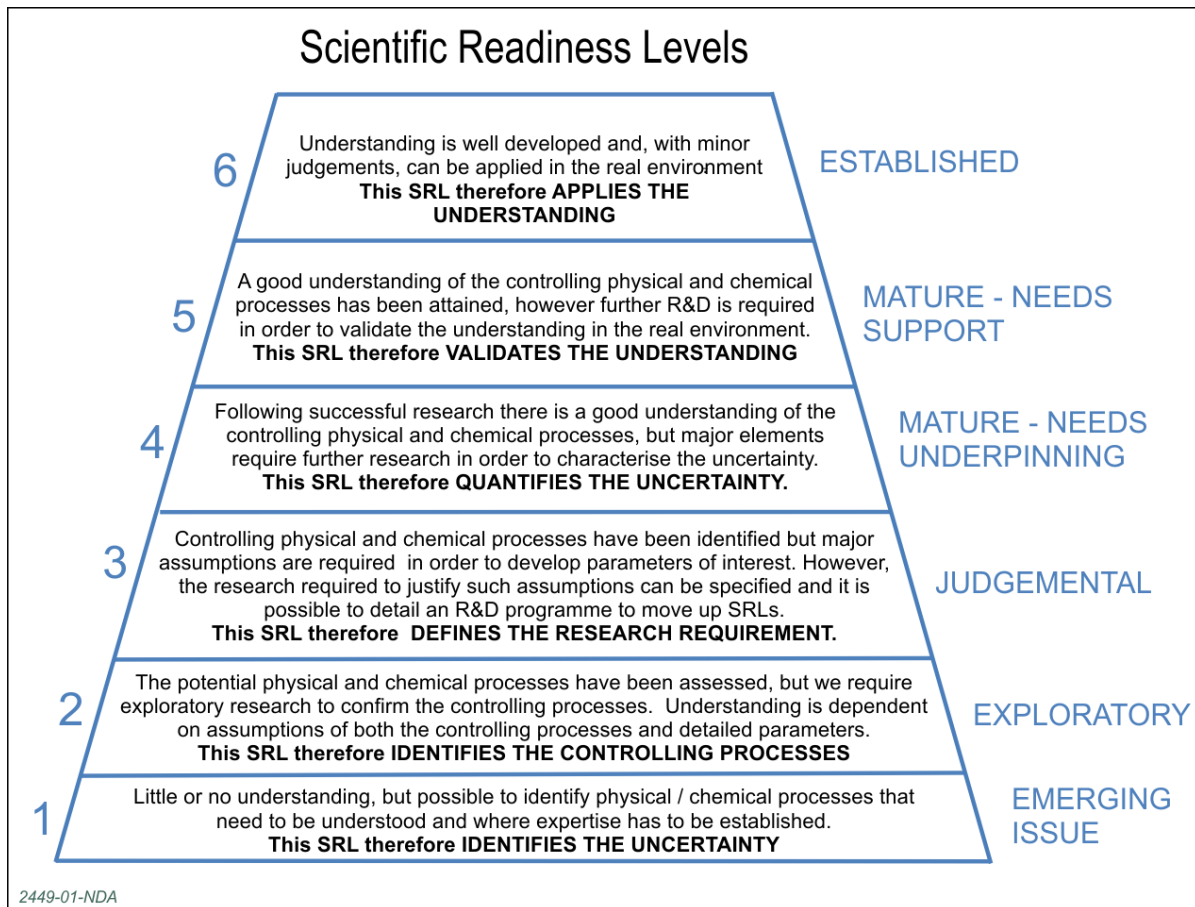


Figure 4-8. Scientific readiness levels (RWM 2020a).

If the scientific basis is seen to be relevant enough to move forward, other aspects can also be taken into account. This could be done e.g. based on the multi-attribute analysis (MAA) approach, which can be modified according to the economical, strategical or sociological needs, depending on the relevance of these aspects in the decision-making process (Table 4-2). There are a multitude of decision-making analyses processes, and here, only one simple example is provided. If needed, very complex weighed decision making processes can be employed, however, in most cases, relatively simple assessment should be sufficient. For cost estimates NWS (RWM 2020a) has also proposed a specific parametric cost estimation matrix (see Table 1, in RWM 2020a).

Table 4-2. Example of a multi-attribute analysis: for an existing NA project. The lower the number in the ranking the less significant/important is the topic evaluated.

NA study	Hypothesis – how useful	Hypothesis – Strategic	How much is the information	What is the cost/benefit	Other attributes?	Total
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17.4.2023

	would the results be in ESC? (1-5)	significance (1-5)	needed in communications? (1-3)	estimate of the work initiated? (1-5)		
Site A	1	4	3	3		11
Site B	2	2	3	3		9
Site A with alternative approach	4	1	3	5		13
Site B with alternative approach	5	1	3	5		14

An example of the use of MAA in a NA project (CNAP)

MAA has been previously used in the planning phase of the CNAP project and why Cyprus was selected for NA study (Alexander & Milodowski 2011). The authors explain that as such, the system studied in Cyprus was agreed to be an excellent analogy to that of the repository EBS following repository closure and resaturation. This being the case, the project technical focus was on:

- Long-term bentonite stability during reaction with analogue low alkali cement leachates;
- Where possible, a range of leachate chemistries were to be examined as the precise composition of the low alkali cements remained open at that time;
- Integration with existing laboratory data;
- Identifying any requirements for future R&D;
- Providing feedback to the Safety Case.

What is of interest here is that Alexander & Milodowski (2011) point out that: *“In principle, there are a number of locations worldwide where such a NA might be found, including New Caledonia, Bosnia, California, China, Japan, Korea, Portugal, Oman, United Arab Emirates and the Philippines. Based on a multi-attribute analysis, considering factors such as:*

- *Probability of finding suitable locations,*
- *Relevance to European programmes,*
- *Low risk of disrupting calls for volunteers,*
- *Political stability and*
- *Cost-effectiveness,*

Cyprus was selected by the Technical Steering Committee (TSC, consisting of NDA-RWMD, Posiva and SKB) as the preferred option and has since been the focus of the project.”

17.4.2023

Similar justification was also used in development of both the LPB and IBL projects but, as these processes usually are undertaken during the planning phase of the project, few examples are found in published reports.

RWM (now NWS) has established a prioritisation scheme for the Planning and Prioritisation of the Technical Programme (RWM 2020a). There are six key drivers that underpin the Technical Programme:

“1. Develop and maintain geological disposal concepts to underpin packaging advice and provide a basis for siting and development of a GDF.

2. Improve our capability to provide expert advice to NDA and Government on radioactive waste management strategies.

3. Improve our capability to provide packaging advice and support the prioritised programme of disposability assessments.

4. Improve confidence in the feasibility of the geological disposal system and our understanding of it.

5. Develop and test our capability to support site evaluation/community engagement and deliver inputs.

6. Develop and test our capability to develop site specific designs and safety cases based on site data and apply for environmental permits and DCOs. “

For practical work NWS (RWM 2020a) has proposed a set of questions to aid in the prioritisation (Figure 4-9). A similar approach is useful also for the NA project development.

17.4.2023

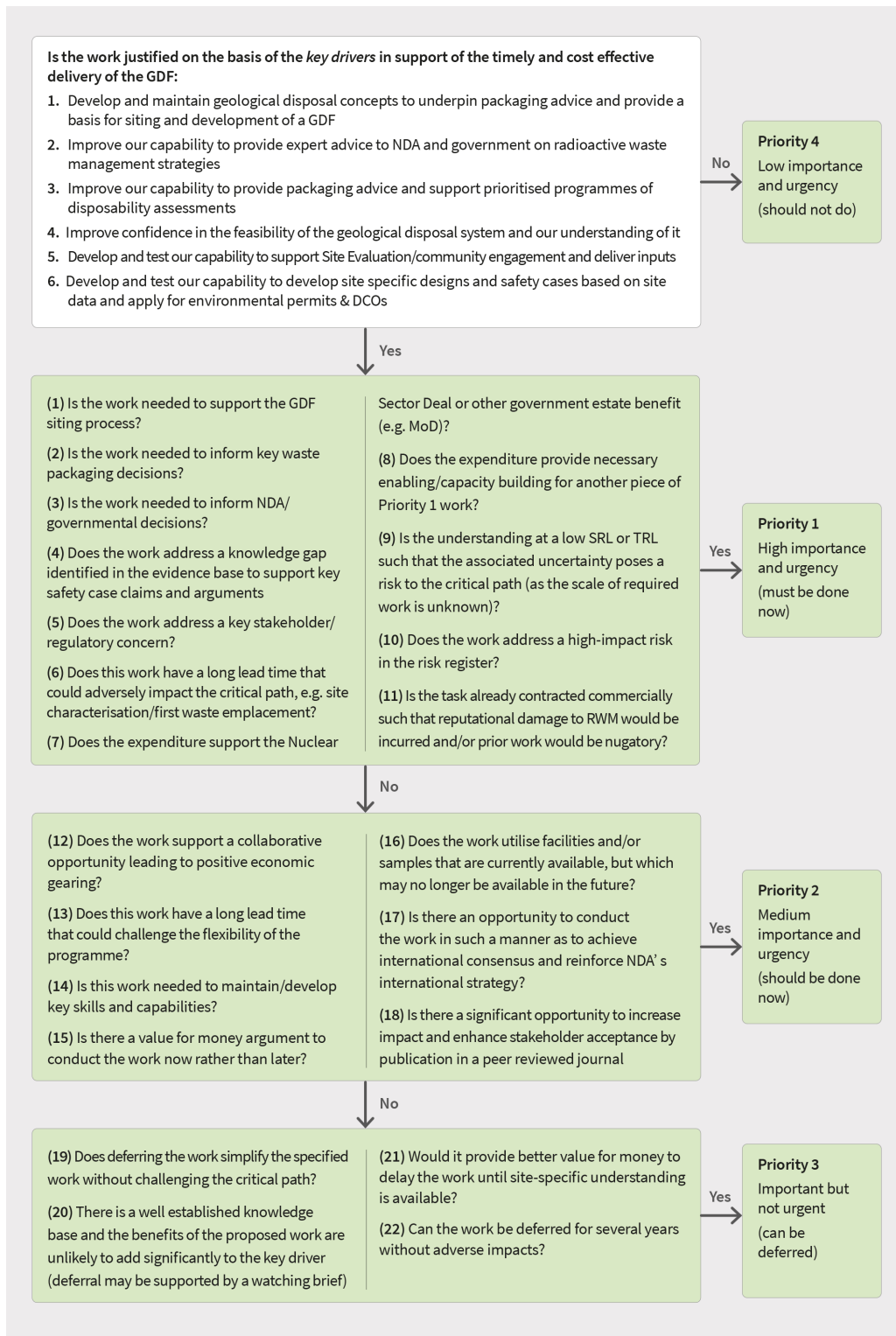


Figure 4-9. Structured approach to prioritisation of the Technical Programme (RWM 2020a).

17.4.2023

4.7 Role in training

NA projects and their role in training is explicitly mentioned here, as it has been seen as an important part of staff development in many organisations. Training should be considered as one aspect in the prioritisation assessment of new projects. Specifically, regional NAs are ideal for staff training for site evaluation and such work is ongoing within the IBL study. Previously, Nagra indirectly funded postgraduate studies within the Pocos de Caldos study (e.g. Waber 1990), SKB included junior staff in the field team for the CNAP project (e.g. Alexander & Milodowski 2017) and RWMC indirectly funded several MSc and PhD students from the University of Hokkaido within the Philippines NA Project (e.g. Fujii et al. 2015).

4.8 Role in stakeholder communication

Stakeholder communications and the nature of the materials utilised depend on the type of group involved in the discussion. This might mean different levels of complexity in the messages, especially when discussing NAs that may sometimes be quite complex when presented within the ESC. Nevertheless, NAs have been/are being used to explain geological disposal and related safety aspects to various stakeholder groups. From the point of view of NAs, if there is a need to simplify the message, it should be made clear that even when an example is set in a very simplified manner, “i.e. this piece of copper is so and so many years old” it has a good scientific basis and the trail of documentation can be followed from the stakeholder communications examples, to the technical reports and scientific literature. Here, NA catalogue updates can be used as a starting point.

It has long been stated (e.g. Miller et al. 1994) that NAs have an important role, beyond their application in the SC, as providers of illustrative and sometimes non-technical information to a broad range of audiences. From outside the confines of the waste ‘community’, this aspect is sometimes perceived as the main reason why NAs are studied. NAs and comparisons with natural systems, have been mentioned as important components of the process of evaluating and accepting disposal concepts (e.g. USNRC, 1957, IAEA, 1999) and that safety assessments are only credible if shown to have strong natural and archaeological parallels which are easily understood by a wide range of audiences (e.g. West & McKinley, 2007). For many audiences, the nature of predictive assessments themselves is difficult to understand and accept. For example, as stated by Blowers et al. (1991):

“Enormous scientific effort has been expended in Europe and North America researching and demonstrating the proposition that such repositories will be safe, for all practical purposes, for ever. Yet clearly the assertion is preposterous. The safety of an untried method cannot be proven until repositories have been constructed and monitored over many generations and the radionuclides have decayed to safe levels. Running such an empirical experiment is inconceivable. Sophisticated geological analysis, risk assessment or modelling of repository behaviour must rest upon heroic assumptions and are no substitute for empirical knowledge. Scientific predictions for periods of 10,000 years or more lie in the realm of fantasy, not rationality. In conditions of such

17.4.2023

uncertainty it must be concluded that there is no technical solution to the problem of radioactive waste.” No amount of scientific argument or proof is going to convince many people of the truth of a safety case that is inherently very complex and extends predictions far into the future.

It is thus necessary that appropriate demonstrations of safety are made to the range of stakeholder groups involved in the national GDF programme. What these groups have in common is that they, generally, are not familiar with the conceptual and technical aspects of geological disposal, even though they may have (in the case of academic peers) a high level of scientific training. For all of these interested groups, it is necessary to make demonstrations of safety that are appropriate to their level of understanding and concern, bearing in mind that many groups may find the concepts and conclusions from a SC credible only if provided with natural parallels for comparison.

Unfortunately, analogue information or illustrative cases can be misrepresented. The nuclear industry itself has not always represented NAs honestly (see, for example, the discussion in Miller et al. 2000), sometimes tending to oversimplify and overstate the facts. No doubt it may be argued that some simplification is necessary to make the scientific data readily digestible but there is a fine line between necessary simplification and misrepresentation of the facts, as discussed by, for example, Lindqvist (1996).

Aside from some very focussed programmes (e.g. Blyth & Kremer 2023), there has been little recent use of NA information in stakeholder communications and there is a need to develop new and better illustrative materials – and to maintain the link to the national GDF programme (as is the case in Canada, for example). While it is hard to define exactly what form these materials should take, it is important that the analogues they discuss should be presented as simply and as unambiguously as possible, but without over-stating the interpretation of the analogue.

4.9 Potential activities and research needs in NWS’s evolving programme

As outlined in section 4.4, the type of activities change and evolve with time and the stage in the GDF programme. In this section, a closer look at the potential paths forward regarding activities and research needs is taken, with emphasis on the types of NA investigations that could be included. The current situation (activities during consultation, see section 4.8.1) is briefly discussed regarding activities that will continue over the transition from consultation to the next phase.

The greatest emphasis is placed on the current and near future phases in the programme (for activities during site investigations, please see section 4.9.2) where various aspects from the site evaluation will affect the NA strategic planning. This discussion becomes increasingly more uncertain regarding the future, but some guidelines can nevertheless be set (section 4.9.3) that reflect the objectives changing during the construction and operation phases.

17.4.2023

4.9.1 Activities during consultation

During the consultation phase, NWS has been active in the field of NA project development and execution (see section 2.6). Partly, the work is still ongoing and the results from the most recent projects have not yet been implemented in the safety case. The results of the NA projects have been disseminated via NWS/RWM reports and papers in scientific journals along with NAWG and other scientific meetings. Ongoing activities should be continued in the site investigation phase, as they will support the overall safety case (see section 4.5).

Activities to be continued include:

- Integration of the updated NA data in the safety case (includes the current catalogue update and integration of the data, see section 4.5)
- Continued participation in the ongoing projects
- Maintaining networks in the NA research groups
- Dissemination of the results within the geological disposal community
- Further identification of NAs to improve the knowledge base

4.9.2 Activities during site investigations

Site evaluation is a step-wise process that is envisaged to follow the outline provided in NWS's planning documentation (RWM 2020a) (Figure 4-10). During the initial phase of local studies, no drilling is foreseen to take place, but the following tasks are needed in order to select sites for more detailed investigation (including drilling) (see Figure 4-11):

- New surveys and studies commissioned
- Search Area refined
- Potential sites identified
- Potential sites evaluated
- Greater certainty around implications of developing a GDF
- Recommendation for site(s) to be characterised

After this, more detailed investigations can begin at selected site(s). This will be a multi-year programme aiming to increased site-understanding that will also allow design development work to proceed to a more site-specific level and thus allowing better assessment of the suitability of the site(s). The final aim is to recommend the preferred site for the GDF.

17.4.2023



Figure 4-10. Overview of Siting Process (RWM 2020a)

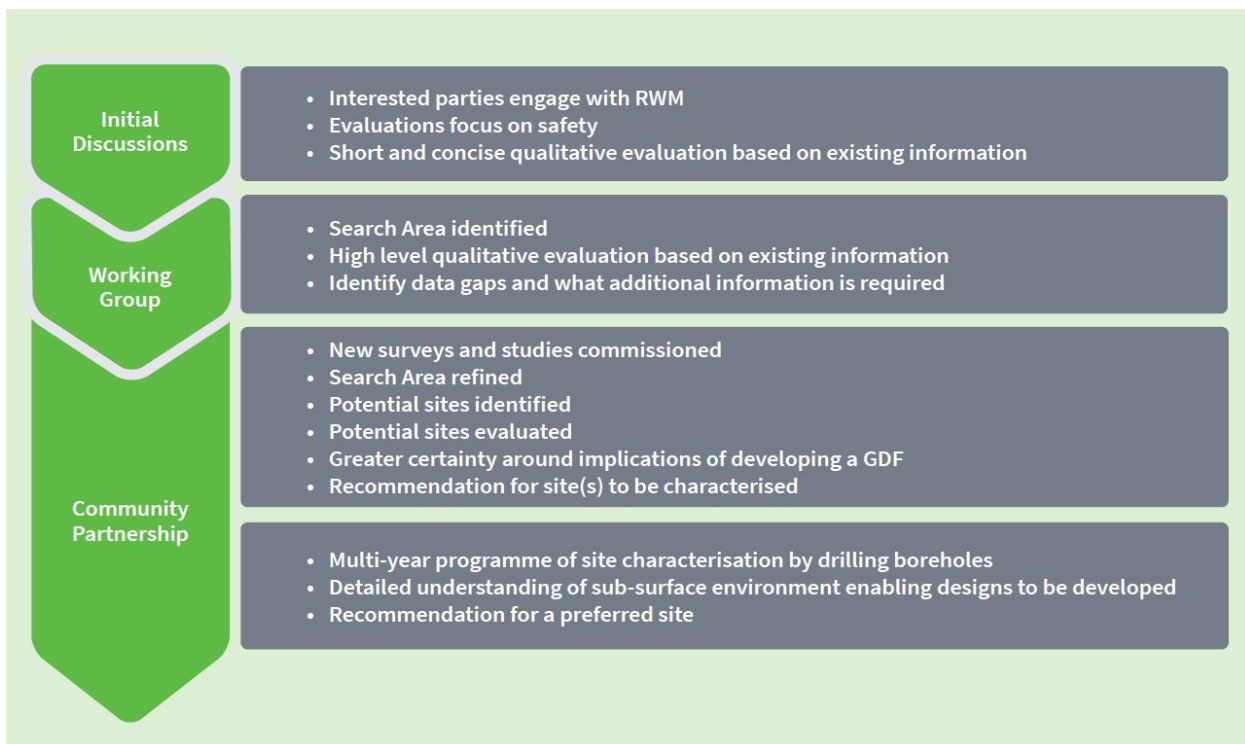


Figure 4-11. The siting process and site evaluations summary (RWM 2020a)

17.4.2023

4.9.2.1 Drivers of NA activities during site investigations phase

As the site investigation phase is starting during the time of writing of this report, more detailed discussion and suggestions are made for this phase than for those occurring later in the future (operation of GDF and finally closing the facility).

NA studies are involved in several aspects during this particular phase of the programme:

1. Regional NAs (NAs that are only possible to study in the vicinity of the actual site)
2. NAs for stakeholder communication (NAs and overall communication)
3. NAs related to material properties and other GDF relevant processes (can be studied anywhere suitable, see Alexander & Reijonen 2023)

In general, needs for NA studies are primarily derived based on the needs of the safety case (see section 4.5) and FEP screening process. Otherwise, the needs may arise also from operational, siting, design or stakeholder communication needs. Siting related aspects are discussed below in more detail, as they form a new frontier for the NA work compared to the generic stage of the GDF development programme. For an overview of the potential work in general, consult the updated NA Catalogue (Alexander & Reijonen 2023).

4.9.2.2 Assessing potential needs arising from the siting

Taking a closer look at the site evaluation related potential needs, an overall assessment (below) has been conducted at a general level. This is to serve as an example of the strategic thinking process aiming to map potential NA studies to siting requirements. Of course, another step to screen the activities of relevance to the new R&D plans would be necessary later.

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 (2020b) and it provides 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 4-3 to 4-5, the most relevant topics (Safety and Security, Environment, Engineering Feasibility) presented in Annex B of RWM (2020b) 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 4-3 to 4-5, 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).

17.4.2023

Table 4-3. Evaluation Considerations for the Siting Factor – Safety and Security (RWM 2020b) and potential for seeking support through NAs.

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.		
	<i>The ability to safely carry out investigations from a surface environment either onshore or inshore.</i>	N	
	<i>The ability to carry out investigations so as to protect the long-term safety functions of the geological environment.</i>	Y	Regional analogues, locally (e.g. Alexander & Reijonen, 2023, section 6.3.1)
Safety during Construction	The ability to build a GDF safely and the long-term implications of that construction.		
	<i>The ability to construct a GDF safely.</i>	Y	Industrial analogues, local mines, quarries and other underground facilities can provide valuable lessons
	<i>The implications of natural and other external hazards such as flooding.</i>	Y	Part of hazard assessment. For example, tsunami – e.g. DEFRA (2005)
	<i>The ability to design and construct a GDF in such a way as to protect the safety functions of the geological environment.</i>	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.		
	<i>The implications of natural and other external hazards.</i>	Y	Regional analogues (for example impact of GDF construction and operational phase on the host rock and EBS)
	<i>The implications of nearby hazardous facilities or protected military areas.</i>	Y	Industrial analogues
	<i>The ability to develop and implement emergency and contingency plans.</i>	N	
Safety after closure	This ability to isolate and contain radioactive waste for the time required for the radioactivity to naturally reduce to acceptable levels.		
	<i>The suitability of the host geological environment including the consideration of:</i> <ul style="list-style-type: none"> ° 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

17.4.2023

		communities (cf. NWMO approach; Blyth & Kramer 2023)
<i>The ability of the potential site to isolate radioactive waste from people and the biosphere over the long-term after closure.</i>	Y	Biosphere transport analogues (e.g. Posiva, 2023c, chapter 3), other near-surface transport analogues (anthropogenic contaminants) Geosphere transport analogues of natural elements (e.g. Brookins, 1986)
<i>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 or glaciation which could cause the site to be disturbed at some point in the future.</i>	Y	Regional consideration of the groundwater dynamics and potential impacts of coastal transgression/regression (cf. Amano et al. 2011). Analogues for glaciation 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)
<i>The likelihood of human intrusion at some point in the future.</i>	N	
<i>The ability for a GDF to provide adequate protection against any non-radiological hazards.</i>	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 'targetted' 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.	
<i>The likely period required after closure to address institutional control requirements. The arrangements for maintaining the information on a GDF.</i>	N	
Security	The ability to design, construct, operate and close a GDF such that the relevant security Requirements are satisfied.	
<i>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.</i>	N	
Safeguards	The ability to design, construct, operate and close a GDF such that the relevant safeguarding Requirements are satisfied.	
<i>The ability to safeguard the wastes and ensure it is not diverted for military uses or other undeclared purposes.</i>	N	

17.4.2023

Table 4-4. Evaluation Considerations for the Siting Factor – Environment (RWM 2020b)

Evaluation Consideration	Description	NA relevance (Y/N)	Comment
Environmental Implications	The implications of the investigation, construction, operation and closure of a GDF on the environment.		
<p><i>Air quality, including effects on existing air quality and sensitive receptors.</i></p> <p><i>Noise, vibration and lighting, including effects on existing baseline levels of noise and sensitive receptors.</i></p> <p><i>Biodiversity and nature conservation, including effects on flora and fauna, habitats and designated sites.</i></p> <p><i>Climatic factors including effects of climate change and ability to use low carbon technologies and renewable energy sources.</i></p> <p><i>Historic environment implications, including effects on the historic landscape, heritage assets and their setting as well as archaeological and palaeontological assets.</i></p> <p><i>Land use, including effects on and compatibility with existing land uses.</i></p> <p><i>Landscape and visual implications, including effects on the character of the landscape, townscape and seascape (as appropriate).</i></p> <p><i>Waste management, including the ability to adhere to the waste management hierarchy and management of waste, such as spoil.</i></p> <p><i>Resources, including the ability to utilise resources efficiently.</i></p>		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
<p><i>Flood risk and coastal change, including drainage and hydrology implications.</i></p> <p><i>Water quality, including surface and groundwater quality.</i></p>		Y	Regional hydrogeological analogues (see also above table 3) and Tsunami risks, (see table 3)
<p><i>Geology and soils, including effects on soil quality and features of geological interest.</i></p>		Y	Regional analogues as a source of information (see Alexander & Reijonen, 2023, for details)
<p><i>Any mitigation measures which are required as a consequence of satisfying relevant Requirements.</i></p>		N	
Protected Habitats and Species	The implications of the investigation, construction, operation and closure of a GDF on Protected Habitats and Species.		
<p><i>Any likely significant impacts on internationally, nationally and locally designated sites of ecological or geological conservation importance (including those outside the UK) including:</i></p> <ul style="list-style-type: none"> ° <i>International Sites;</i> ° <i>Sites of Special Scientific Interest (SSSIs);</i> ° <i>Marine Conservation Zones (MCZs);</i> ° <i>Regional and Local Sites;</i> ° <i>Ancient Woodland, and Ancient and Veteran Trees;</i> ° <i>Biodiversity within and around developments; and</i> ° <i>Protection of Other Habitats and Species</i> 		Y	E.g., biosphere reference site investigations (cf. Posiva, 2023c, chapter 3)

17.4.2023

Table 4-5. Evaluation Considerations for the Siting Factor - Engineering Feasibility (RWM 2020b)

Evaluation Consideration	Description	NA relevance (Y/N)	Comment
Flexibility	The ability to apply a variety of design solutions to a given area or site.		
<i>Whether there are particular characteristics of an area or site which may provide greater flexibility in terms of design, construction, operation and closure</i>		Y	Regional studies help to understand the site properties. See 'regional analogues' in Alexander & 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.		
<i>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.</i>		Y	Regional analogues will be useful.
Ability to Design and Construct	The ability to design and construct a GDF within the constraints of the area / site.		
<i>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.</i>		N	Site characterisation, but the comments in Table 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.		
<i>Whether there is sufficient volume of suitable rock available at a suitable depth. The ability to accommodate potential changes in waste quantities.</i>		N	Site characterisation
Sustainable Design	The ability to design, construct and operate a GDF in a sustainable manner.		
<i>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.</i>		Y	Regarding the latter: Future scenarios related analogues (see Alexander & 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.		
<i>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.</i>		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.		
<i>The host geological environment, depth and likely underground rock stresses. The types of engineered barriers that are likely to be used.</i>		Y	Industrial analogues can provide valuable lessons.

17.4.2023

4.9.2.3 Roadmap development for siting related NAs

In order to get best benefits from NAs during the siting process, the timing of the activities plays a major role. For this purpose, it is proposed that roadmaps will be used to map potential activities in relation to the potential investigation areas and needs arising from the siting, operational safety and communications aspects.

Potential topics are included in this report (see especially Tables 4-3 and 4-4) as well as in the NA Catalogue (Alexander & Reijonen 2023). However, the full mapping of the cost & benefits needs to be produced internally in order to take into account the full set of boundary conditions.

4.9.3 Activities during construction, operation and closure

When moving to construction and operation, the overall GDF programme becomes an industrial project. While some research for the safety case may still be appropriate in order to stay abreast of ongoing scientific developments, benefits from nuanced NA studies regarding issues more relevant to the implementation of the project are also possible. Implementation related NA needs can include, for example:

- Optimisation of the system
 - Methods
 - Materials
- Safety case updates
- Operational safety
- Black swans (anything that comes along unexpectedly)

Below, these topics are discussed in more detail with examples of potential NA studies.

4.9.3.1 Optimisation

Optimisation of the design in order to update the GDF process due to technical advances of the industrial process or for example material development reasons.

NA example(s):

- Material providers may change, e.g. for bentonite, and including wide range of NA studies in different bentonite sites can help to estimate potential differences in long-term behaviour of different materials, in addition to other R&D work.
- Optimisation of repository layout may mean higher thermal loads to the EBS (cf. EURAD-HITEC project in Villar et al. 2020) requiring novel studies of long-term behaviour of bentonite at higher temperatures than have been studied to date.

17.4.2023

4.9.3.2 Safety case updates

Safety cases are updated regularly and during the update, new scientific information may become available (from the site or from general science) that requires new NA studies, or NA studies could help to reduce uncertainties or over conservative approaches.

NA example(s):

- To obtain better understanding of the bounding conditions for native copper stability, several organisations are involved in the MICA project.
- Similarly, NAs for less studied materials could benefit the safety cases in the future (e.g. longevity of natural low-pH concretes or closure materials). Such topics are listed in the NA Catalogue update (Alexander & Reijonen 2023).

4.9.3.3 Operational safety/ changes due to operation

Underground operation is always a form of disturbance to any site. How significant the disturbances are can be controlled by designing the construction measures (supported by monitoring). Some of the disturbances may have operational safety impacts as well (e.g. foreign materials introduced to the repository).

NA example(s):

- Plenty can be learned from the experiences of ongoing programmes on similar sites.
- One example of assessing the overall effects of the construction in advance is the work of Alexander & Neall (2007) on assessment of potential perturbations to Posiva's SF repository at Olkiluoto caused by construction and operation of the ONKALO facility.

4.9.3.4 Black swans

Anything that comes along unexpectedly.

NA example(s): many of the NA projects have been driven by the need of obtaining new information on a topic that is not well enough understood (e.g. long-term bentonite stability).

4.10 Summary of the strategy development

The strategy provides tools for an effective and systematic approach to NA project development and utilisation of the NA information in NWS's evolving national programme. The components of the strategy are briefly summarised here:

1. Knowledge base

- The systematic handling of existing information needs a well-established knowledge base that is connected to NWS's overall system
- ViSI tool provides an excellent opportunity to implement this

17.4.2023

- In addition to including the NA data in the knowledge base, it needs to be included in a dynamic form, meaning that it is reviewed and updated based on the needs arising from the change management system
- New information from the literature, international WMOs and NWS's own projects should be updated in the knowledge base in a systematic form
- It is of importance to be aware that information can become obsolete meaning that the data/information should be deactivated and this act recorded (and potentially revisited, if they become of relevance again)

2. New NA work

- The evolving national programme can lead to more specific NA needs, but this does not necessarily mean that the currently ongoing work would be outdated
- New projects should be approached in a systematic needs-based assessment (ideally based on FEP screening and assessment of conceptual understanding and related potential for learning from the NAs)
- The possibilities for staff training should not be overlooked when planning new work

3. Disseminating information in NWS

NA information and the strategy presented here will be implemented so that NWS staff will become familiar and utilise NA information throughout the programme. To do so, several steps are required:

1. Implementation of the NA catalogue in ViSI
2. Integration of NAs in the FEPs (see NA catalogue, Alexander & Reijonen 2023)
3. Planning how the NA content links to CAE and other needed metadata (such as requirements, readiness levels, science and technology plans)
4. Project planning, roadmap development for NAs supporting siting
5. Overall collaboration between safety case, design, siting and communication groups (including development of NA use in wider stakeholder group discussions, see section 4.8)
6. Ongoing projects, staff training through participation

See Figure 4-12 for compilation.

17.4.2023

The conclusions from chapter 4 are that:

1. there is only one strategy that aims to support the GDF development programme, but there are several potential activities that may be valid in the near future and during the evolving programme.
2. NA information and projects can and should be handled through the same procedures as any research utilising existing and upcoming NWS protocols (see section 4.6)
3. the key to success in utilising NA information is its inclusion in NWS's digital environment
 - *Has to be evolving, accessible and part of the same knowledge base as other experimental or modelling information*
 - *Systematic knowledge management (including recording obsolete data), and*
 - *Subsequent project development (regional analogues especially during the site evaluation phases)*
4. Moving from the generic phase will drive the research towards additional needs that are site- and design-specific
5. NA projects can provide significant new input to future safety cases

The overall aim of this strategy report is to raise awareness in a wider group of stakeholders and provide a path forward in taking strong ownership of NA related work internally in NWS.

17.4.2023

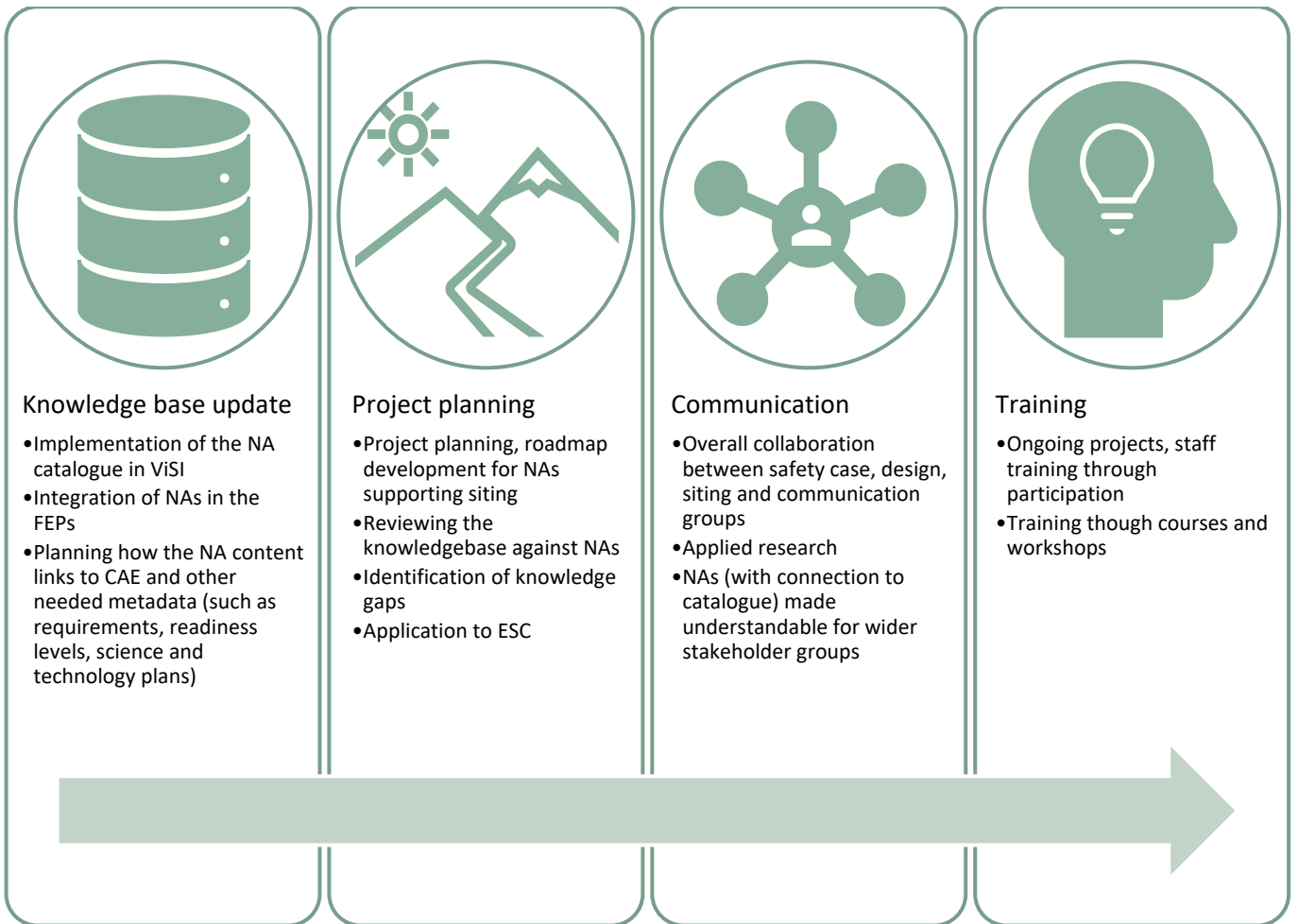


Figure 4-12. Main components of assuring effective use of NAs in NWS framework in the near future. The overall order of the activities follows the arrow, but activities can be simultaneous/overlapping. Knowledge base update is a continuous process. NA Catalogue refers to Alexander & Reijonen (2023)

17.4.2023

5 CONCLUDING REMARKS

This report presents a strategy for the future use of NA information in NWS' national GDF programme. In some countries, NAs are required to be included in the safety case through regulatory guidance, and this report is based on an extensive review of the strategic use of NAs by other WMOs worldwide. Nevertheless, it should be noted that 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.

There is a longstanding misunderstanding of the value of NA information (see the comments on safety case culture in section 3.4), but it is also due to the language barrier in NA studies. As noted in Alexander & Reijonen (2023), most NA reports to date are characterised by the use of geoscientific terms which can obscure the true nature of the available information. The latter point can be addressed with some thought and effort to disseminate information, but the former may take more time.

As noted in section 4.10, 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).

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

Moving from the current generic phase of GDF development in the UK towards evaluation of specific sites will drive the research (including regional analogues) towards additional needs that are site specific and examples are provided here (and in Alexander & 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. Then the link to communicating the NAs becomes more transparent as well.

17.4.2023



17.4.2023

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17.4.2023

REFERENCES

Aaltonen, I., Reijonen, H., & Bornhorst, T. 2022. Michigan International Copper Analogue (MICA) project. In: Skyttä, P., Nikkilä, K., Heilimo, E., Kukkonen, I.T., Veikkolainen, T., Karell, F., Kozlovskaya, E., Luttinen, A., Nykänen, V., Poutanen, M., Tanskanen, E., and Tiira, T. (Eds.), 2022. Lithosphere 2022 – Twelfth Symposium on the Structure, Composition and Evolution of the Lithosphere. Programme and Extended Abstracts, November 15-17, 2022, Turku, Finland. Institute of Seismology, University of Helsinki, Report S-72, 200 p.

AEC 1994. Long-Term Programme for Research, Development and Utilisation of Nuclear Energy. AEC (Atomic Energy Commission of Japan), Tokyo, Japan.

AECL 1994. Environmental Impact Statement on the concept for disposal of Canada's nuclear fuel waste. AECL-10711, COG-93-1. Chalk River, Canada: Atomic Energy of Canada Ltd (AECL) 496 p.

Andersson, J., Ström, A., Svemar, C., Almén, K.-E. & Ericsson, L.O. 2000. What requirements does the KBS-3 repository make on the host rock? Geoscientific suitability indicators and criteria for siting and site evaluation. TR-00-12. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Co. (SKB), 148 p.

Anh, H.N., Anh, H., Jo, H.Y. & Kim, G.-Y. 2017. Effect of alkaline solutions on bentonite properties. *Environ Earth Sci* 76, 374. <https://doi.org/10.1007/s12665-017-6704-8>

Åkesson, M., Kristensson, O., Börgesson, L. & Dueck, A. 2010. THM modelling of buffer, backfill and other system components. Critical processes and scenarios. SKB TR-10-11, SKB, Stockholm, Sweden.

Alexander, W.R. 1993. Assessment of conservative matrix diffusion depths (in crystalline rock) via studies of natural systems (a support document for the Kristallin-1 safety assessment) in U.Frick, Beurteilung der diffusion im grundwasser von Kristallingesteinen. Nagra Unpublished Internal Report, Nagra, Wettingen.

Alexander, W.R. 2003. in U.K.Mäder (Ed) Effect of high-pH fluids from cement degradation on Opalinus Clay. Nagra Unpublished Internal Report NIB 02-44, Nagra, Wettingen, Switzerland.

Alexander, W.R. 2012. The impact of a hyperalkaline plume on fractured crystalline rock. Proc. NEA-IGSC Workshop on cementitious materials in safety cases for geological repositories for radioactive waste: role, evolution and interaction. Brussels, 17-20th November, 2009. Radioactive Waste Management, NEA/RWM/R(2012)3/REV, NEA/OECD, Paris, France.

17.4.2023

Alexander, W.R., McKinley, I.G. & Kawamura, H. 2014. The process of defining an optimal natural analogue programme to support national disposal programmes. Proc. NEA-GRS Workshop on natural analogues for Safety Cases of repositories in rock salt. 4 – 6 September, 2012, Braunschweig, Germany. Radioactive Waste Management NEA/RWM/R(2013) pp 29-43, NEA/OECD, Paris, France.

Alexander, W.R., Reijonen, H.M. & McKinley, I.G. 2015. Natural analogues: studies of geological processes relevant to radioactive waste disposal in deep geological repositories. Swiss Journal of Geosciences 108, 75-100. DOI 10.1007/s00015-015-0187-y

Alexander, W.R. 2017. Sealing site investigation boreholes: Phase 2. The use of natural, industrial and archaeological analogues in support of the borehole sealing project, Amec Foster Wheeler Report 202580/07 for RWM Ltd, Harwell, UK.

Alexander, W.R. 2021. NUMO 2015SC - Supporting Report 14: multiple lines of evidence for safety. Commercial-in-Confidence report to NUMO, Tokyo, Japan (*in Japanese*).

Alexander, W.R. & McKinley, I.G. 1994. Constraints on the use of "in situ distribution coefficients (Kd)" values in contaminant transport modelling. Eclogae geol. Helv. 87/2, 321-324.

Alexander, W.R. & Mazurek, M. 1996. The Maqarin natural analogue: possible implications for the performance of a cementitious repository at Wellenberg. Unpubl. Internal Report, Nagra, Wettingen, Switzerland.

Alexander, W.R. & Milodowski, A.E. 2008. Low-alkali cement leachate/bentonite interaction natural analogue study. Cyprus Natural Analogue Project (CNAP) Phase I. Bedrock Geosciences Technical Report BG08-01, Bedrock Geosciences, Auenstein, Switzerland.

Alexander, W.R. & Milodowski, A.E. (Eds) 2011. Cyprus Natural Analogue Project (CNAP) Phase II Final Report. Posiva Working Report WR 2011-08, Posiva, Eurajoki, Finland.

Alexander, W.R. & Milodowski, A.E. 2017. Cyprus Natural Analogue Project (CNAP) Phase IV Final Report. Posiva Working Report WR 2014-02, Posiva, Eurajoki, Finland.

Alexander, W.R. & Havlova, V. (eds.), 2023. Proceedings of the NAWG-15 Workshop, 23-26th May, 2017, Rez, Czech Republic. Bedrock Geosciences Technical Report 2023-01, Bedrock Geosciences, Auenstein, Switzerland. (*in press*) Alexander, W.R. & Neall, F.B. 2007. Assessment of potential perturbations to Posiva's SF repository at

17.4.2023

Olkiluoto caused by construction and operation of the ONKALO facility. Posiva Working Report 2007-35, Posiva, Olkiluoto, Finland.

Alexander, W.R. & Reijonen, H. (Eds) 2023. A Catalogue of Analogues for Radioactive Waste Management – an update. *In prep.*

Alexander, W.R., Gautschi, A. & Zuidema, P. 1998. Thorough testing of performance assessment models: the necessary integration of in situ experiments, natural analogues and laboratory work. Extended abstract in Sci. Basis Nucl. Waste Manag. XXI, 1013-1014.

Alexander, W.R., Gieré, R., Hidaka, H. & Yoshida, H. 2006. Natural immobilisation processes aid the understanding of long-term evolution of deep geological radioactive waste repositories. *Geochemistry: Exploration, Environment, Analysis* 6, 3-4 Special issue on the Tono Analogue Project (TAP).

Alexander, W.R., McKinley, I.G. & MacKenzie, A.B. 2007. Development of an optimised natural analogue programme to support the Japanese HLW/TRU disposal programme (Part 1), MCM-TR-07-01 for RWMC, Tokyo, Japan.

Alexander, W.R., Milodowski, A.E. & Pitty, A.F. (Eds) 2012. Cyprus Natural Analogue Project (CNAP) Phase III Final Report. Posiva Working Report WR 2011-77, Posiva, Eurajoki, Finland.

Alexander, W.R., McKinley, I.G. and Kawamura, H. 2014. The process of defining an optimal natural analogue programme to support national disposal programmes. Proc. NEA-GRS Workshop on natural analogues for Safety Cases of repositories in rock salt. 4 – 6 September, 2012, Braunschweig, Germany. *Radioactive Waste Management NEA/RWM/R(2013)* pp 29-43, NEA/OECD, Paris, France.

Alexander, W.R., Ruskeeniemi, T. & Reijonen, H.M. (Eds) 2015. Proceedings (abstract book) of the NAWG-14 Workshop, Rauma, Finland, 9-11 June, 2015. Geological Survey of Finland (GTK) Guide 61. GTK, Espoo, Finland. http://tupa.gtk.fi/julkaisu/opas/op_061.pdf

Alexander, W.R., Reijonen, H.M., McKinley, I.G. 2015. Natural analogues: studies of geological processes relevant to radioactive waste disposal in deep geological repositories. *Swiss Journal of Geosciences* 108, 75-100. DOI 10.1007/s00015-015-0187-y

Alexander, W.R., Reijonen, H.M., MacKinnon, G., Milodowski, A.E., Pitty, A.F. & Siathas, A. 2017. Assessing the long-term behaviour of the industrial bentonites

17.4.2023

employed in a repository for radioactive wastes by studying natural bentonites in the field. *Geosciences* 7 (1), 5. doi:10.3390/geosciences7010005

Alexander, W.R., Ota, K., Yamada, S. & Yamada, M. (Eds) 2023. Proceedings of the NAWG-16 Workshop, 15-18th October, 2019, Zao, Yamagata, Japan. *Bedrock Geosciences Technical Report 2023-02*, Bedrock Geosciences, Auenstein, Switzerland. (in press)

Amano, K., Niizato, T., Ota, K., Alexander, W.R. & Lanyon B. 2011. Evaluation of the palaeohydrogeological evolution of the coastal site at Horonobe – Assessment of uncertainty in the site evolution model. In: Annual Meeting of the Atomic Energy Society of Japan, March 28-30, 2011. Fukui, Japan. 241 p.

Andersson, J., Riggare, P. & Skagius, K. 1998. Project Safe. Update of the SFR-1 safety assessment – Phase 1. SKB R-98-43. Stockholm, Sweden. 65p.

Arenius, M., Hansen, J., Juhola, P., Karttunen, P., Koskinen, K., Lehtinen, A., Lyytinen, T., Mattila, J., Partamies, S., Pitkänen, P., Raivio, P., Sievänen, U., Vuorinen, U. & Vuorio, M. 2008. R20 summary report: The groundwater inflow management in ONKALO – the future strategy. Posiva Working Report 2008-44, Posiva, Olkiluoto, Finland.

Aro, L. 2021. Safety Case for the Operating License Application: Description and Data of the Surface Environment 3 - Forests and Mires. Working Report 2019-13. Eurajoki: Posiva Oy.

Arthur, R., & Savage, D. 2012. Equilibrium constraints on buffer erosion based on the chemistry and chemical evolution of glacial meltwaters. Proc. of 5th International meeting on Clays in Natural and Engineered Barriers for Radioactive Waste Confinement. 22-25 October, 2012, Montpellier, France.

Bailey, L., Carter, A., Gray, L. & Hall, O. 2020a. ViSI: Supporting RWM's Business Cycle. Poster at NDA showcase event 'The NDA Safety & Wellbeing Awards', Manchester, UK, September 2019.

Bailey, L., Carter, A., Gray, L. & Hall, O. 2020b. ViSI: Moving toward a digital safety case. Poster at NDA showcase event 'The NDA Safety & Wellbeing Awards', Manchester, UK, September 2019.

Béland Otis, C. 2012. 29. Project Unit 09-024. Preliminary results: potential Ordovician Shale gas units in southern Ontario. Summary of field work and other activities 2012. Ontario Geological Survey, Open File Reports 6280, 29-1 – 29-12. Ontario Geological Survey, Geology Ontario, Ottawa, Canada.

17.4.2023

Björnelund, M. 2018. Timefulness – How thinking like a geologist can help save the world. Princeton University Press, 224 p.

Blowers A, Lowry D and Solomon BD (1991) The international politics of nuclear waste. Macmillan Academic and Professional Ltd, London, UK.

Blyth, A.R. & Kremer, E.P. 2023. The use of natural analogues in building stakeholder confidence in Canada's plan for the long-term management of used nuclear fuel. *In* Alexander, W.R. & Havlova, V. (eds.), 2023. Proceedings of the NAWG-15 Workshop, 23-26th May, 2017, Rez, Czech Republic. Bedrock Geosciences Technical Report 2023-01, Bedrock Geosciences, Auenstein, Switzerland. (*in press*)

Bodén, A. & Sievänen, U. 2006. Low-pH Injection Grout for Deep Repositories Summary Report from a Co-operation Project Between NUMO (Japan), Posiva (Finland) and SKB (Sweden). Posiva Working Report 2005-24, Posiva, Olkiluoto, Finland.

Bock, H., Dehandschutter, B., Martin, C.D., Mazurek, M., de Haller, A., Skoczylas, F. & Davy, C. 2010. Self-sealing of fractures in argillaceous formations in the context of geological disposal of radioactive waste: review and synthesis. OECD/NEA No. 6184, OECD/NEA, Paris, France.

Börgesson, L. & Hernelind, J. 2006. Canister displacement in KBS-3V: a theoretical study. SKB TR-06-04, SKB, Stockholm, Sweden.

Börgesson, L., Dueck, A. & Johannesson, L.-E. 2010. Material model for shear of the buffer- evaluation of laboratory test results. SKB TR-10-31, SKB, Stockholm, Sweden.

Brans, M., Ferraro, G. & von Estorff, U. 2015. The OECD Nuclear Energy Agency's Forum on Stakeholder Confidence, radioactive waste management and public participation. A synthesis of its learnings and guiding principles. EUR 27449 EN, EU, Luxembourg.

Brasser, T., Brewitz, W., Gies, H., Noseck, U., Pohl, W. & Schönwiese, D. 1999. Untersuchung der Uran-/Thorium-Mobilisation als natürliches Analogon für den Radionuklidtransport im Deckgebirge eines Endlagers für radioaktive Abfälle. GRS (Gesellschaft für Anlagen- und Reaktorsicherheit mbH), GRS-A-2652, Braunschweig, Germany (*in German*).

Brasser, T., Bletz, B., Noseck, U. & Schmidt, G. 2008. Anhang Natürliche Analoga Die Rolle Natürlicher Analoga bei der Sicherheitsbewertung von Endlagern. Appendix to GRS-Report 247, GRS (Gesellschaft für Anlagen- und Reaktorsicherheit mbH), Braunschweig, Germany (*in German*).

17.4.2023

Brasser, T., Fahrenholz, C., Kull, H., Meleshyn, A., Mönig, H., Noseck, U., Schönwiese, D. & Wolf, J. 2014. *Natürliche Analoga im Wirtsgestein Salz. Teil 1 Generelle Studie (2011). Teil 2 Detailstudien (2012 – 2013).* GRS-Report 365, GRS (Gesellschaft für Anlagen- und Reaktorsicherheit mbH), GRS-A-2652, Braunschweig, Germany (*in German*).

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

Bruggeman, C., Altmaier, M., Bosbach, D., Churakov, S., Galson, D. et al. 2019. "EURADSCIENCE", A NETWORK OF RESEARCH ORGANISATIONS FOR RADIOACTIVE WASTE MANAGEMENT SCIENCE WITHIN EUROPE. FISA 2019 and EURADWASTE '19: 9th European Commission Conferences on EURATOM Research and Training in Safety of Reactor Systems Radioactive Waste Management, Jun 2019, Pitesti, Romania. in2p3-02169313

Chapman, N. A. & Sargent, F.P. (Eds) 1984. *The geochemistry of HLW disposal in granitic rocks. Proceedings of a AECL-CEC workshop, September 12th-16th, 1983, Minster Lovell, UK.* AECL-Report 8361, CEC Report No. EUR9162, CEC, Luxembourg.

Chapman, N. A., McKinley, I.G. & Smellie, J. A. T. 1984. *The potential of natural analogues in assessing systems for deep disposal of high-level radioactive waste.* SKB TR 84-16 and Nagra, NTB 84-41, Nagra, Wettingen, Switzerland.

Clark, I.D., Al, T., Jensen, M., Kennell, L., Mazurek, M., Mohapatra, R., Raven, K.G. 2013. *Paleozoic-aged brine and authigenic helium preserved in an Ordovician shale aquiclude.* *Geology.* Geol Soc America, Boulder, USA. doi:10.1130/G34372.1

CNSC 2006. *Regulatory Guide G-320: Assessing the Long-Term Safety of Radioactive Waste Management.* Canadian Nuclear Safety Commission. Ottawa, Canada.

Come, B. & Chapman, N. (Eds) 1985. *Natural Analogue Working Group, Final Meeting Report from the First Meeting, November 5-7, 1985.* CEC Report No. EUR 10315, CEC, Luxembourg.

Come, B. & Chapman, N.A. (Eds), 1987a. *Natural Analogue Working Group, Final Meeting Report from the Second Meeting, 1986.* CEC Report No. EUR 10671 EN, CEC, Luxembourg.

Come, B. & Chapman, N. (Eds) 1987b. *Natural Analogues in radioactive waste disposal. Proceedings of a Symposium organised by the Commission of the European Communities under the Programme on Radioactive Waste Management*

17.4.2023

(Directorate-General Science, Research and Development) and held in Brussels on 28-30 April 1987. CEC Report No. EUR 11037 EN, CEC, Luxembourg.

Come, B. & Chapman, N.A. (Eds), 1989. Natural Analogue Working Group, Final Meeting Report from the Third Meeting, 1986. CEC Report No. EUR 11725 EN, CEC, Luxembourg.

Come, B. & Chapman, N. (Eds) 1991. Fourth natural analogue working group meeting and Poços de Caldas project final workshop Pitlochry, 18 to 22 June 1990, Scotland. CEC Report No. EUR 13014 EN, CEC, Luxembourg.

David, D. 2001. Analogues archéologiques et corrosion. Andra Report, Chatenay-Malabry, France (*in French*).

Emerson, T.E., McElrath, D.L. and Fortier, A.C. (Eds) 2000. Late Woodland Societies: Tradition and Transformation across the Midcontinent. University of Nebraska Press, Nebraska, USA.

Environment Agency and Northern Ireland Environment Agency, Geological Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation, February 2009.

Front, K., Paulamäki, S., Paananen, M. 1998. Updated lithological bedrock model of the Olkiluoto study site, Eurajoki, southwestern Finland. Posiva Working Report 98-57. Posiva Oy, Helsinki, Finland. (*in Finnish with English abstract*).

Front, K., Paulamäki, S., Ahokas, H., Anttila, P. 1999. Lithological and structural bedrock model of the Hästholmen study site, Loviisa, SE Finland. POSIVA Report 99-31. Posiva Oy, Helsinki, Finland.

Fujii, N., Yamakawa, M., et al. 2015. Alkaline alteration processes of bentonite sediment in the Philippines natural analogue and perspective on the survey of the active type. In Alexander, W.R., Ruskeeniemä, T. and Reijonen, H.M. (Eds) 2015. Proceedings (abstract book) of the NAWG-14 Workshop, Rauma, Finland, 9-11 June, 2015. Geological Survey of Finland (GTK) Guide 61. GTK, Espoo, Finland. http://tupa.gtk.fi/julkaisu/opas/op_061.pdf

Gehör, S. 2007. Mineralogical Characterization of Gouge Fillings in ONKALO Facility at Olkiluoto. Posiva Working Report 2007-33. Posiva Oy, Olkiluoto, Finland.

GRA 2009. Environment Agency and Northern Ireland Environment Agency, Geological Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation, February 2009.

17.4.2023

Haapanen, R., Aro, L., Kirkkala, T., Koivunen, S. & Lahdenperä, A.-M. 2010. Potential Reference Mires and Lakes for Biosphere Assessment of Olkiluoto Site. Working Report 2010-67. Posiva Oy, Eurajoki, Finland. 218 p.

Haavisto, F. & Toivola, M. 2021. Safety Case for the Operating License Application: Description and data of the surface environment 5 - fauna. Working Report 2019-15. Eurajoki: Posiva Oy.

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

Hamblin, J.D. 2020. Learning to think long-term. *Science* 370: 1043.

Havlová V., Zuna M., Brázda L., Kolomá K., Galeková E., Rosendort T. & Jankovský F. 2020. Radionuclide migration processes in a crystalline rock environment and the migration parameters of rocks of the Bohemian Massif. SURAO Final report 333/2018/EN. SURAO, Prague, Czech Republic. https://inis.iaea.org/collection/NCLCollectionStore/_Public/53/101/53101813.pdf.

Heath, M.J. 1995. Rock matrix diffusion as a mechanism for radionuclide retardation: natural radioelement migration in relation to the microfractography and petrophysics of fractured crystalline rock. CEC Nuclear Science and Technology Report, EUR 15977, CEC, Luxembourg.

Heikola, T., Kumpulainen, S., Vuorinen, U., Kiviranta, L. & Korkeakoski, P. 2013. Influence of alkaline and saline solutions on chemical, mineralogical and physical properties of two different bentonites – batch experiments at 25°C. *Clay Mins* 48, 309-329.

Hellmuth, K-H. 1991a. The existence of native iron - implications for nuclear waste management, Part I: evidence from existing knowledge. Finnish Centre for Radiation and Nuclear Safety, STUK-B-VALO 67, Helsinki, Finland.

Hellmuth, K-H. 1991b. The existence of native iron - implications for nuclear waste management, Part II: evidence from investigation of samples of native iron. Finnish Centre for Radiation and Nuclear Safety, STUK-B-VALO 68, Helsinki, Finland.

Höglund, L. 2014. The impact of concrete degradation on the BMA barrier function. SKB R-13-40. SKB, Stockholm, Sweden.

Höglund, L., Sidborn, M., Crawford, J., Keith-Roach, M., Hoek, J. & Grundfelt, B. 2018. Modelling of Chemical Influences from Posiva's Low and Intermediate Level Waste

17.4.2023

Repository on the Spent Nuclear Fuel Repository. Posiva Working Report 2017-03, Posiva, Olkiluoto, Finland.

Hooker, P.J., MacKenzie, A.B., Scott, R.D., Ridgway, I., McKinley, I.G. and West, J.M. 1985. A study of natural and long term ($10^3 - 10^4$ year) elemental migration in saturated clays and sediments, part III. BGS Technical Report FLP 85-9, BGS, Keyworth, UK.

HYDROCOIN 1992. The International HYDROCOIN Project, Summary Report, Swedish Nuclear Power Inspectorate and OECD/Nuclear Energy Agency, Paris, France.

IAEA 1975. Proceedings of a symposium on the Oklo phenomena. IAEA Technical Report, STI/PUB/405, International Atomic Energy Agency, Vienna, Austria.

IAEA 1978. Proceedings of the technical committee meeting on natural fission reactors. IAEA Technical Report, STI/PUB/475, International Atomic Energy Agency, Vienna, Austria.

IAEA 1985. Acceptance Criteria for Disposal of Radioactive Wastes in Shallow Ground and Rock Cavities. IAEA Safety Series No. 71, International Atomic Energy Agency, Vienna, Austria.

IAEA 1989. Natural Analogues in Performance Assessments for the Disposal of Long Lived Radioactive Wastes, Technical Reports Series No. 304, International Atomic Energy Agency, Vienna, Austria.

IAEA 1993. Bitumenization processes to condition radioactive wastes. IAEA Technical Report, 352, International Atomic Energy Agency, Vienna, Austria.

IAEA 1994a. Safety indicators in different time frames for the safety assessment of underground radioactive waste repositories: first report of the INMAC subgroup on principles and criteria for radioactive waste disposal. IAEA Technical Report, 767, International Atomic Energy Agency, Vienna, Austria.

IAEA 1994b. Nuclear Communications: A Handbook for Guiding Good Communications Practices at Nuclear Fuel Cycle Facilities. STI/PUB 966, IAEA, Vienna, Austria.

IAEA 1997. Regulatory decision making in the presence of uncertainty in the context of the disposal of long lived radioactive wastes. Third report of the Working Group on Principles and Criteria for Radioactive Waste Disposal. IAEA-TECDOC-975, IAEA, Vienna, Austria.

17.4.2023

IAEA 1999. Use of natural analogues to support radionuclide transport models for deep geological repositories for long lived radioactive wastes. IAEA Technical Report 1109, International Atomic Energy Agency, Vienna, Austria.

IAEA 2003a. Scientific and Technical Basis for the Geological Disposal of Radioactive Wastes. Technical Reports Series 413, International Atomic Energy Agency, Vienna, Austria.

IAEA 2003b. Safety indicators for the safety assessment of radioactive waste disposal. Sixth report of the Working Group on Principles and Criteria for Radioactive Waste Disposal. IAEA-TECDOC-1372, IAEA, Vienna, Austria.

IAEA 2005. Final Report of IAEA CRP Anthropogenic Analogues for Geological Disposal of High Level and Long Lived Radioactive Waste (1999 - 2004). IAEA TECDOC 1481, IAEA, Vienna, Austria.

IAEA 2013. The Behaviours of Cementitious Materials in Long Term Storage and Disposal of Radioactive Waste: results of a co-ordinated research project. IAEA, Vienna, Austria.

IAEA 2017. Selection of Technical Solutions for the Management of Radioactive Waste. IAEA-TECDOC-1817, IAEA, Vienna, Austria.

IAEA 2018. Regulations for the Safe Transport of Radioactive Material, 2018 Edition. Specific Safety Requirements No. SSR-6 (Rev. 1), International Atomic Energy Agency, Vienna, Austria.

Ialenti, V. 2020. Deep Time Reckoning – How future thinking can help earth now. The MIT Press One Planet – series 208 p.

INTRACOIN 1984. INTRACOIN, Final Report Level 1, code verification, SKI 84:3, Swedish Nuclear Power Inspectorate, Stockholm, Sweden.

INTRAVAL 1994. The International INTRAVAL Project, Summary Report, Swedish Nuclear Power Inspectorate and OECD/Nuclear Energy Agency, Paris, France.

Irvine, R.D.G. 2020. An Anthropology of Deep Time – Geological Temporality and Social Life. Cambridge University Press, 212 p.

Jackson, R. 2009. Organic Geochemistry and Clay Mineralogy of DGR-3 and DGR-4 Core. DGR Site Characterization Document Intera Engineering Project 08-200. Intera TR-08-29. Intera, Ottawa, Canada.

IAEA 2007. Second Progress Report on Research and Development for TRU Waste Disposal in Japan – Repository Design, Safety Assessment and Means of

17.4.2023

Implementation in the Generic Phase. JAEA/FEPCO joint report, JAEA-Review 2007-010, JAEA, Tokai, Japan.

Jefferies, N.L., Joyce, S., et al. 2016. Sealing site investigation boreholes. Phase II Annual Report for 2014/2015. RWM Ltd Report RWM/03/046, RWM Ltd, Harwell, UK.

Jensen, M., Lam, T., Luhowy, D., McLay, J., Semec, B. & Frizzell, R. 2009. Overview of Ontario Power Generation's Proposed L&ILW Deep Geologic Repository Bruce Site, Tiverton, Ontario. ROCKENG09: Proceedings of the 3rd CANUS Rock Mechanics Symposium, Toronto, May 2009 M.Diederichs and G. Grasselli (Eds). Canadian Rock Mechanics Association, Toronto, Canada.

JNC 2000. H12: Project to Establish Technical Basis for HLW Disposal in Japan, Project Overview Report and three Supporting Reports, JNC TN1410 2000-001-004. JAEA, Tokai, Japan.

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, Japan.

Johnson, A.B. & Francis, B. 1980. Durability of metals from archaeological objects metal meteorites and native metals. Battelle Pacific Northwest Laboratory, PNL-3198, Battelle PNL, Richmond, USA.

Kärki, A., Gehör, S., Suoperä, S., Taikina-aho, O. 1997. Romuvaara, Kuhmo, Petrology and low temperature fracture minerals in the R0-R11 drill core samples. Posiva Working Report 97-19. Posiva Oy, Helsinki, Finland. (*in Finnish with English abstract*).

Kirkkala, T. & Mikkilä, E. 2021. Safety Case for the Operating License Application: Description and data of the surface environment 2 – Aquatic Environment. Working Report 2019-12. Eurajoki: Posiva Oy.

Kontula, A., Pitkänen, P., Claesson Liljedahl, L., Näslund, J.-O., Selroos, J.-O., Puigdomenech, I., Vidstrand, P., Harper, J., Hobbs, M., Hirschorn, S., Kennell, L., Follin, S., Jansson, P., Marcos, N., Ruskeeniemi, T. & Tullborg, E.-L. 2016. The Greenland Analogue Project: Final Report. POSIVA 2016-17, Eurajoki, Finland: Posiva Oy 152 p.

Koroleva, M., de Haller, A., Mäder, U., Waber, H.N. & Mazurek, M. 2009. Borehole DGR-2: pore-water investigations. Technical Report TR-08-02. Rock-Water Interaction, Institute of Geological Sciences, University of Berne, Switzerland.

17.4.2023

Kremer, E.P. & Alexander, W.R. 2015. Long-term durability of shaft sealing materials under highly saline groundwater conditions. In Alexander, W.R., Ruskeeniemi, T. and Reijonen, H.M. (Eds) 2015. Proceedings (abstract book) of the NAWG-14 Workshop, Rauma, Finland, 9-11 June, 2015. Geological Survey of Finland (GTK) Guide 61. GTK, Espoo, Finland. http://tupa.gtk.fi/julkaisu/opas/op_061.pdf

Lahdenperä, A.-M. & Kuusisto, J. 2021. Safety Case for the Operating License Application: Description and data of the surface environment 1 – Overburden properties and sorption. Working Report 2019-11. Eurajoki, Finland: Posiva Oy.

Larsson, A., Pers, K., Skagius, K. & Dverstorp, B. (Eds) 1994. The international INTRAVAL project to study validation of geosphere transport models for performance assessment of nuclear waste disposal: Phase II summary report. Swedish Nuclear Power Inspectorate and OECD/Nuclear Energy Agency, Paris, France.

Laul, J.C. & Papike, J.J. 1982. Chemical migration by contact metamorphism between granite and silt-carbonate systems. In: Environmental migration of the long-lived radionuclides. IAEA Technical Report, STI/PUB/597, International Atomic Energy Agency, Vienna, Austria.

Lindqvist J (1996) The use of natural analogues in public relations. In von Maravic H and Smellie J.A.T. (eds) Natural analogue working group, sixth meeting, Santa Fe, September 1994. CEC Nuclear Science and Technology Report, EUR 16761, 283-286, CEC, Luxembourg.

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

Martinetto, E., Bertini, A., et al. 2014. The plant record of the Dunarobba and Pietrafitta sites in the plio-pleistocene palaeoenvironmental context of central Italy. Alpine and Mediterranean Quaternary, 27, 29 – 72.

Mazurek, M., Gautschi, A. & Vomvoris, S. 1992. Deriving input data for discrete transport models from deep borehole investigations: an approach for crystalline rocks. In: IAEA/CEC International Symposium on Geological Disposal of Spent Fuel High Level and Alpha-Bearing Waste. International Atomic Energy Agency, Vienna, Austria.

Mäder, U.K. (Ed) 2003. Effect of high-pH fluids from cement degradation on Opalinus Clay. Nagra Unpublished Internal Report NIB 02-44, Nagra, Wettingen, Switzerland.

17.4.2023

Mäkiäho, J-P. 2005. Development of shoreline and topography in the Olkiluoto area, western Finland, 2000 BP – 8000 AP. Working Report 2005-70. Posiva Oy, Olkiluoto, Finland. 47 p.

McKinley, I.G. & Alexander, W.R. 2007a. Development of an optimised natural analogue programme to support the Japanese HLW/TRU disposal programme (Part 2), MCM-TR-07-02 for RWMC, Tokyo, Japan.

McKinley, I.G. & Alexander, W.R. 2007b. Development of an optimised natural analogue programme to support the Japanese HLW/TRU disposal programme MB-TR-07-01 for RWMC, Tokyo, Japan.

Metcalf, R., Milodowski, A.E., Field, L.P., Roy Wogelius, R.A., Carpenter, G., Yardley, B.W.D. & Norris, S. 2021. Natural analogue evidence for controls on radionuclide uptake by fractured crystalline rock. *Applied Geochemistry*, 124, <https://doi.org/10.1016/j.apgeochem.2020.104812>

Meyer-Ohle, H. 2009. Japanese Workplaces in Transition – Employee Perceptions. Palgrave Macmillan, London, UK. DOI <https://doi.org/10.1057/9780230274242>

Miller, W.M. 2002. Communicating with natural analogues. *In* von Maravic, H. & Alexander, W.R. (Eds) 2002. Eighth EC Natural Analogue Working Group Meeting. Proceedings of an international workshop held in Strasbourg, France from 23 to 25 March 1999. CEC Report No. EUR 19118 EN, CEC, Luxembourg.

Miller, W.M. & Marcos, N. 2007. Process report. FEPs and scenarios for a spent fuel repository at Olkiluoto. POSIVA 2007-12, Eurajoki, Finland: Posiva Oy 274 p.

Miller, W.M., Alexander, W.R., Chapman, N.A., McKinley, I.G., Smellie, J.A.T. (1994). Natural analogue studies in the geological disposal of radioactive wastes. *Studies in Environmental Science* 57 (395 pp). Elsevier, Amsterdam, The Netherlands.

W.M.Miller, W.R.Alexander, N.A.Chapman, I.G.McKinley & J.A.T.Smellie 2000. Geological disposal of radioactive wastes and natural analogues. Waste management series, vol. 2, Pergamon, Amsterdam, The Netherlands.

Milodowski, A.E., Alexander, W.R., West, J.M., Shaw, R.P., McEvoy, F.M., Scheidegger, J.M. & Field, L.P., 2015a. A Catalogue of Analogues for Radioactive Waste Management. BRITISH GEOLOGICAL SURVEY COMMISSIONED REPORT CR/15/106. Keyworth, Nottingham British Geological Survey 2015. 1849p.

Milodowski, A.E., Alexander, W.R., West, J.M., Shaw, R.P., McEvoy, F.M., Scheidegger, J.M. & Field, L.P., 2015b. A Catalogue of Analogues for Radioactive Waste Management (in Japanese). BRITISH GEOLOGICAL SURVEY COMMISSIONED

17.4.2023

REPORT CR/15/106. Keyworth, Nottingham British Geological Survey 2015. 1849p. Translation by NUMO, published as NUMO-TR-19-01.

Milodowski, A.E., Norris, S. & Alexander, W.R. 2016. Minimal alteration of montmorillonite following long-term reaction in natural alkali solutions: implications for geological disposal of radioactive waste. *Appl. Geochem.* 66, 184-197.

Nagra 1984. An assessment of the corrosion resistance of the high-level waste containers proposed by Nagra. Nagra Technical Report Series NTB 84-32, Nagra, Wettingen, Switzerland.

Nagra 1985. Project Gewähr 1985 - Nuclear waste management in Switzerland - Feasibility studies and safety analyses. Nagra Project Gewähr Report series, NGB 85-09, Nagra, Wettingen, Switzerland

Nagra 1994. Kristallin-1. Safety assessment report. Nagra Technical Report Series NTB 93-22, Nagra, Wettingen, Switzerland.

Nagra 1997. Geosynthese Wellenberg 1996 – Ergebnisse der Untersuchungsphasen I und II. Nagra Technical Report NTB 96-01, Nagra, Wettingen, Switzerland (in German).

Nagra 2002. Project Opalinus Clay Safety Report. Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis). Nagra Technical Report NTB 02-05, Nagra, Wettingen, Switzerland.

Nakayama, M., Niunoya, S. & Minamide, M. 2016. Confirmation of the applicability of low alkaline cement-based material in the Horonobe Underground Research Laboratory. *Genshiryoku Bakuendo Kenkyu*, 23, 25-30 (*in Japanese*).

NAnet 2006a. Network to review natural analogue studies and their applications to repository safety assessment and public communication (NAnet). CEC Report No. EUR 21919 EN, CEC, Luxembourg.

NAnet 2006b. Workshop Summary. Natural Analogues: Their Application to Repository Safety Assessment and Stakeholder Communication. Proceedings of the NAnet International Workshop, 12-13 May 2004, Château de Cadarache, France. Appendix in CEC Report No. EUR 21919 EN, CEC, Luxembourg.

NAnet 2006c. Synthesis Report. Network to review natural analogue studies and their applications to GDF safety assessment and public communication (NAnet). CEC Report No. EUR 21919 EN, CEC, Luxembourg.

17.4.2023

NDA 2010. NDA, Geological Disposal: Generic Environmental Safety Case, Main Report NDA/RWMD/021, December 2010.

NDA 2012. Nuclear Decommissioning Authority, Technical baseline and underpinning research and development requirements, EGG 10, 2012.

NEA 2004. Post-Closure Safety Case for Geological Repositories: Nature and Purpose, NEA No. 3679, NEA, Paris.

NEA 2013. Natural Analogues for Safety Cases of Repositories in Rock Salt. "Salt Club" Workshop Proceedings (Braunschweig, Germany, 5-7 September 2012). NEA/RWM/R(2013)10, OECD/NEA, Paris, France.

NEA, 2017. Communication on the Safety Case for a Deep Geological Repository. NEA Report 7336, OECD/NEA, Paris, France.

Neall, F., Baertschi, P., McKinley, I.G., Smith, P., Sumerling, T. & Umeki, H. 1994. Kristallin-1: results in perspective. Nagra Technical Report NTB 93-23, Nagra, Wettingen.

Neall, F., Baertschi, P., McKinley, I.G., Smith, P., Sumerling, T. & Umeki, H. 1995. Putting HLW performance assessment results in perspective. Sci. Basis Nucl. Waste Manag. XVIII, pp503-510

Neall, F.B. & Smith, P.A. (Eds) 2004. H12: examination of safety assessment aims, procedures and results from a wider perspective. JNC Technical Report JNC TY1400 2004-001, JNC, Tokai, Japan.

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 2007-10, Eurajoki, Finland: Posiva Oy 208 p.

Noronha, J. 2016. Deep Geological GDF Conceptual Design Report Crystalline / Sedimentary Rock Environment. Nuclear Waste Management Organization Technical Report NWMO- APM-REP-00440-0015 R001. Toronto, Canada.

Noseck, U. 2000. Zusammenstellung und Auswertung geochemischer Untersuchungen zum Radionuklidverhalten aus ausgewählten Studien über Natürliche Analoga (Compilation and evaluation of geochemical investigations of the behavior of far-field radionuclide retardation from selected natural analogue studies). GRS-Report 155, GRS (Gesellschaft für Anlagen-und Reaktorsicherheit mbH), Braunschweig, Germany (*in German*).

17.4.2023

Noseck, U. & Brassler, T. 2006. Radionuclide transport and retention in natural rock formations – Ruprechtov site. GRS-Report 218, GRS (Gesellschaft für Anlagen-und Reaktorsicherheit mbH), Braunschweig, Germany.

Noseck, U. & Havlova, H. (Eds) 2014. Natural Analogue Study Ruprechtov (CZ): An Experience Report. GRS-Report 349, GRS (Gesellschaft für Anlagen-und Reaktorsicherheit mbH), Braunschweig, Germany.

NUMO 2021. The NUMO pre-siting SDM-based Safety Case. NUMO TR-21-01. NUMO, Tokyo, Japan.

NWMO 2016a. Nuclear Fuel Waste Projections in Canada – 2016 Update. Nuclear Waste Management Organization Technical Report NWMO-TR-2016-09. Toronto, Canada.

NWMO 2016b. Indigenous Knowledge Policy. NWMO short note, October, 2016. Nuclear Waste Management Organization. Toronto, Canada.

Ojala, A. E.K., Mattila, J., Ruskeeniemi, T., Markovaara-Koivisto, M., Palmu, J-P., Nordbäck, N., Lindberg, A., Sutinen, R., Aaltonen, I. & Savunen, J. 2019. Postglacial Faults in Finland -a Review of PGSDyn Project Results. POSIVA 2019-01, Eurajoki, Finland: Posiva Oy 118 p.

Ota, K. 2023. Natural system evidence underpinning the NUMO 2015 safety case. In Alexander, W.R., Ota, K., Yamada, S. & Yamada, M. (Eds) 2023. Proceedings of the NAWG-16 Workshop, 15-18th October, 2019, Zao, Yamagata, Japan. Bedrock Geosciences Technical Report 2023-02, Bedrock Geosciences, Auenstein, Switzerland. (in press)

Pearcy, E.C., Prikryl, J.D., Murphy, W.M. & Leslie B.W. 1994. Alteration of uraninite from the Nopal I deposit, Peña Blanca District, Chihuahua, Mexico, compared to degradation of spent nuclear fuel in the proposed US high-level nuclear waste repository at Yucca Mountain, Nevada. Applied Geochemistry, 9, 713-732.

Pitty, A.F. & Alexander, W.R. (Eds), 2011. A natural analogue study of cement buffered, hyperalkaline groundwaters and their interaction with a repository host rock IV: an examination of the Khushaym Matruk (central Jordan) and Maqarin (northern Jordan) sites. Bedrock Geosciences Technical Report 11-02 for NDA-RWMD. RWM Ltd, Harwell, UK. See <http://nora.nerc.ac.uk/20953/>

PNC 1992. Research and Development on Geological Disposal of High-level Radioactive Waste, First Progress Report - H3, PNC TN1410 93-059. JAEA, Tokai, Japan.

17.4.2023

Posiva 2008. Safety case plan 2008. POSIVA 2008-05, Eurajoki, Finland: Posiva Oy 80 p.

Posiva 2012a. Safety case for the disposal of spent nuclear fuel at Olkiluoto – Complementary Considerations 2012. POSIVA 2012-11, Eurajoki, Finland: Posiva Oy 262 p.

Posiva 2012b. Safety case for the disposal of spent nuclear fuel at Olkiluoto – Features, Events and Processes 2012. POSIVA 2012-07, Eurajoki, Finland: Posiva Oy 460 p.

Posiva 2013a. Olkiluoto Biosphere Description 2012. POSIVA 2012-06, Eurajoki, Finland: Posiva Oy 292 p.

Posiva 2013b. Safety case for the disposal of spent nuclear fuel at Olkiluoto – Performance Assessment 2012. POSIVA 2012-04. Eurajoki, Finland: Posiva Oy 520 p.

Posiva 2016. Safety evaluation for a KBS-3H spent nuclear fuel repository at Olkiluoto - Features, Events and Processes. POSIVA 2016-03, Eurajoki, Finland: Posiva Oy 368 p.

Posiva 2017. Safety case plan for the operating licence application. POSIVA 2017-02, Eurajoki, Finland: Posiva Oy 152 p.

Posiva 2018. Safety Evaluation for a KBS-3H Spent Nuclear Fuel Repository at Olkiluoto - Performance Assessment. POSIVA 2016-2. Eurajoki, Finland: Posiva Oy 506 p.

Posiva 2022. Palaeohydrogeochemical data, concepts and interpretation for the Olkiluoto site. Posiva Report 2021-13. Posiva, Eurajoki, Finland.

Posiva 2023a. Safety Case for the Operating Licence Application - Complementary Considerations (CC). POSIVA 2021-02. Eurajoki, Finland: Posiva Oy. (*in press*)

Posiva 2023b. Safety Case for the Operating Licence Application – Performance Assessment and Formulation of Scenarios (PAFOS). POSIVA 2021-06. Eurajoki, Finland: Posiva Oy. (*in press*)

Rasmussen, T.C., Rhodes, S.C., Guzman, A. & Neuman, S.P. (Eds) 1996. Apache Leap Tuff INTRAVALEXperiments: Results and lessons learned, NUREG/CR-6096, U.S. Nuclear Regulatory Commission, Washington, D.C., USA.

17.4.2023

Raven, K.G., Sterling, S.N., Jackson, R.E., Avis, J.D. & Clark, I.D. 2010. Geoscientific site characterization of the proposed Deep Geologic Repository, Tiverton, Ontario. Proceedings of GeoCanada 2010 Convention "Working with the Earth – Terre d'Avenir", Calgary, May 10 to 14, 2010. University of Calgary, Canada.

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, 101-110. DOI 10.1007/s00015-015-0185-0

Reijonen, H. & Marcos, N. 2016. Chemical erosion of bentonite buffer – do we observe it in nature?. In: Norris, S., Bruno, J., Van Geet, M. & Verhoef, E. (Eds). Radioactive Waste Confinement: Clays in Natural and Engineered Barriers. Special Publications 443, London, UK: The Geological Society of London pp. 307-317.

Reijonen, H., Alexander, W.R., Marcos, N. & Lehtinen, A. 2015. Complementary considerations in the safety case for the deep repository at Olkiluoto, Finland: support from natural analogues. Swiss Journal of Geosciences. 108(1) pp. 111-120.

Reijonen, H., Alexander, W.R., Marcos, N. & Pastina, B. 2022. Implementing natural analogue information in Posiva's safety case – methodology and case-specific review. Abstract for Clay Conference 2022, Nancy, France.

Reijonen, H.M., Vuorio, M., Marcos, N. & Pastina, B. 2023. Use of natural analogues in the Finnish safety case – status update on Complementary Considerations. In: Alexander, W.R. & Havlova, V. (eds.), 2023. Proceedings of the NAWG-15 Workshop, 23-26th May, 2017, Rez, Czech Republic. Bedrock Geosciences Technical Report 2023-01, Bedrock Geosciences, Auenstein, Switzerland. (*in press*)

RWM 2016a. Geological Disposal: Generic Environmental Safety Case – Main Report. NDS Report no. DSSC/203/01. Harwell, Didcot, UK. 185 p.

RWM 2016b. Radioactive Waste Management, Geological Disposal: Generic Operational Environmental Safety Assessment, DSSC/315/01, December 2016.

RWM 2020a. Geological Disposal – Science and Technology Plan 2020. NDA/RWM/176. 769p.

RWM 2020b. Geological Disposal - Site Evaluation, How we will evaluate sites in England. Radioactive Waste Management 2020. 72p. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/866403/RWM_Site_Evaluation_for_England_2020.pdf

17.4.2023

Salo, T. 2021. Safety Case for the Operating License Application: Description and data of the surface environment 4 – Agriculture. Working Report 2019-14. Eurajoki, Finland: Posiva Oy.

Sandström, B., Tullborg, E.-L., Smellie, J.A.T., MacKenzie, A.B. & Suksi, J. 2008. Fracture mineralogy of the Forsmark site: Final report. SKB R-08-102. SKB, Stockholm, Sweden.

Savage, D. 2011. A Review of Analogues of Alkaline Alteration with regard to Long-term Barrier Performance. Mineralogical Magazine 75: 1–18.

Schönwiese, D., Noseck, U. & Brasser, B. 2006. Radionuclide transport and retention in natural rock formations – Heselbach site. GRS-Report 217, GRS (Gesellschaft für Anlagen- und Reaktorsicherheit mbH), Braunschweig, Germany.

Sidborn, M., Marsic, Crawford, N.J., Joyce, S., Hartley L., Idiart, A., de Vries, L.M., Maia, F., Molinero, J., Svensson, U., Vidstrand, P. & Alexander, W.R. 2014. Potential alkaline conditions for deposition holes of a repository in Forsmark as a consequence of OPC grouting. SKB Report SKB R-12- 17, SKB, Stockholm, Sweden.

Sievänen, U., Karvonen, T.H., Dixon, D., Hansen, J. & Jalonen, J. 2012. Closure Production Line 2012 – Design, production and initial state of closure. POSIVA 2012-19, Eurajoki, Finland: Posiva Oy 104 p.

SKB 1983. Final storage of spent nuclear fuel - KBS-3. Stockholm, Sweden: Svensk Kaernbraenslefoersorjning AB / Swedish Nuclear Fuel Supply Co/Div KBS.

SKB 1992. Final disposal of spent nuclear fuel, Importance of the bedrock for safety. SKB Technical report 92-20. Stockholm, Sweden. 230p.

SKB 1999. Deep repository for spent nuclear fuel. SR 97 – Post-closure safety. Main Report –Volume I, Volume II and Summary. Technical Report TR-99-06, Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Co. (SKB) 217+265+1p.

SKB 2010a. FEP report for the safety assessment SR-Site. Technical Report TR-10-45, Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Co. (SKB) 269 p.

SKB 2010b. Buffer, backfill and closure process report for the safety assessment SR-Site. Technical Report TR-10-47, Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Co. (SKB) 360 p.

SKB 2010c. Fuel and canister process report for the safety assessment SR-Site. Technical Report TR-10-46, Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Co. (SKB) 143 p. (updated version 2015-06)

17.4.2023

SKB 2011. Long-term safety for the final repository for spent nuclear fuel at Forsmark - Main report of the SR-Site project. Technical Report TR-11-01, Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Co. (SKB) 893 p.

SKB 2014. Barrier process report for the safety assessment SR-PSU. SKB TR-14-04, SKB, Stockholm, Sweden.

Smellie, J.A.T. (Ed) 1984. Natural analogues to the conditions around a final repository for high-level radioactive waste. Proceedings of the natural analogue workshop held at Lake Geneva, Wisconsin, USA (October 1-3, 1984). SKB TR 84-18, SKB, Stockholm, Sweden.

Smellie, J.A.T. & Karlsson, F. (Eds) 1996. The Cigar Lake analogue project: A reappraisal of some key issues and their relevance to repository performance assessment. Technical Report 96-08, Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Co. (SKB) 101 p.

Smellie, J., Tullborg, E-L., Nilsson, A-C., Gimeno, M., Sandström, B., Waber, N. & Gascoyne, M. 2008. Explorative analysis of major components and isotopes, SDM-Site Forsmark. R-08-84, Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Co. (SKB).

Smith, P., Schatz, T., Reijonen, H. & Hellä, P. 2017. Chemical erosion and mass redistribution of bentonite in a KBS-3H repository. POSIVA 2016-12, Eurajoki, Finland: Posiva Oy.

STUK 2018. Disposal of nuclear waste. Guide YVL D.5 (13.2.2018). Helsinki, Finland: Radiation and Nuclear Safety Authority (STUK).

Tylecote, R.F. 1979. The effect of soil conditions on the long-term corrosion of buried tin-bronzes and copper. *J. Archaeol. Sci.* 6, 3435.

USNRC 1957. The Disposal of Radioactive Waste on Land. Washington, DC: The National Academies Press. <https://doi.org/10.17226/10294>

Vieno, T., Hautojärvi, A., Koskinen, L. & Nordman, H. 1992. TVO-92 safety analysis of spent fuel disposal. YJT-92-33E, Helsinki, Finland: Nuclear Waste Commission of Finnish Power Companies (YJT) 254 p.

Vieno, T. & Nordman, H. 1999. Safety assessment of spent fuel disposal in Hästholmen, Kivetty, Olkiluoto and Romuvaara - TILA-99. POSIVA 99-07, Helsinki, Finland: Posiva Oy 253 p.

17.4.2023

Vieno, T., Lehtikainen, J., Löfman, J., Nordman, H. & Mészáros, F. 2003. Assessment of disturbances caused by construction and operation of ONKALO. Posiva Report 2003-06, Posiva, Oulkuoto, Finland.

Villar, M.V., Armand, G., Conil, N., de Lesquen, Ch., Herold, Ph., Simo, E., Mayor, J.C., Dizier, A., Li, X., Chen, G., Leupin, O., Niskanen, M., Bailey, M., Thompson, S., Svensson, D., Sellin, P. & Hausmannova, L. 2020. D7.1 HITEC. Initial State-of-the-Art on THM behaviour of i) Buffer clay materials and of ii) Host clay materials. Deliverable D7.1 HITEC. EURAD Project, Horizon 2020 No 847593. 214 pp.

Vola, G., Gotti, E., Brandon, C., Oleson, J.P. & Hohlfelder, R.L. 2011. Chemical, mineralogical and petrographic characterization of Roman ancient hydraulic concretes cores from Santa Liberata, Italy, and Caesarea Palestinae, Israel. *Periodico di Mineralogia*, 80(2).

von Maravic, H. & Smellie, J.A.T. (Eds) 1994. Fifth CEC Natural Analogue Working Group meeting and Alligator Rivers Analogue Project (ARAP) final workshop. Proceedings of an international workshop held in Toledo, Spain from 5 to 9 October 1992. CEC Report No. EUR 15176 EN, CEC, Luxembourg.

von Maravic, H. & Smellie, J.A.T. (Eds) 1996. Sixth EC Natural Analogue Working Group Meeting. Proceedings of an international workshop held in Santa Fe, New Mexico, USA on 12-16 September 1994. CEC Report No. EUR 16761 EN, CEC, Luxembourg.

von Maravic, H. & Alexander, W.R. 2002. Eighth EC Natural Analogue Working Group Meeting. Proceedings of an international workshop held in Strasbourg, France from 23 to 25 March 1999. CEC Report No. EUR 19118 EN, CEC, Luxembourg.

Vovk, I.F. 1988. The IAEA report on the role of natural analogues in performance assessment. In: Côme B and Chapman NA (editors) Natural analogue working group, third meeting, Snowbird, June 1988. CEC Nuclear Science and Technology Report, EUR 11725, 141-145, CEC, Luxembourg.

Waber, H.N. 1990. Hydrothermal and supergene evolution of the Osamu Utsumi uranium deposit and the Morro do Ferro thorium - rare earth deposit, Minas Gerais, Brazil, PhD-Thesis, University of Bern, 179 pp.

West, J.M. 2000. Life with Auntie (BBC). *Biologist*, 47, 136-138.

West, J.M. & McKinley, L.E. (2007). Building Confidence in the Safe Disposal of Radioactive Waste. In W.R.Alexander & L.E.McKinley (Eds.), *Deep geological disposal of radioactive wastes* (pp. 227-249). Amsterdam: Elsevier.

17.4.2023

White, M.J. (Ed). 2019. Modern2020 Project Synthesis Repository Monitoring: Strategies, Technologies and Implementation Luxembourg: European Commission. MoDeRn deliverable D6.5, 143 p.

Wogelius, R.A., Milodowski, A.E., Field, L.P., Metcalfe, R., Lowe, T., van Veelen, A. Carpenter, G., Norris, S. & Yardley, B. 2020. Mineral reaction kinetics constrain the length scale of rock matrix diffusion. *Sci Rep* 10, 8142 (2020). <https://doi.org/10.1038/s41598-020-65113-x>

Wolf, J. & Noseck, U. 2015. Natural Analogues for containment providing barriers for a HLW repository in salt. *Swiss Journal of Geosciences*. April 2015. DOI 10.1007/s00015-015-0184-1.

Xiang, G., Ye, W., & Lv, L. 2019. Swelling characteristics of bentonite after long-term dissolution in alkaline solution. *Clay Minerals*, 54, 409-416. doi:10.1180/clm.2019.54

Yamada, S. 2023. Use of self-analogue information for site investigations in Japan. In Alexander, W.R., Ota, K., Yamada, S. & Yamada, M. (Eds) 2023. Proceedings of the NAWG-16 Workshop, 15-18th October, 2019, Zao, Yamagata, Japan. *Bedrock Geosciences Technical Report 2023-02*, Bedrock Geosciences, Auenstein, Switzerland. (*in press*).

17.4.2023

APPENDICES

A1: List of NA studies considered in NAnet project

A2: Nagra NA-studies 1984-2003

A3: Spuren der Zukunft, Nagra NA brochure from 2007

A4: Long-term safety of a GDF Nagra 2018

A5: Details of two BBC radio programmes including NA information

INDEX

A

Akrotiri (Santorini, Greece)
Alligator Rivers (Australia)
Asse Mine (Germany)

B

Bangombé (Gabon)
BARRA project (Spain)
Bézier Gallo-Roman Circus (France)
Bitumens
Björklund and Pleutajokk (Sweden)
Boom Clay (Belgium)
Borehole Depths
BORIS (Russia)
Broubster (Scotland)
Busachi (Sardinia, Italy)

C

Caves and caverns: man-made
Caves and caverns: natural
Caves and caverns: preservation of materials
Caves and caverns: seepage in man-made caverns
Caves and caverns: seepage in natural caves
Caves and caverns: stability of man-made caverns
Chernobyl (Ukraine)
Cigar Lake (Canada)
Col du Perthus (France)
Cryptokarsts (Belgium)

D

Disko Island (Greenland)
Dunarobba Forest (Italy)

E

El Berrocal (Spain)
Eye-Dashwa Lakes Pluton (Canada)

G

Gas migration: crystalline and mudrocks
Gas migration: evaporites
Geothermal and hydrothermal systems
Glasses: archaeological and historical
Glasses: natural
Gorleben Salt Dome (Germany)
Grimsel underground laboratory (Switzerland)

H

Hadrian's Wall (Scotland)
Heselbach (Germany)
Hyrkkölä (Finland)

I

Inchtuthil Roman fort (Scotland)
Isle of Skye (Scotland)

J

Josephinite

K

Keweenaw Peninsula (USA)

Khushaym Matruk (Jordan)

Kinnekuille (Finland)

Klipperås study (Sweden)

Kråkemåla and Kamlunge (Sweden)

Krasnoyarsk (Russia)

Kronan cannon (Sweden)

L

Littleham Cove native copper (UK)

Loch Lomond (Scotland)

Lupin Mine (Canada)

M

Maqarin (Jordan)

Marysvale (USA)

Menzenschwand (Germany)

Mina Fe (Spain)

Morro do Ferro (Poços de Caldas, Brazil)

Morsleben Salt Dome (Germany)

Murakami (Japan)

N

Non-aqueous phase liquid migration

Needle's Eye (Scotland)

O

Oklo (Gabon)

Opalinus Clay (Switzerland)

Orciatico Intrusion (Italy)

Osamu Utsumi Mine (Poços de Caldas, Brazil)

P

Palmottu (Finland)

Peña Blanca (Mexico)

Poços de Caldas (Brazil – see Osamu Utsumi Mine and Morro do Ferro)

R

Ruprechtov (Czech Republic)

Resins: natural

S

Saltmines

Scawt Hill (Northern Ireland)

Seismic shaking

Semail Ophiolite (Oman)

Shinkolobwe (Zaire)

South Terras (UK)

T

Tono Mine (Japan)

W

Whiteshell underground laboratory (Canada)

Z

Zechstein salt (Germany)

Zirconolite

Bibliography of Nagra's publications in the field of natural analogues

1984 - January, 2003

W.R.Alexander, Bedrock Geosciences, Switzerland.

Overview of Nagra's Natural Analogue Studies (1984-2003)

<u>Theme</u>	<u>Examples (see list for details)</u>
Reviews	Chapman et al. (1984), Miller et al. (1994, 2000), Alexander and Blaser (2002)
PA	McKinley (1989b), McKinley et al. (1989, 1992), McKinley und Alexander (1992), Alexander und McKinley (1999), EN2002 (ongoing)
Archaeology	EWI (1983), Alexander and Miller (1994)
Mensenschwand	Hofmann (1989), Degueldre et al. (1996)
Poços de Caldas	Chapman et al. (1991, 1993), MacKenzie et al. (1991)
Oman	Bath et al (1987), McKinley (1987c,d)
Jordan	Alexander (1992), Linklater (1998), Smellie (1998)
Redox systems 1992)	Hofmann et al. (1987), Cross et al. (1991, 1992)
Matrix diffusion	Smellie et al. (1985), Alexander et al. (1987), Mazurek et al. (1996)
Glass	Jercinovic und Ewing (1988)
Colloids	Miekeley et al. (1989), McCarthy and Degueldre (1993), Wetton et al., 1998
BPM (Blind Predictive Modelling)	Bath et al. (1987), Alexander et al. (1992), Pate et al. (1994)
Retardation	McKinley and Alexander (1992, 1993, 1996), Alexander et al., 2002
Microbiology	McKinley et al. (1997), West et al. (1991, 1995, 2002)
PR	Chapman und McKinley (1990), Güntensperger (1993), McKinley and Tsuboya (2001), West et al. (2001)

Listed below are the numerous papers, reports, books and newspaper and magazine articles (plus a video) produced under the auspices of Nagra's natural analogue programme. A wide range of subjects and issues have been dealt with and, to ensure complete coverage, papers which deal only in part with natural analogues have also been included *in italics*.

Books:

W.R.Alexander and I.G.McKinley (1999) The chemical basis of near-field containment in the Swiss high-level radioactive waste disposal concept. *in* Chemical containment of wastes in the geosphere (ed R.Metcalf and C.A.Rochelle), Geol.Soc.Spec.Publ. No. 157, 47-69.

Chapman, N.A. and I.G. McKinley (1987), The Geological Disposal of Nuclear Waste; John Wiley and Sons. 280 p.

Chapman, N.A., I.G. McKinley, M.E. Shea and J.A.T. Smellie (Editors, 1993), The Poços de Caldas project: natural analogues of processes in a radioactive waste repository; Elsevier, Amsterdam, (also printed in the Journal of Geochemical Exploration, Vol. 45, Nos. 1-3): contains 20 papers on the Poços de Caldas project.

Miller, W.M., W.R. Alexander, N.A. Chapman, I.G. McKinley and J.A.T. Smellie (1994), Natural analogue studies in the geological disposal of radioactive wastes; Studies in Environmental Sciences 57, Elsevier, Amsterdam (also Nagra Technical Report NTB 93-03).

W.M.Miller, W.R.Alexander, N.A.Chapman, I.G.McKinley and J.A.T.Smellie (2000) The geological disposal of radioactive waste and natural analogues: lessons from nature and archaeology. Waste management series, vol. 2, Pergamon, Amsterdam, The Netherlands.¹

J.M.West, I.G.McKinley and S.Stroess-Gascoyne (2002) Microbial effects on waste repository materials. Ch. 9 in M.J.Keith-Roach and F.R.Livens (eds), Interactions of micro-organisms with radionuclides. Radioactivity in the Environment, Vol. 2 Elsevier, Amsterdam, The Netherlands.

W.R.Alexander, P.A.Smith and I.G.McKinley (2003). Modelling radionuclide transport in the geological environment: a case study from the field of radioactive waste disposal. Ch.5 in E.M.Scott (ed), Modelling Radioactivity in the Environment, Elsevier, Amsterdam, The Netherlands (in press).

Papers, technical reports and newspaper/magazine articles:

Alexander, W.R. (1992), (ed), A natural analogue study of cement-buffered, hyperalkaline groundwaters and their interaction with a sedimentary host rock - I: Source-term description and geochemical code database validation; Nagra Technical Report NTB 91-10. Nagra, Wettingen, Switzerland.

¹ This and the 1994 edition can both be downloaded free-of-charge at <http://pdfmojo.net/search.php?title=Geological+disposal+of+radioactive+wastes+and+natural+analogues>

Alexander, W.R. (1993), Assessment of conservative matrix diffusion depths (in crystalline rock) via studies of natural systems (a support document for the Kristallin- 1 safety assessment) in U.Frick, Beurteilung der Diffusion im Grundwasser von Kristallingesteinen. Nagra Unpublished Internal Report, Nagra, Wettingen.

Alexander, W.R. (1995), Natural cements: How can they help us safely dispose of radioactive waste?. Radwaste Magazine 2, vol 5, Sept. 1995, pp61-69.

Alexander, W.R. and T.Shimmiel (1990), Microwave oven dissolution of geological materials: implications for natural decay series analyses. J. Radioanal. Nucl. Chem. Lett. 145, pp301-310.

W.R.Alexander and I.G.McKinley (1990) Natural analogues in performance assessment: improving models of radionuclide transport in groundwaters by studying the natural environment. CEC Report EUR13014EN, Brussels.

Alexander, W.R. and I.G. McKinley (1992), A review of the application of natural analogues in performance assessment: improving models of radionuclide transport in groundwaters; in N.A. Chapman, I.G. McKinley, M.E. Shea, J.A.T. Smellie (Editors), The Poços de Caldas Project: Natural Analogues of Processes in a Radioactive Waste Repository. J. Geochem. Explor. 46, 1992, pp. 83-115.

Alexander, W.R. and I.G. McKinley (1992), Natural analogues in performance assessment: Improving models of radionuclide transport in groundwaters by studying the natural environment; in Fourth natural analogue working group meeting (NAWG) and Poços de Caldas project final workshop, EUR 13014 EN, Pitlochry, Scotland, 18 to 22 June 1990.

Alexander, W.R. and I.G. McKinley (eds, 1993), Technical workshop on hyperalkaline plumes associated with cementitious radwaste repositories; February 1993, Nagra Unpublished Internal Report, Nagra, Wettingen.

Alexander, W.R. and I.G.McKinley (1994), Constraints on the use of "in situ distribution coefficients (Kd)" values in contaminant transport modelling. Eclogae geol. Helv. 87/2, pp 321-324 (extended abstract).

Alexander, W.R. and W.M.Miller (1994), Natural analogues of bituminous waste - are there any? Fourth Inter. Conf. Chem. Migration Behaviour Actinides and Fission Products, Charleston, USA, 12-17/12/93, pp559-563.

Alexander, W.R. and M.Mazurek (1996), The Maqarin natural analogue: possible implications for the performance of a cementitious repository at Wellenberg. Nagra Unpublished Internal Report, Nagra, Wettingen.

W.R.Alexander and J.A.T.Smellie (1997) The Maqarin natural analogue project: an overview. Proc. 7th NAWG Workshop, Stein am Rhein, Sept. 1996. CEC EUR Report EN 18734

W.R.Alexander and J.A.T.Smellie (1998) Maqarin natural analogue project: synthesis report on Phases I, II and III. Nagra Unpublished Project Report, Nagra, Wettingen, Switzerland.

Alexander, W.R. and Blaser, P.C. (eds) (2002) The use of technical natural analogues in radioactive waste disposal. Nagra Unpublished Project Report, Nagra, Wettingen, Switzerland.

Alexander, W.R., R.D. Scott, A.B. MacKenzie and I.G. McKinley (1987), Natural analogue studies at Grimsel, Southern Switzerland; in Natural Analogues in Radioactive Waste Disposal, CEC Report EUR 11037 EN, Commission of the European Communities, Brussel.

Alexander, W.R., R.D. Scott, A.B. MacKenzie and I.G. McKinley (1988), A Natural Analogue Study of Radionuclide Migration in a Water Conducting Fracture in Crystalline Rock; *Radiochim Acta* 44/45, pp.283-289.

Alexander, W.R., A.B. MacKenzie, R.D. Scott and I.G. McKinley (1990), Natural Analogue Studies in Crystalline Rock: Influence of Water Bearing Fractures on Radionuclide Immobilization in a Granitic Repository; Nagra Technical Report NTB 87-08, Nagra, Baden, Switzerland.

Alexander, W.R., I.G. McKinley, A.B. MacKenzie and R.D. Scott (1990), Verification of matrix diffusion by means of natural decay series disequilibria in a profile across a water conducting fracture in granitic rock; *Sci. Basis Nucl. Waste Manag.* XIII, pp.567-576.

Alexander, W.R., U. Frick, A. Gautschi and I.G. McKinley (1990), Natural analogue studies in the radioactive waste research programme of Switzerland (status 1990 and bibliography); in Fourth natural analogue working group meeting (NAWG) and Poços de Caldas project final workshop, EUR 13014 EN, Pitlochry, Scotland, 18 to 22 June 1990.

Alexander, W.R., R. Dayal, L. Eagleson, J. Eikenberg, E. Hamilton, C.M. Linklater, I.G. McKinley and C.J. Tweed (1992), A natural analogue of high pH cement pore waters from the Maqarin area of Northern Jordan. II: results of predictive geochemical calculations; in N.A. Chapman, I.G. McKinley, M.E. Shea and J.A.T. Smellie (Editors). *J. Geochem. Explor.* 46, 1992, pp. 133-146.

Alexander, W.R., A.E. Milodowski, H.N. Khoury and E. Salameh (1995) Why go to Jordan to worry about Wellenberg? A study of the interaction between cement derived hyperalkaline water and sedimentary rocks. Abstract *in* *Schweiz. Miner. Petr. Mitt.* 75, pp 467-468.

Alexander, W.R., A. Gautschi and I.G. McKinley (1996) Overview of the Swiss natural analogue programme 1994. Proc. 6th NAWG Workshop, Santa Fe, Sept. 1994. CEC EUR Report EN16761.

Alexander, W.R., J.A.T. Smellie and I. Crossland (1996), Potential effects of hyperalkaline leachates on cementitious repository host rocks: an example from northern Jordan. Extended abstract, Proc. Chem. Containment Waste, BGS, 3-4 Sept., 1996, BGS, Keyworth, UK.

W.R. Alexander, A. Gautschi and P. Zuidema (1998) Thorough testing of performance assessment models: the necessary integration of in situ experiments, natural analogues and laboratory work. Abstract *in* *Sci. Basis Nucl. Waste Manag.* XXI, 1013-1014.

W.R. Alexander, K. Ando, A. Shimmura, W. Miller, J. West and H. Kawamura (2001) Using natural analogues in public communication. Poster presented at Earth Systems Conference, Edinburgh, June, 2001

W.R.Alexander, R.Bros, T.Iwatsuki, G.Kamei, A.B.MacKenzie, W.M.Miller, K.Ota, M.Shiotsuki, J.A.T.Smellie and M.Yui (2001) Nagra-JNC Bilateral Programme: March 2001 Tokai Workshop Series 3. JNC Natural Analogue Programme Review (and associated field trip), 6th & 7th March, 2001. Nagra Unpublished Project Report NPB 01-12, Nagra, Wettingen.

W.R.Alexander, N.A.Chapman, I.G.McKinley, F.B.Neall and J.A.T.Smellie (2002) The use of technical natural analogues in radioactive waste disposal Nagra Unpublished Project Report NPB 02-03, Nagra, Wettingen.

Baertschi, P. (1995), Radiation risk from a HLW repository compared with other risks. Nagra Bulletin No. 25, March, 1995. Nagra, Wettingen

Baertschi, P., W.R. Alexander and H. Dollinger (1991), Uranium migration in crystalline rocks: capillary solution transport in the granite of the Grimsel Test Site; Nagra Technical Report NTB 90-15, Nagra, Baden, Switzerland.

Bath A., M. Cave, U. Berner, I.G. McKinley and C. Neal (1987), Testing geochemical models in a hyperalkaline environment; in Natural Analogues in Radioactive Waste Disposal, CEC Report EUR 11037 EN, Commission of European Communities, Brussels.

Bath, A.H., N. Christofi, C. Neal, J.C. Philp, M.R. Cave, I.G. McKinley and U.Berner (1988), Trace Element and Microbiological Studies of Alkaline Groundwaters in Oman, Arabian Gulf: A Natural Analogue for Cement Pore Waters; Nagra Technical Report NTB 87-16, Nagra, Baden, Switzerland.

Bruno, J., J.E. Cross, J. Eikenberg, I.G. McKinley, D. Read, A. Sandino and P. Sellin (1991), Poços de Caldas Report No. 11: Testing of geochemical models in the Poços de Caldas analogue study; January 1991, Nagra Technical Report NTB 90-29. Also published as SKB TR 90-20 and UK-DOE WR 90-051.

Cathles, L.M. and M.E. Shea (1991), Poços de Caldas Report No. 13: Near-field high-temperature transport: Evidence from the genesis of the Osamu Utsumi uranium mine, Poços de Caldas alkaline complex, Brazil; January 1991, Nagra Technical Report NTB 90-31. Also published as SKB TR 90-22 and UK-DOE WR 90-053.

Chapman, N.A. and I.G. McKinley (1990), Radioactive waste: back to the future? *New Scientist* 5 May, pp. 54-58, also *Atom* no. 408, pp. 22-26.

Chapman, N.A., I.G. McKinley and J.A.T. Smellie (1984), The Potential of Natural Analogues in Assessing Systems for Deep Disposal of High-Level Radioactive Waste; Nagra Technical Report NTB 85-41, Nagra, Baden, Switzerland. Also published as EIR Bericht Nr.545, Federal Institute for Reactor Research, Würenlingen, Switzerland and KBS Technical Report 84-16, SKB Swedish Nuclear Fuel and Waste Management Co, Stockholm, Sweden.

Chapman, N.A., I.G. McKinley, M.E. Shea and J.A.T. Smellie (1991), Poços de Caldas Report No. 15: Summary and implications for radioactive waste management; January 1991, Nagra Technical Report NTB 90-33. Also published as SKB TR 90-24 and UK-DOE WR 90-055

Chapman, N.A., I.G. McKinley, M.E. Shea and J.A.T. Smellie (1993), Poços de Caldas: nature`s experiment. Nagra Bulletin 1/1993

Coombs, P., S.J.Gardner, C.A.Rochelle and J.M.West Microbial processes under hyperalkaline conditions - results from Phase III of the Maqarin natural analogue study. Nagra Unpublished Internal Report, Nagra, Wettingen, Switzerland.

Cross, J.E., A. Haworth, P.C. Lichtner, A.B. MacKenzie, L. Moreno, I. Neretnieks. D.K. Nordstrom, D. Read, L. Romero, R.D. Scott, S.M. Sharland and C.J. Tweed (1991), Poços de Caldas Report No.12: Testing models of redox front migration and geochemistry at the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil; January 1991, Nagra Technical Report NTB 90-30. Also published as SKB TR 90-21 and UK-DOE WR 90-052.

Cross J.E., Gabriel D.S., Haworth A., Neretnieks I., Sharland S.M. and Tweed C.J. (1992) Modelling of Redox Front and Uranium Movement in a Uranium Mine at Poços de Caldas, Brazil. - *Radiochimica Acta*, 52/53, p. 445-451.

Dearlove, J.P.L. (1989), Analogue studies in natural rock systems: Uranium series radionuclide and REE distribution and transport; unpubl. Ph.D Thesis, Cambridgeshire College of Arts and Technology, May 1989.

Dearlove, J.P.L., D.C. Green and M. Ivanovich (1988), Uranium transport and the partitioning of U, Th, and Ra isotopes between solid and aqueous phases; *Sci. Basis Nucl. Waste Manag.* XII, pp.927-932.

Dearlove, J.P.L., M. Ivanovich and D.C. Green (1989), Partition coefficients (Rd) for the U-series radionuclides in ion exchange sites and amorphous Fe phase in illite and granite samples; in *Proceedings of the 6th Water-Rock Interaction Conference (WRI-6)*, Malvern, August 1989, pp.191-195.

Deguedre, C., H.-R.Pfeiffer, W.R.Alexander, B.Wernli and R.Bruetsch (1996), Colloid properties in granitic groundwater systems. I: sampling and characterisation. *Appl. Geochem.* 11, pp677-695.

Eikenberg, J. and P.C. Lichtner (1992), Propagation of hyperalkaline cement pore waters into the geologic barrier surrounding a radioactive waste repository, in Proceedings of the 7th international symposium on water-rock interaction - WRI-7, Park City, Utah, 13-18 July 1992. Edited by Y.K. Kharaka and A.S. Maest.

EWI (1983), Bitumen, ein Verfestigungsmaterial für radioaktive Abfälle und seine historischen Analoga. Nagra Technical Report NTB 83-11, Nagra, Baden, Switzerland.

Frick, U., P. Baertschi and E. Hoehn (1988), Migration Experiment; Nagra Bulletin, special issue on the Grimsel Test Site 1988.

Gautschi, A. (2002). Self-sealing Faults in the Opalinus Clay - Evidence from Field Observations, Hydraulic Testing and Pore water Chemistry. Proceedings of the self-healing topical session of the IGSC Working Group on Measurement and Physical Understanding of Groundwater Flow through Argillaceous Media (Clay Club). NEA/OECD, NEA, Paris, France.

Güntensperger, M. (1993), International Video Project on Natural Analogues, EMS PIME '93, Karlovy Vary, 31.1.-3.2.93.

Hadermann, J., H.R. von Gunten, C. McCombie and I.G. McKinley (1988), Radionuclide migration in the geosphere - Swiss research activities in laboratory and field experiments and in model validation; Rad. Waste Manag. Nuc.Fuel Cycle 10, pp.233-255.

Heitz, E. and D. Zur Megede (1982), Korrosionsverhalten von unlegiertem Stahl, Stahlguss und Gusseisen als Endlagerbehälter-werkstoff in wasserführendem Granit Gestein. Nagra Technical Report NTB 82-08, Nagra, Baden, Switzerland.

Herzog, F.(1987), Modelling isotope distributions in borecores; Natural Analogues in Radioactive Waste Disposal, CEC Report EUR11037EN, Commission of the European Communities, Brussels.

Hofmann, B.A. (1986), Small-scale multi-element accumulations in Permian red-beds of Northern Switzerland; N Jb. Mineral. (Mh.) 1986, pp.367-375.

Hofmann, B.A. (1987), Geochemical analogue study in the Krunkelbach mine, Menzenschwand, Southern Germany: geology and water-rock interaction; Sci. Basis Nucl. Waste Manag. XII, pp.921-926.

Hofmann, B.A. (1989), Genese, Alteration und rezentes Fliess-System der Uranlagerstätte Krunkelbach (Menzenschwand, Südschwarzwald); Dissertation Universität Bern, und Nagra Technischer Bericht NTB 89-30, Nagra, Baden, Switzerland.

Hofmann, B.A. (1990), Reduction spheroids from Northern Switzerland: mineralogy, geochemistry and genetic models; Chem. Geol. 81 PP.55-81.

Hofmann, B.A. (1990), Reduction Spheres in Hematitic Rocks from Northern Switzerland: Implications for the Mobility of Rare Earth Elements; Nagra Technical Report NTB 89-17, Nagra, Baden, Switzerland.

Hofmann, B.A. (1991), An uranium series disequilibrium investigation of reduction spheroids in red beds; Schweiz. Mineral. Petrogr. Mitt. 71, 1991, pp. 333-340.

Hofmann, B.A. (1992), Isolated reduction phenomena in red beds: A result of porewater radiolysis?; in Proceedings of the 7th International Symposium on Water-Rock Interaction - WRI-7, Park City, Utah, USA, 13-18 July 1992, edited by Y.K. Kharaka and A.S. Maest.

Hofmann, B.A. (1993), Element mobilisation/immobilisation across redox gradients in red bed sediments. Extended abstract, EUG (Strasbourg), 1993.

Hofmann, B.A. (1996), Radiolysis in nature and natural analogue studies of radiolytical processes. Proc. 6th NAWG Workshop, Santa Fe, Sept. 1994. CEC EUR Report EN16761.

Hofmann, B.A. (1999), Geochemistry of natural redox fronts - a review. Nagra Technical Report 99-05, Nagra, Wettingen, Switzerland.

Hofmann, B.A., J.P.L. Dearlove, M. Ivanovich, D.A. Lever, D.C. Green, P. Baertschi and Tj. Peters (1987), Evidence of fossil and recent diffusive element migration in reduction haloes from Permian red-beds of Northern Switzerland; in Natural Analogues in Radioactive Waste Disposal, CEC Report EUR 11037 EN, pp.217-238, Commission of European Communities, Brussels.

Hofmann, B.A., J.O.Nyström and U.Krähenbühl (1996), The Ordovician chondrite from Brunflo, central Sweden, III: geochemistry of terrestrial alteration.

Holmes, D.C., A.E. Pitty and D.J. Noy (1991), Poços de Caldas Report No. 5: Geomorphological and hydrogeological features of the Poços de Caldas caldera and the Osamu Utsumi mine and Morro do Ferro analogue study sites, Brazil; January 1991, Nagra Technical Report NTB 90-23. Also published as SKB TR 90-14 and UK-DOE WR 90-045.

Ivanovich M. and M.A. Wilkins (1984), Harwell report on the Analysis of Nagra groundwater samples from deep boreholes: uranium series disequilibrium measurements; AERE Report G3135, UKAEA, Harwell, UK.

Ivanovich M. and M.A. Wilkins (1984), Harwell report on the Analysis of Nagra rock and fracture infilling samples from the Böttstein core: uranium series disequilibrium measurements; AERE Report G 33171, UKAEA, Harwell, UK.

Ivanovich, M., M.A. Wilkins and J.P.L. Dearlove (1986), Analysis of uranium disequilibrium data in Nagra's deep borehole solid and liquid samples; AERE Report 12482, UKAEA, Harwell, UK.

Ivanovich, M., J.P.L. Dearlove and D.A. Lever (1986), Uranium series disequilibrium profiles from reduction haloes in Permian red-beds of Northern Switzerland ; AERE - G 4194 and AERE - R 12483, UKAEA, Harwell, UK.

Jercinovic, M.J. and R.C. Ewing (1988), Basaltic glasses from Iceland and the deep sea: natural analogues to borosilicate nuclear waste form glasses. JSS report 88-01.

Khoury, H.N., E. Salameh, I.D. Clark, P. Fritz, W. Bajjali, A.E. Milodowski, M.R. Cave and W.R. Alexander (1992), A natural analogue of high pH cement pore waters from the Maqarin area of northern Jordan. I: introduction to the site; J. Geochem. Explor. 46, 1992, pp. 117-132.

Linklater, C.M. (1998) (*ed*), A natural analogue study of cement-buffered, hyperalkaline groundwaters and their interaction with a repository host rock. Phase II. Nirex Science Studies Report S/98/003, Nirex, Harwell, UK.

Linklater, C.M., C.J. Tweed, E. Hamilton, I.G. McKinley, J. Eikenberg, R. Dayal and K. Eagleson (1991), Predictive modelling of the geochemistry of hyperalkaline

groundwater in the Maqarin area, Jordan; in Fourth natural analogue working group meeting (NAWG) and Poços de Caldas project final workshop, EUR 13014 EN, Pitlochry, Scotland, 18 to 22 June 1990.

Linklater, C.M., Y.Albinsson, W.R.Alexander, I.Casas, I.G.McKinley and P.Sellin (1996), A natural analogue of high pH cement pore waters from the Maqarin area of northern Jordan: comparison of predicted and observed trace element chemistry of uranium and selenium. *J.Contam. Hydrol.* 21, pp 59-69.

MacKenzie, A.B., R.D. Scott, P. Linslata, N. Miekeley, J.K. Osmond and D.B. Curtis (1991), Poços de Caldas Report No. 7: Natural radionuclide and stable element studies of rock samples from the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil; Janaury 1991, Nagra Technical Report NTB 90-25. Also published as SKB TR 90-16 and UK-DOE WR 90-047.

McCarthy, J.F. and C. Degueldre (1993), Sampling and characterization of colloids and particles in ground water for studying their role in contaminant transport; in Environmental Particles, H.P. van Leeuwen and J. Buffle, Eds., IUPAC Environmental Analytical and Physical Chemistry Series, Vol. II, in press.

McCombie, C. (1991), Critical uncertainties in safety assessments and how to address them; in Fourth natural analogue working group meeting (NAWG) and Poços de Caldas project final workshop, EUR 13014 EN, Pitlochry, Scotland, 18 to 22 June 1990.

McCombie, C., P. Zuidema and I.G. McKinley (1991), Sufficient validation: The value of robustness in performance assessment and system design. Validation of geosphere flow and transport models (Geoval), OECD, Paris, pp. 598-610.

McCombie, C. and I.G.McKinley (1995), Natural analogues: confidence-building tools for HLW repositories. *Radwaste Magazine*, 2, vol 1, pp27-31.

McKinley, I.G. (1986), Applications of analogues in near-field geochemistry; in Proceedings of the 1st Meeting of the Natural Analogue Working Group in Brussels, November 5-7, 1985; CEC Report EUR 10315, pp.76-85, Commission of the European Communities, Brussels.

McKinley, I.G. (1987), A review of Swiss natural analogue studies; CEC Report EUR 10671, pp.89-92, Commission of the European Communities, Brussels.

McKinley, I.G. (1987), Das Poços de Caldas Projekt, EIR Bulletin 62, pp. 24-26, Federal Institute for Reactor Research, Würenlingen, Switzerland.

McKinley, I.G. (1987), Natürliche Analoga - ihre Bedeutung für die nukleare Entsorgung; EIR Bulletin 63, pp.35-39, Federal Institute for Reactor Research, Würenlingen, Switzerland.

McKinley, I.G. (1987), Natürliche Analoga in Oman; in Nagra Informiert 3/87 (September 1987, 9.,Jahrgang), pp.38-42; Nagra Baden, Switzerland.

McKinley, I.G. (1989), Applying natural analogues in predictive performance assessment; Nagra Internal Report 89-02, Nagra, Baden, Switzerland.

McKinley, I.G. (1989), Applying natural analogues in predictive performance assessment (1): principles and requirements; (2): examples and discussions; in Risk analysis in nuclear waste management, pp.357-396, Kluwer Academic Publ., Netherlands.

McKinley, I.G. (1993), The role of natural analogues in nuclear waste repository performance assessment with particular emphasis on experience in Switzerland. Reliability Engineering and System Safety, 42, pp233-246.

McKinley, I.G. (1995), Poços de Caldas: testing models of radionuclide transport processes. Radwaste Magazine, 2, vol 4, pp34-38.

McKinley, I.G. and H.A. Grogan (1987), Natural analogues support for geomicrobiological modelling; CEC Report EUR 10671, pp153-159, Commission of the European Communities, Brussels.

McKinley, I.G., Berner, U. and Wanner, H. (1987). Predictions of radionuclide chemistry in a highly alkaline environment; PTB-SE-14, pp.77-89.

McKinley, I.G., Bath, A.H., Berner, U., Cave, M. and Neal, C. (1988). Results of the Oman analogue study. Radiochim Acta 44/45, 311-316

McKinley, I.G. and U. Frick (1989), Swiss natural analogue research; in Proc. 3rd CEC Meeting of the Natural Analogue Working Group NA WG, EUR 11725, pp.104-109, Commission of the European Communities, Brussels.

McKinley, I.G. and W.R.Alexander (eds.) (1991), An overview of the potential perturbations of the far field by high pH leachate from a cementitious L/ILW repository. Nagra Unpublished Internal Report, Nagra, Wettingen.

McKinley, I.G. and W.R. Alexander (1992), Use of Natural Analogues to test performance assessment models of a cementitious near field; Waste Manag. 12, pp. 253-259.

McKinley, I.G. and W.R. Alexander (1992), Constraints on the Applicability of 'In-Situ Distribution Coefficient' Values; accepted 5 January, 1991, J. Environ. Radioactivity 15, pp. 19-34.

McKinley, I.G. and W.R. Alexander (1993), Assessment of radionuclide retardation: Uses and abuses of natural analogue studies; J. Contamin. Hydrol., 13, pp249-259 (plus comments, pp260-270, and reply to comments, pp271-275).

McKinley, I.G. and C.McCombie (1995), Natural analogues: a look into the future. Radwaste Magazine, 2, vol 6, p46.

McKinley, I.G. and W.R.Alexander (1996), The uses of natural analogue input in repository performance assessment: an overview. Proc. 6th NAWG Workshop, Santa Fe, Sept. 1994. CEC EUR Report EN16761, pp273-282.

McKinley, I.G. and W.R.Alexander (1996), On the incorrect derivation and use of in situ retardation factors from natural isotope profiles. Radiochim Acta 74, pp 263-267.

McKinley, I.G. and W.R.Alexander (2002) Integration of TRU disposal studies in Switzerland. Waste Management 2002, Tucson, Arizona, USA (*submitted*).

McKinley, I.G., U. Berner and H. Wanner (1987), Predictions of radionuclide chemistry in a highly alkaline environment; PTB-SE-14, pp.77-89.

McKinley, I.G., W.R. Alexander, C. Bajo, U. Frick, J. Hadermann, F. Herzog and E. Hoehn (1988), The radionuclide migration experiment at the Grimsel Rock Laboratory, Switzerland; Sci. Basis Nucl. Waste Manag. XI, pp.179-187.

McKinley, I.G., A.Bath, U. Berner, M. Cave and C. Neil (1988), Results of the Oman analogue study; Radiochim Acta 44/45, pp.311-316.

McKinley, I.G., C. McCombie and P. Zuidema (1989), Applications of natural analogues in Swiss safety analysis; in Proc. 3rd CEC Meeting of the Natural Analogue Working Group NAWG, CEC Report EUR 11725, pp.174-180, Commission of the European Communities, Brussels.

McKinley, I.G., W.R. Alexander, C. McCombie and P.Zuidema (1992), Application of results from the Poços de Caldas Project in the Kristallin-I HLW performance assessment; in Proceedings of the International Conference of High-Level Radioactive Waste Management in Las Vegas, April 12-16, 1992, pp357-361.

McKinley, I.G., A.Scholtis and W.R.Alexander (1994), The Nagra thermodynamic database: compilation, testing and application. Proc. Inter. Conf. Geological Disposal Rad. Waste, Tokai, November,1993. PNC Report, PNC, Tokyo.

I.G.McKinley, I.Hagenlocher, W.R.Alexander and B.Schwyn (1997) Microbiology in nuclear waste disposal: interfaces and reaction fronts. FEMS Microbiol.Rev. 20, pp545-556.

I.G.McKinley, W.R.Alexander, A.Gautschi and H.N.Waber (1998) An approach to validation of solubility databases for performance assessment. Radiochim Acta 82, 407-412

McKie, D.M., Mäder, U., Alexander, W.R., McKinley, I.G., Yoshida, H. and Ota, K. (1997), Development of a mechanistic model to interpret natural decay series disequilibrium data. 7th Meeting of the Natural Analogue Working Group, Stein am Rhein, CEC Report EUR 18734, pp.35-37, Commission of the European Communities, Brussels.

Mazurek, M. (1990), Geochemical study of oxidation effects in Opalinus Clay from the Siblingen clay pit. Nagra Internal Report, Nagra, Wettingen, Switzerland.

Mazurek, M., W.R.Alexander and A.B.MacKenzie (1996), Contaminant retardation in fractured shales: matrix diffusion and redox front entrapment. J.Contam. Hydrol. 21, pp 71-84.

Miekeley N., Jesus H.C., Silveira C.L.P. and Kuechler I.L. (1989) Colloid investigations in the Pocos de Caldas natural analogue project. Scientific Basis for Nuclear Waste Management XII, Berlin, 1988. Materials Research Society, p. 831-842.

Miekeley, N., H. Coutinho de Jesus, C.L. Porto da Silveira, P. Linslata, R. Morse and K. Osmond (1991), Poços de Caldas Report No. 8: Natural series radionuclide and rare-earth element geochemistry of waters from the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil; January 1991, Nagra Technical Report NTB 90-26. Also published as SKB TR 90-17 and UK-DOE WR 90-048.

Miekeley, N., H. Coutinho de Jesus, C.L. Porto da Silveira and C. Degueldre (1991), Poços de Caldas Report No. 9: Chemical and physical characterisation of suspended particles and colloids in waters from the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil; January 1991, Nagra Technical Report NTB 90-27. Also published as SKB TR 90-18 and UK-DOE WR 90-049.

Miller, W.M., W.R. Alexander, N.A. Chapman, I.G. McKinley and J.A.T. Smellie (1994), Natural analogues revisited. Proc. Fourth Inter. Conf. Chem. Migration Behaviour Actinides and Fission Products, Charleston, USA, 12-17/12/93, pp559-563.

Milodowski, A.E., J.M. Pearce, C.R. Hughes and H.N. Khoury (1992), A preliminary mineralogical investigation of a natural hyperalkaline groundwater interaction with marl, Maqarin, Northern Jordan; June 1992, Nagra Internal Report, Nagra, Wettingen, Switzerland.

Müller-Vonmoos, M. and G. Kahr (1985), Langzeitstabilität von Bentonit unter Endlagerbedingungen; Nagra Technischer Bericht NTB 85-25, Nagra, Wettingen,, Switzerland.

Nagra (1994). Kristallin-1. Safety assessment report. Nagra Technical Report Series NTB 93-22, Nagra, Wettingen, Switzerland.

Nagra (1997). Geosynthese Wellenberg 1996 – Ergebnisse der Untersuchungsphasen I und II. Nagra Technical Report NTB 96-01, Nagra, Wettingen, Switzerland (*in German*).

Nagra (2002a). Projekt Opalinuston, Entsorgungsnachweis für abgebrannte Brennelemente, verglaste hochaktive sowie langlebige mittelaktive Abfälle. Synthese der geowissenschaftlichen Untersuchungsergebnisse. Nagra Technical Report NTB 02-03, Nagra, Wettingen, Switzerland (*in German*).

Nagra (2002b). Project Opalinus Clay, Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis). Safety Report. Nagra Technical Report NTB 02-05, Nagra, Wettingen, Switzerland.

F. Neall and W.R.Alexander (1999). Examination of the potential effects of cement leaching on radioactive waste containment in a cementitious repository: overview report. Nagra Unpublished Project Report, Nagra, Wettingen, Switzerland.

Neall, F., P-Baertschi, I.G.McKinley, P.Smith, T.Sumerling and H.Umeki (1994), Kristallin-1: results in perspective. Nagra Technical Report NTB 93-23, Nagra, Wettingen.

Neall, F., P-Baertschi, I.G.McKinley, P.Smith, T.Sumerling and H.Umeki (1995), Putting HLW performance assessment results in perspective. Sci. Basis Nucl. Waste Manag. XVIII, pp503-510

Nordstrom, D.K., J.A.T. Smellie and M. Wolf (1991), Poços de Caldas Report No. 6: Chemical and isotopic composition of groundwaters and their seasonal variability at the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil; January 1991, Nagra Technical Report NTB 90-24. Also published as SKB TR 90-15 and UK-DOE WR 90-046

Nordstrom, D.K., I. Puigdomènech and R.H. McNutt (1991), Poços de Caldas Report No. 14: Geochemical modelling of water-rock interactions at the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil; January 1991, Nagra Technical Report NTB 90-32. Also published as SKB TR 90-23 and UK-DOE WR 90-054.

Pate, S.M., I.G. McKinley and W.R. Alexander (1994), Use of natural analogue test cases to evaluate a new performance assessment TDB; in Proceedings of the 5th NAWG workshop, Toledo, Spain, September 1992. Eds. H. von Maravic and J.A.T. Smellie. CEC Report EUR 15176 EN, pp321-331.

Pearce, J.M., W.R.Alexander, P.D.Wetton and A.E.Milodowski (1996), A natural analogue study of the Maqarin hyperalkaline groundwaters: interim report on the production of colloids at the cement/host rock interface. Nagra Unpublished Internal Report, Nagra, Wetingen, Switzerland.

Romero L., Moreno L. and Neretnieks I. (1991) Modelling of the large scale redox front evolution in an open pit uranium mine in Pocos de Caldas, Brazil. - GEOVAL 90: Symposium on Validation of Geosphere Flow and Transport Models. Stockholm (Sweden), 14-17 May 1990, Nuclear Energy Agency, Paris, 1991, p. 131-138.

Santschi, P.M., C. Bajo, M. Mantovani, D. Orciuolo, R.E. Cranston and J. Bruno (1988), Uranium in pore waters from North Atlantic (GME and Southern Nares Abyssal Plain) Sediments; Nature 331 pp.155-157.

Schorscher, H.D. and M.E. Shea (1991), Poços de Caldas Report No. 1: The regional geology, mineralogy and geochemistry of the Poços de Caldas alkaline caldera complex, Minas Gerais, Brazil; January 1991, Nagra Technical Report NTB 90-19. Also published as SKB TR 90-10 and UK-DOE WR 90-041.

Scott, R.D., A.B. MacKenzie and W.R. Alexander (1992), The Interpretation of ^{238}U - ^{234}U - ^{230}Th - ^{226}Ra disequilibria produced by rock-water interactions; in N.A. Chapman, I.G. McKinley, M.E. Shea, J.A.T. Smellie (Editors), The Poços de Caldas Project: Natural Analogues of Processes in a Radioactive Waste Repository. J. Geochem. Explor. 45, 1992, pp. 323-343.

Shea, M.E. (1991), Poços de Caldas Report No. 4: Isotopic geochemical characterization of selected nepheline syenites and phonolites from the Poços de Caldas alkaline complex, Minas Gerais, Brazil; January 1991, Nagra Technical Report NTB 90-22. Also published as SKB TR 90-13 and UK-DOE WR 90-044.

Shin, W.S. (1982), The long-term stability of cement and concrete for nuclear waste disposal under normal geologic conditions; Nagra Technical Report NTB 82-03, Baden, Switzerland.

Smellie, J.A.T. (1998) (*ed*), A natural analogue study of cement-buffered, hyperalkaline groundwaters and their interaction with a repository host rock. Phase III. SKB Report TR 98-04, SKB, Stockholm.

Smellie, J.A.T., A.B. MacKenzie and R.D. Scott (1984), Natural analogues to the conditions around a final repository for high-level radioactive waste; in KBS Technical Report 84-18, SKB, Stockholm, Sweden.

Smellie, J.A.T., A.B. MacKenzie and R.D. Scott (1985), An analogue validation study of natural radionuclide migration in crystalline rocks using uranium series disequilibrium studies; in Proceedings of the 1st Meeting of the Natural Analogue Working Group in Brussels, November 5-7, 1985; CEC Report EUR 10315, pp.76-85, Commission of the European Communities, Brussels.

Smellie, J.A.T., A.B. MacKenzie and R.D. Scott (1985), An analogue validation study of natural radionuclide migration in crystalline rocks using uranium series disequilibrium: preliminary results; *Sci. Basis Nucl. Waste Manag.* IX, pp.91-98.

Smellie, J.A.T., A.B. MacKenzie and R.D. Scott (1986), An Analogue Validation Study of Natural Radionuclide Migration in Crystalline Rocks Using Uranium-Series Disequilibrium Studies; *Chem Geol*, 55, pp.233-254.

Smellie, J.A.T., A.B. MacKenzie and R.D. Scott (1986), I: An Analogue Validation Study of Natural Radionuclide Migration in Crystalline Rocks Using Uranium-Series Disequilibrium Studies, II: A Comparison of Neutron Activation and Alpha Spectroscopy analyses of Thorium in Crystalline Rocks. SKB-Technical Report 01, SKB, Stockholm, Sweden.

Smellie, J.A.T., L. Barroso Magno, Jr, N.A. Chapman, I.G. McKinley and E.P. Franca (1987), The Poços de Caldas project feasibility study 1986-1987; in *Natural Analogues in Radioactive Waste Disposal*, CEC Report EUR 11037 EN, Commission of European Communities, Brussels.

Smellie, J.A.T., L. Barroso Magno Jr., N.A. Chapman, I.G. McKinley, E. Penna Franca and M. Shea (1989), Testing safety assessment models using natural analogues in high natural series groundwaters; *Sci. Basis Nucl. Waste Manag.* XII pp.863-870.

Smellie, J.A.T., F.Karlsson and W.R.Alexander (1997) Natural analogue studies: present status and performance assessment implications. *J.Contam. Hydrol.* 26, pp3-17.

H.von Maravaic and W.R.Alexander (2002) *eds* 8th EC NAWG meeting: proceedings of an international workshop held in Strasbourg, France, from 23-25 March, 1999. EC EUR 19118 EN, Luxembourg.

Waber, H.N. (1990), Hydrothermal and supergene evolution of the Osamu Utsumi uranium deposit and the Morro do Ferro thorium-rare earth deposit (Minas Gerais, Brazil). Unpublished PhD Thesis, University of Berne, Berne.

Waber, H.N. (1991), Poços de Caldas Report No. 3: Mineralogy, petrology and geochemistry of the Poços de Caldas analogue study sites, Minas Gerais, Brazil: II. Morro do Ferro; January 1991, Nagra Technical Report NTB 90-21. Also published as SKB TR 90-12 and UK-DOE WR 90-043.

Waber, H.N. (1994a), Berner Geologen im Einsatz in Brasilien: Metall-Lagerstaetten als Naturalanaloge fuer Abfalldeponien. Unipress 83 (Dezember, 1994), pp28-32. Pressestelle der Universitaet Bern, Bern.

Waber, H.N. (1994b), Geochemische Modellierungen. Unipress 83 (Dezember, 1994), pp33-38. Pressestelle der Universitaet Bern, Bern.

Waber, H.N. and W.R.Alexander (1995) Vom Natur-Zement zum Endlager Beton. Schweiz.Techn.Zeitschrift 12/95, STV-Verlags AG, Zürich, Switzerland.

Waber, N.H., H.D. Schorscher and T. Peters (1991), Poços de Caldas Report No. 2: Mineralogy, petrology and geochemistry of the Poços de Caldas analogue study sites, Minas Gerais, Brazil: I. Osamu Utsumi uranium mine; January 1991, Nagra Technical Report NTB 90-20. Also published as SKB TR 90-11 and UK-DOE WR 90-042.

Wayne, L. (1985), Thorium Mobilization in a Terrestrial Environment. Unpublished Ph.D.Thesis, New York University, 415 p.

West, J.M., I.G. McKinley and A. Vialta. (1989), The influence of microbial activity on the movement of uranium at Osamu Utsumi, Poços de Caldas, Brazil; Sci. Basis Nucl. Waste Manag. XII pp.771-777.

West, J.M., A. Vialta and I.G. McKinley (1991), Poços de Caldas Report No. 10: Microbiological analysis at the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil; January 1991, Nagra Technical Report NTB 90-28. Also published as SKB TR 90-19 and UK-DOE WR 90-050.

West, J.M., P.Coombs, S.J.Gardner and C.A.Rochelle (1995), The microbiology of the Maqarin site, Jordan - a natural analogue for cementitious radioactive waste repositories. Sci.Basis Nucl. waste Manag. XVIII, pp181-188.

J.M.West, W.M.Miller, I.G.McKinley and W.R.Alexander (2001) Confidence building in the Japanese radioactive waste disposal programme: the use of natural analogues. Nagra Unpublished Project Report NPB 01-04, Nagra, Wettingen.

Video:

"Traces of the Future" 55min and 24min versions of an exploration of the uses of natural analogues in waste disposal. Production was co-ordinated by Nagra and co-funded by SKB, Nirex, CEC, USDoE, Ondraf, ENRESA, AECL and Nagra. English master translated into German, French, Japanese, Czech, Chinese, Flemish, Spanish and Swedish.

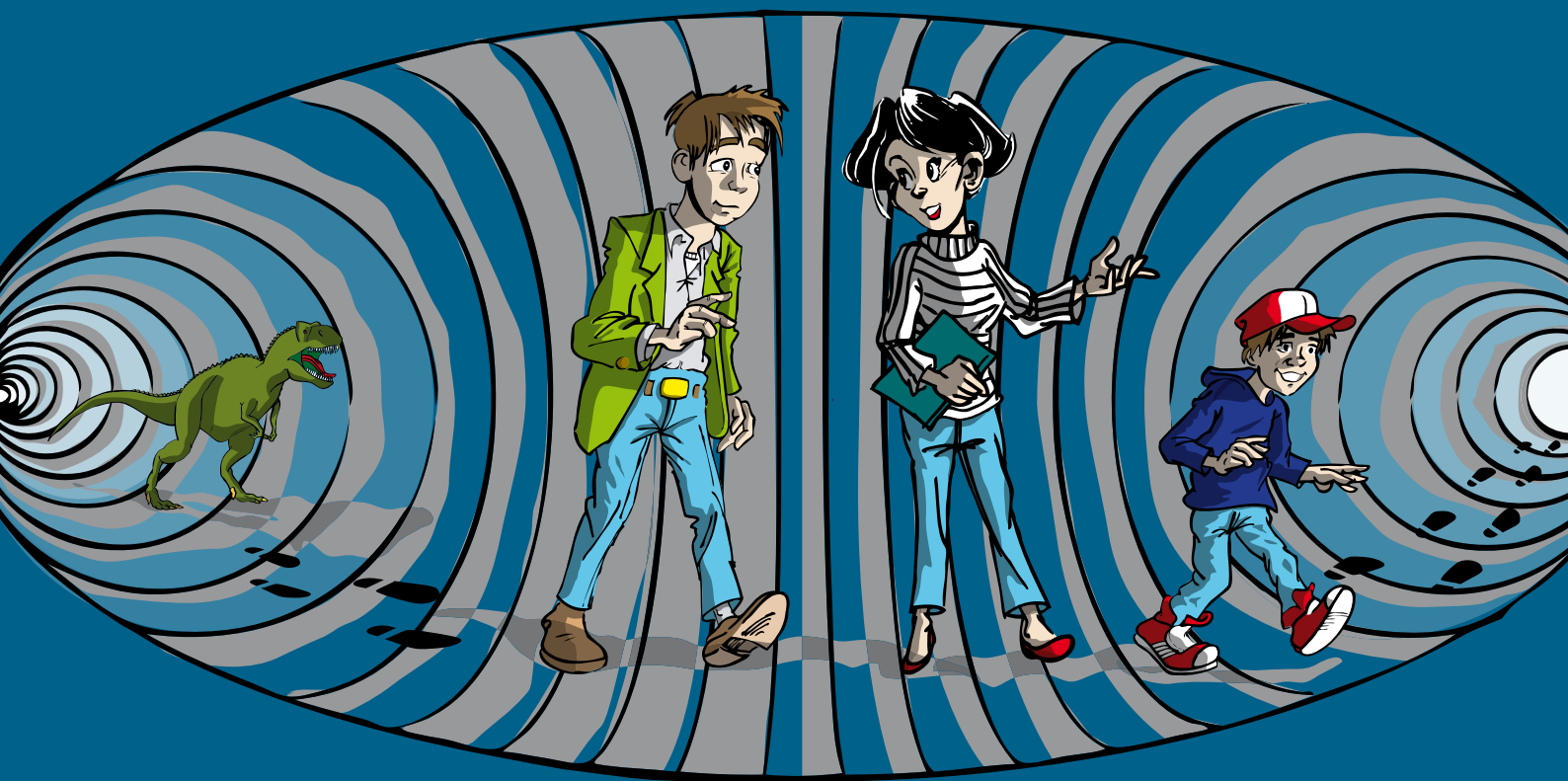
The Czech version of the video was awarded 1st prize in its category at the 34th International Festival of Films and Video Programmes on Science, Technology, Agriculture and the Environment, Hradec Kralove, Czech Republic, 19th October, 1996.

Please note that the short version of the video may be downloaded at <https://www.natural-analogues.com/background/what-are-natural->

[analogues?highlight=WyJ0cmFjZXMiLCJvZiIsInRoZSIsImZ1dHVyZSIsInRyYWNlcyBvZiIsInRyYWNlcyBvZiB0aGUiLCJvZiB0aGUiLCJvZiB0aGUgZnV0dXJlIiwidGhlIGZ1dHVyZSId](#)

spuren der zukunft

**lernen von der natur
für die tiefenlagerung
von radioaktiven
abfällen**



nagra ● aus verantwortung

Zu diesem Heft

Im Hinblick auf die langfristige Sicherheit eines geologischen Tiefenlagers für radioaktive Abfälle können Beobachtungen in der Natur bei der Beurteilung von Laborexperimenten und theoretischen Berechnungen unterstützend wirken. Die in diesem Themenheft beschriebenen Beispiele (Naturanaloge) von natürlichen «Langzeitexperimenten» sollen zeigen, dass es in der Natur Geosysteme, Materialien und Prozesse gibt, deren Stabilität über lange Zeitabschnitte der Vergangenheit untersucht werden kann.

Ein Naturanalogon stellt ein Fallbeispiel dar, das für das jeweilige geologische Umfeld seine Gültigkeit hat und wertvolle Hinweise liefert. Es darf allerdings nicht überbewertet werden.

Die Beispiele in diesem Heft beschränken sich auf Naturanaloge, die sich auf das ganze Lagersystem, die technischen Barrieren oder das Wirtgestein eines geologischen Tiefenlagers für hochaktive Abfälle beziehen. Hochaktive Abfälle fallen beim Betrieb eines Kernkraftwerkes an.

Spuren der Zukunft

Die Nagra veröffentlicht in loser Abfolge Themenhefte zur nuklearen Entsorgung
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Text und Bilder

Andrea Rieser

Redaktionsteam

Andrea Rieser
Meinrad Ammann

Gestaltung

Franca Moser

Illustrationen

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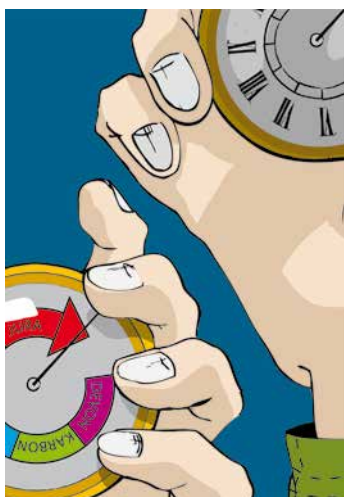
Naturaloga

■ Inspiration durch Beobachten der Natur

Für die Beurteilung der Langzeitsicherheit eines Tiefenlagers können wir viel von der Natur lernen.

4 – 7

6 – 7



Lange heisst lange genug

■ Geologische Tiefenlager – Sicherheit für «lange» Zeit

Ein geologisches Tiefenlager dient dem langfristigen und sicheren Einschluss der radioaktiven Abfälle.

■ Eine Million Jahre – ist das wirklich so lange?

Viel Zeit für den Menschen – ein Augenblick in der Erdgeschichte.

8 – 13

10 – 11

12 – 13



Was wir von der Natur lernen

■ Naturaloga für Lagersysteme

Ein geologisches Tiefenlager entstand vor zwei Milliarden Jahren in Afrika.

■ Naturaloga für technische Barrieren

Die Materialien für technische Barrieren kommen direkt oder in sehr ähnlicher Form in der Natur vor.

■ Das Wirtgestein – die geologische Barriere

Die Natur zeigt, wie Stoffe unter geeigneten Umständen über Millionen von Jahren im Gestein eingeschlossen bleiben.

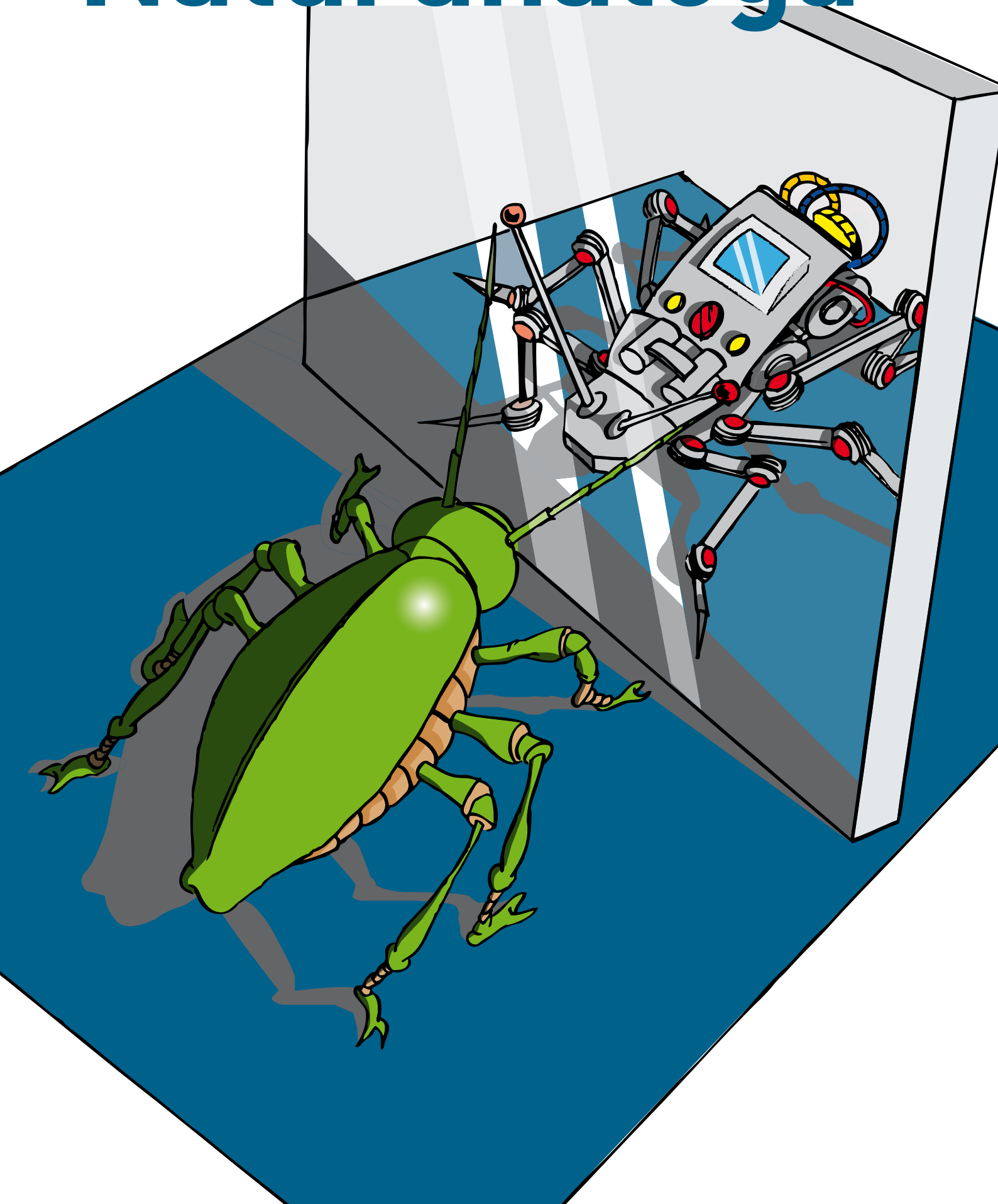
14 – 30

16 – 17

18 – 23

24 – 30

Naturanaloga



Naturanaloga bezeichnen natürliche Vorkommen von Materialien oder Prozessen, wie sie in einem geologischen Tiefenlager für radioaktive Abfälle vorgesehen sind oder erwartet werden. Das Verständnis solcher Naturanaloga hilft den Forschern bei der Abschätzung möglicher Entwicklungen und der Beurteilung der Langzeitsicherheit eines Tiefenlagers.



Inspiration durch Beobac

Der Mensch hat sein Wissen durch Beobachten der Natur stetig vergrößert. Häufig können technische Fragen mit Hilfe der Natur und darin ablaufender Prozesse beantwortet werden.

Ideen aus der Luft gegriffen ...

Die ersten Flugpioniere liessen sich vom Vogelflug inspirieren (Bilder 1). Bis zum ersten erfolgreichen Flug waren viele Testläufe nötig. An Störchen wurde das Auftriebsprinzip von gewölbten Flügeln erkannt.

Nachahmungen natürlicher Dinge und Prozesse begegnen uns vielerorts im Alltag. Der Klettverschluss beispielsweise entstand 1951, nachdem der Haftmechanismus der Klettenfrüchte (Bilder 2) 1948 mit Hilfe eines Mikroskops entdeckt worden war.

... und aus dem vollen Meer geschöpft

In den schier endlosen Tiefen der Ozeane scheint viel Inspirationspotenzial zu schlummern. Die Flugindustrie setzt genauso auf die Haifischhaut



Comet Photoshopping



Nagra

2

Lästige Begleiter – war einmal das Geheimnis der anhänglichen Klette (*Arctium lappa*, oben) gelüftet, entstand der praktische Klettverschluss.



Archiv Otto-Lilienthal-Museum

1

Die Motivation zum Fliegen kam ursprünglich aus der Luft. Die Entwicklungsschritte über Otto Lilienthals Normalsegelapparat bis zu modernen Langstreckenflugzeugen verliefen relativ schnell.

hten der Natur

wie Schiffbauer und sogar Sportler. Die Furchen auf den Schuppen von Haifischen (Bilder 3) verkleinern den Strömungswiderstand und reduzieren den Energieverbrauch.

Der Variantenreichtum der Natur bleibt für den Menschen aber trotz ausgeklügelter Technik unerreichbar (Bilder 4).

Die Natur hat viel – der Mensch nur wenig Zeit

Die Natur hat für ihre Experimente und Entwicklungen viel Zeit. Oft zeigt sich aber erst nach einer gewissen Zeit, ob eine Lebensform oder ein System «funktioniert», das heisst überlebensfähig ist. Für ein geologisches Tiefenlager fehlt diese Testzeit, es muss von Beginn weg funktionieren. Auch in einem Felslabor am Standort sind keine Langzeitexperimente im Massstab 1:1 mehr möglich vor Inbetriebnahme des Lagers. Deshalb liefern Naturanaloga wichtige Informationen, selbst wenn sie immer nur einen einzelnen Aspekt unter einmaligen geologischen Bedingungen widerspiegeln.



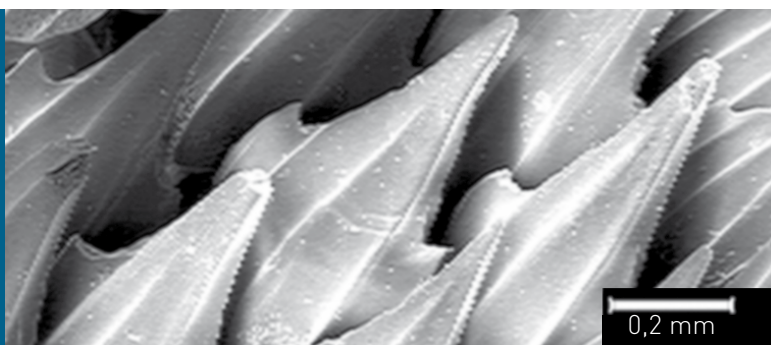
G. Cortese, AWI Bremerhaven



bab.ch/mauritus images

4

Die feinen Kieselskelette der Strahlentierchen (Radiolarien, oben) stehen Modell für filigrane und leichte Bauwerke.



R. Liedert, HS Bremen

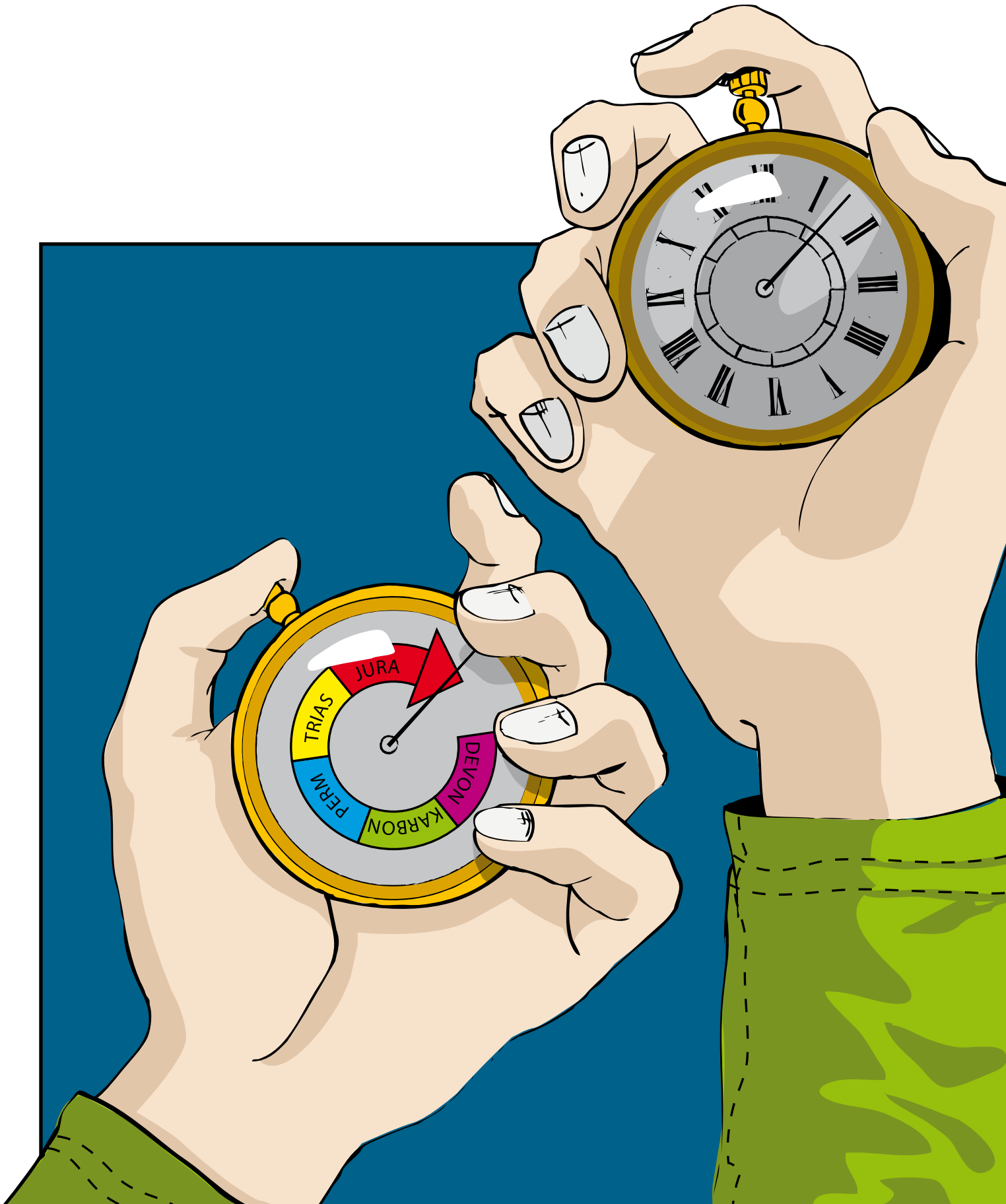


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3

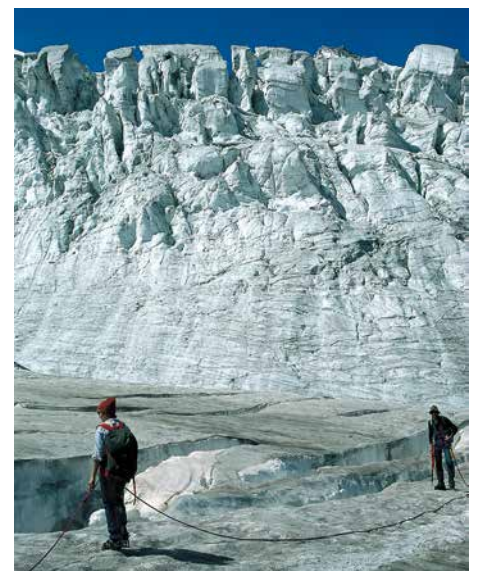
In Ganzkörperanzügen, deren Oberfläche der Haifischhaut (oben) nachempfunden ist, schwimmen Sportler neuen Rekorden entgegen.

Lange heisst lan



ge genug

Fundierte Kenntnisse der erdgeschichtlichen Abläufe von den Anfängen bis zur Gegenwart schärfen den Blick in die geologische Zukunft. Die Verhältnisse im tieferen Untergrund bleiben vergleichsweise stabil. Wir können aber zum Beispiel nicht sagen, ob unser heutiger Lebensraum als nächstes zuerst von tropischer Vegetation überwuchert oder von eiszeitlichen Gletschern überfahren wird.



Nagra

Geologische Tiefenlager –

Die hochaktiven Abfälle müssen während sehr langer Zeit vom Lebensraum und damit der Erdoberfläche ferngehalten werden.

Sicherheit durch Einschluss

Die Wissenschaftler sind sich weltweit einig, dass es am sichersten ist, die Abfälle tief im Gestein in geologischen Tiefenlagern einzulagern, wo sie über Jahrtausende bis zur «Unschädlichkeit» zerfallen können. Als Mass der Unschädlichkeit dient die natürliche Strahlung.

Sicherheitsbarrieren

Ein sicherer Einschluss von hochaktiven Abfällen in einem Tiefenlager wird durch die Kombination von technischen und natürlichen Barrieren angestrebt (Abbildung Seite 11). Jede einzelne Barriere hat die Aufgabe, die hochaktiven Abfälle vor Störeinflüssen zu schützen, beziehungsweise die radioaktiven Stoffe möglichst lange am Verlassen des Tiefenlagers zu hindern (Bild 1).

Radiotoxizität

Zum Zeitpunkt der Entnahme aus dem Reaktor ist die Radiotoxizität (strahlungsbedingte Giftigkeit bei körperlicher Aufnahme) von verbrauchtem Kernbrennstoff 10000 mal grösser als die des einst dazu abgebauten Uranerzes (Bild 2). In Rund 200000 Jahren erreicht die Radiotoxizität des hochaktiven Abfalls die Werte des ursprünglichen Uranerzes.



1 Sicherheitsbarrieren in geologischen Tiefenlagern dürfen für radioaktive Stoffe nicht so durchlässig sein wie diese Bahnschranke für die Teilnehmer an der Tour de Suisse 1955.



Nagra

2

In Erzen kommen radioaktive Stoffe in konzentrierter Form natürlich vor.

RDB

Sicherheit für «lange» Zeit

Sicherheitsbarrieren in einem geologischen Tiefenlager für verglaste hochaktive Abfälle

		Seite	
<p>Geologische Barriere (ca. 400 - 1200 Meter überlagerndes Gestein)</p>		<ul style="list-style-type: none"> Die Glasmatrix mit den darin verschmolzenen hochaktiven Abfällen ist sehr schwer korrodierbar. 	18 – 19
		<ul style="list-style-type: none"> Der Metallbehälter verhindert die Freisetzung von radioaktiven Stoffen während mindestens 10 000 Jahren. 	20 – 21
		<ul style="list-style-type: none"> Die Stollenverfüllung aus Bentonit (Ton) ist sehr gering durchlässig, quillt bei Feuchtigkeitzutritt und kann dadurch Risse und Klüfte abdichten. Die Tonminerale binden Schadstoffe. 	22 – 23
		<ul style="list-style-type: none"> Die Lagerstollen liegen im Wirtgestein. Das Gestein muss gering durchlässig und mechanisch stabil sein, sowie die Abfälle und die technischen Barrieren (z. B. vor Gletschererosion) schützen. Es kann auch Schadstoffe binden. 	Kristallin 24 – 25 Salz 26 – 27 Ton 28 – 30

Eine Million Jahre – ist d

Jeder weiss wie lange ein Jahr ist, wie lange zehn Jahre sind und wie lange ein Menschenleben dauert (Bild 1). Aber wie viel sind 1000 Jahre? Wie viel sind 1 000 000 Jahre?

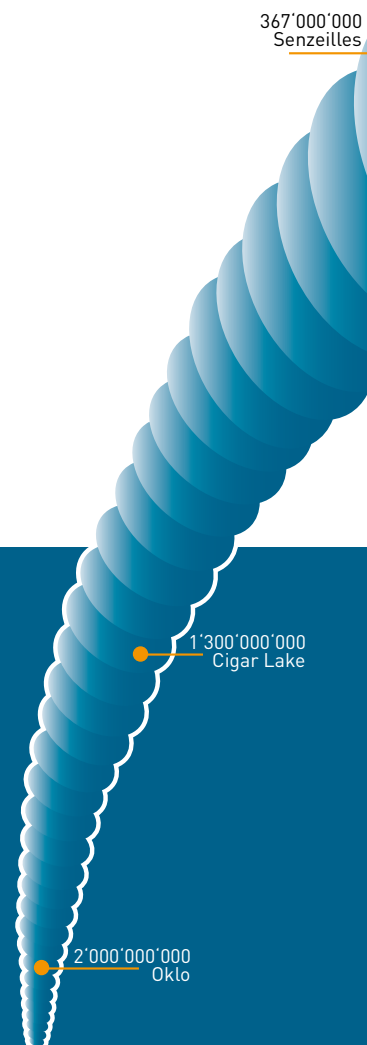
Augenblick in der Erdgeschichte

Wenn es um geologische Zusammenhänge geht, ist oft von unvorstellbar grossen Zahlen die Rede. Erdwissenschaftler müssen häufig in ungewohnt grossen Zeitdimensionen denken (Bild 2). Was aber dem Einzelnen wie eine Ewigkeit erscheint, ist für die Erde ein kurzer Augenblick. Solch grosse Zahlen lassen sich nur durch Vergleiche veranschaulichen (Bilder 3 und 4).

Geologische Geschwindigkeiten

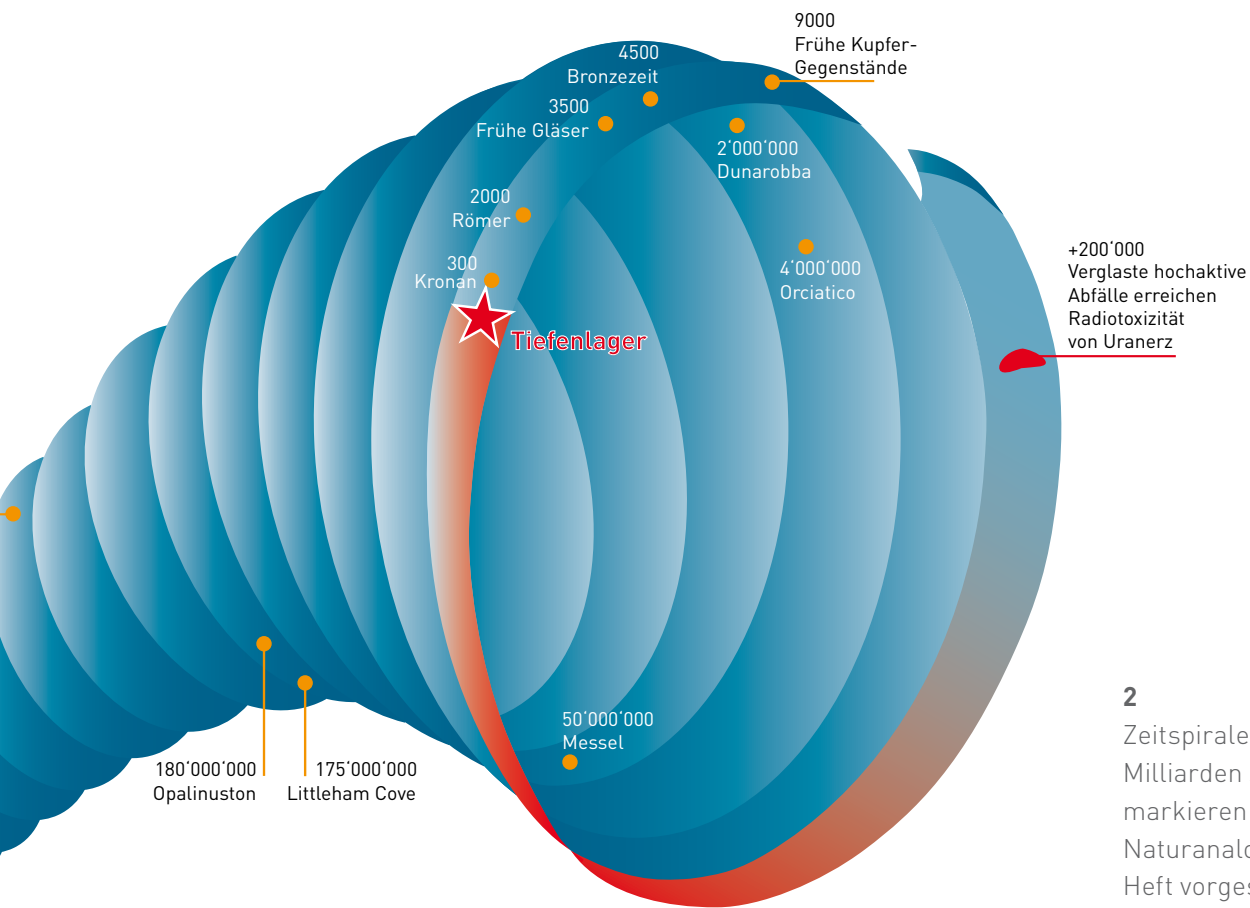
In der Regel laufen im Untergrund viele Prozesse sehr langsam ab – meist über viele Jahrmlionen. Diese langsamen Prozesse können, zwar unter grossen Einschränkungen und mit viel Vorsicht, in die Zukunft projiziert werden.

Abrupte Vorgänge wie Erdbeben und Vulkanausbrüche können lokal innert kürzester Zeit grosse Veränderungen auslösen. Risikogebiete, die durch derart plötzlich auftretende Ereignisse gefährdet sind, kennen die Wissenschaftler meist aus geologischen Untersuchungen. Diese Gebiete kommen nicht in Frage für den Bau eines geologischen Tiefenlagers und werden schon bei der Planung ausgeschlossen.



1
Seine Lebensdauer
kann der Mensch
noch erfassen.

as wirklich so lange?



2
 Zeitspirale über zwei Milliarden Jahre. Die Punkte markieren Beispiele von Naturanaloga, die in diesem Heft vorgestellt werden. Die Zahlen geben das Alter in Jahren an.



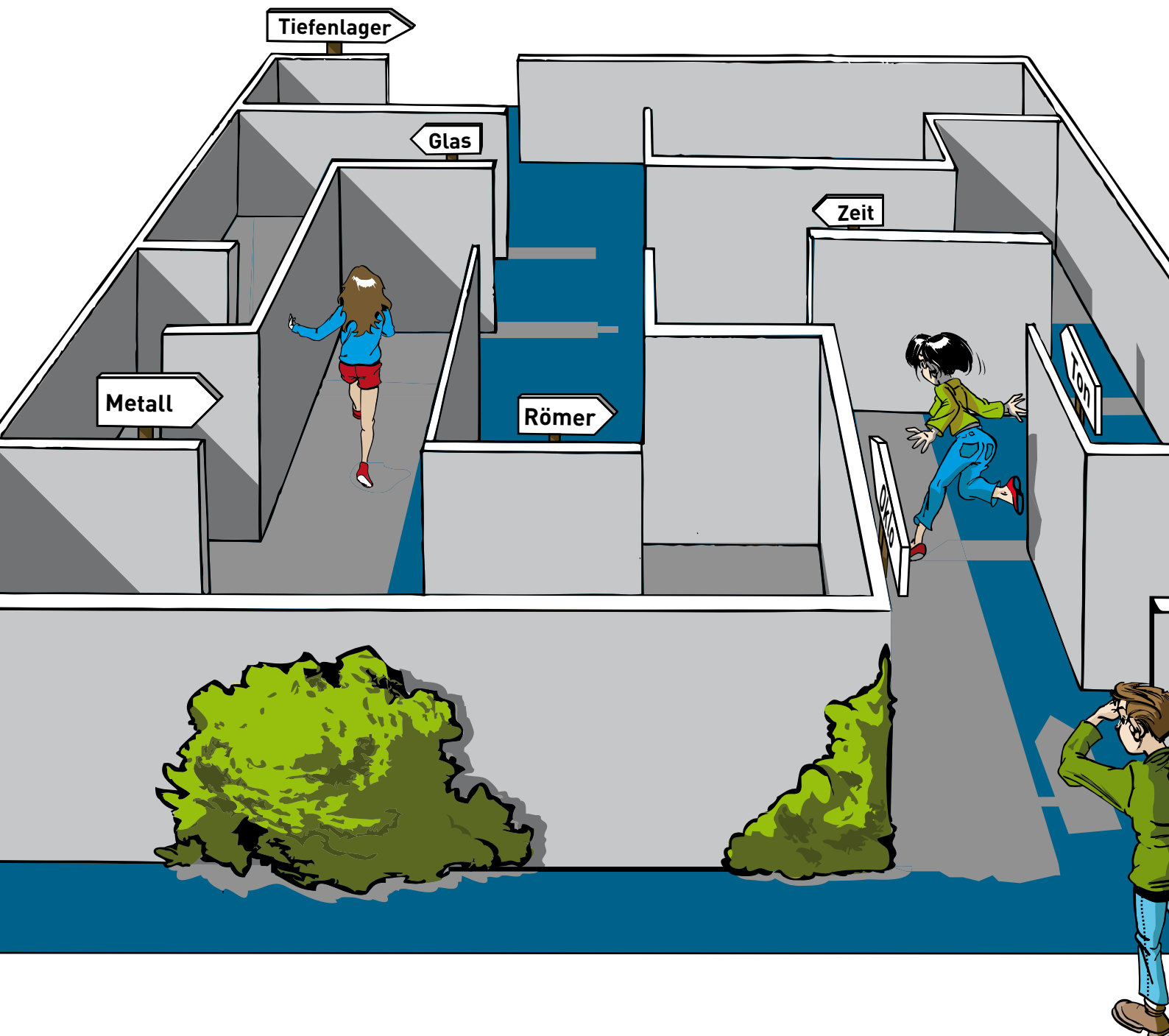
Fotosearch

3
 Eine Million Reiskörner wiegen 300 Kilogramm.

4
 Nach einer Million Sekunden sind 11,57 Tage verstrichen.

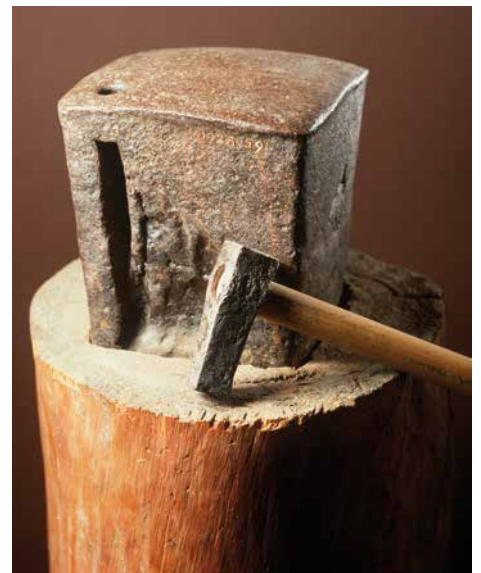
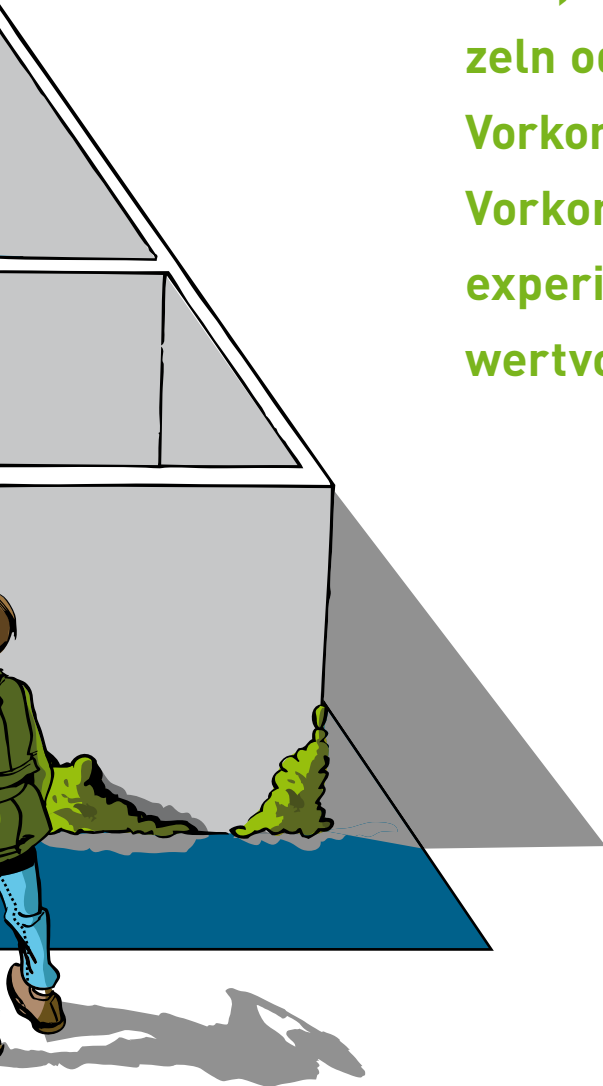
gettyimages

Was wir von der



Natur lernen

Die Materialien, die als technische Barrieren in einem geologischen Tiefenlager vorgesehen sind, existieren in vergleichbarer Form einzeln oder sogar in Kombination als natürliche Vorkommen oder archäologische Relikte. Diese Vorkommen können als eine Art Langzeitexperimente betrachtet werden und bieten wertvolle Anschauungsbeispiele.



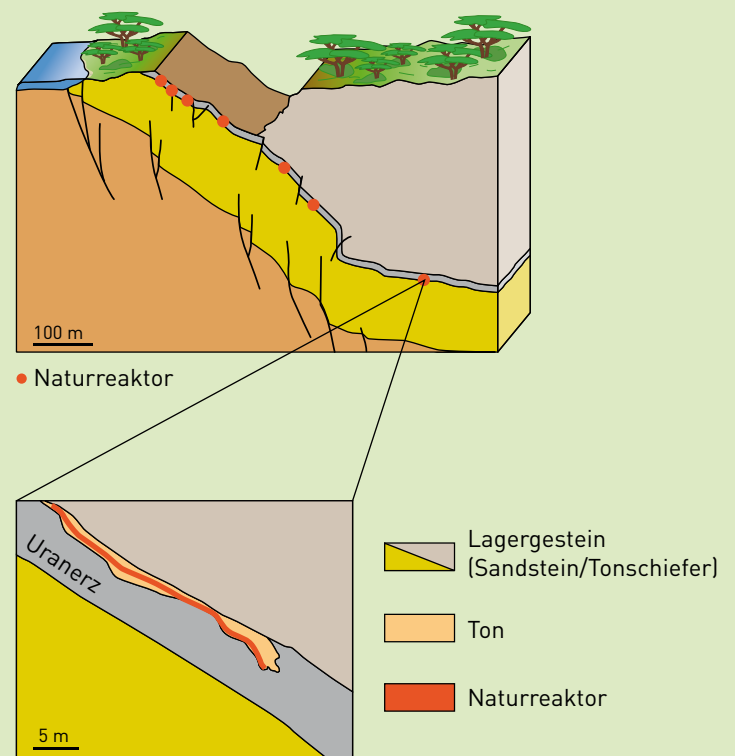
Naturanaloga für Lagers

Die Natur bietet Situationen, die als Beispiele für Lagersysteme dienen, in denen radioaktive Stoffe wirksam eingeschlossen blieben.

Endlager Oklo

In einem Uranerzvorkommen in Oklo (Gabun, Afrika) sind vor fast zwei Milliarden Jahren auf natürliche Weise Kernreaktionen (Kernspaltungen) abgelaufen (Bild 1). Wegen des hohen natürlichen Gehalts an Uran-235 konnten während einigen Jahrtausenden im Gestein spontan Kernreaktionen ablaufen. Dabei entstanden mehrere Tonnen Spaltprodukte (hochaktive Abfälle). Diese Spaltprodukte sind über die Jahrtausende weiter zerfallen. Heute sind nur noch die Endprodukte vorhanden. Geochemische Untersuchungen zeigten, dass seit der Reaktorbildung weniger als 10 Prozent des Urans und der Spaltprodukte in das umliegende Gestein gedrungen waren. Ein grosser Teil der ursprünglich radioaktiven Stoffe blieb im Uranerz eingeschlossen und konnte dadurch die Reaktorzonen nicht verlassen.

Von der Natur geschaffenes Endlager für hochaktive Abfälle in Oklo



1

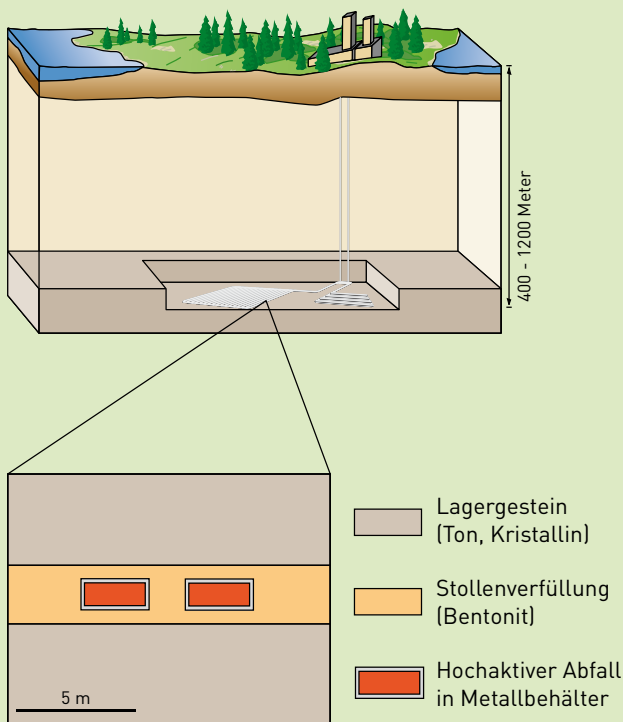
In den ausgebrannten natürlichen Kernreaktoren von Oklo blieben die Spaltprodukte zirka 1,8 Milliarden Jahre im Gestein eingeschlossen. Das Foto zeigt das Zentrum eines Naturreaktors.

Natürliches Tiefenlager

Die Natur hat in Oklo einen natürlichen Kernreaktor und ein «Tiefenlager für hochaktive Abfälle» geschaffen. Dabei sind die Abfälle ohne technische Sicherheitsbarrieren im Gestein eingeschlossen geblieben. Oklo zeigt uns also quasi den Endzustand eines ausgekühlten Tiefenlagers. Die Spuren der Reaktorreste wurden durch den Erztagbau entdeckt.

systeme

Tiefenlager für hochaktive Abfälle in der Schweiz (Planung)



Erzgang Cigar Lake

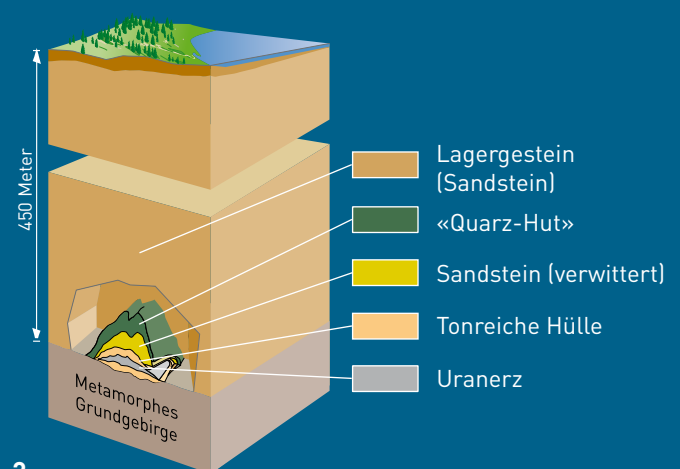
Das 1,3 Milliarden Jahre alte Uranerzvorkommen von Cigar Lake (Saskatchewan, Kanada; Bilder 2) weist weltweit eine der höchsten Urankonzentrationen auf (durchschnittlich 12 Prozent Uranoxid, vereinzelt bis über 50 Prozent).

An der Erdoberfläche lässt sich das Erzvorkommen radiologisch nicht nachweisen. Die vorhandenen Radionuklide werden durch eine 10 bis 50 Meter dicke Tonschicht so wirksam zurückgehalten, dass schon in wenigen Zehnermetern Abstand vom Erzkörper in Bohrungen keine erhöhte Radioaktivität mehr messbar ist.

Entdeckt wurde das Vorkommen eher zufällig. Auf Grund geophysikalischer Messungen und Kenntnissen über andere Vorkommen wurde ein Erzlager vermutet und später durch Bohrungen nachgewiesen.



M. Fritzsche



2

Das Uranerz von Cigar Lake ist von mehreren natürlichen Hüllen umgeben, die die Radionuklide zurückhalten. Dieses Hüllensystem ist vergleichbar mit den Sicherheitsbarrieren, die in einem geologischen Tiefenlager vorgesehen sind.

Naturanaloga für technis

Barrieren verhindern und verzögern die Freisetzung von Radionukliden aus einem Tiefenlager. Der hochaktive Abfall wird mehrfach eingeschlossen. Dafür sind unterschiedliche Materialien wie Glas, Metalle und Tone vorgesehen. Die Untersuchung von natürlichen Vorkommen und archäologischen Funden liefert wichtige Hinweise zur Beurteilung des Langzeitverhaltens dieser Materialien.

Glas

Glas besitzt eine amorphe Struktur, das heisst seine Bestandteile sind unregelmässig angeordnet. Beim Zerschlagen entstehen unebene, muschelartige Flächen (Bild 1), anders als in einem Kristall, der meist entlang ebenen Flächen bricht.

In der Natur gibt es vulkanische Gläser (Obsidian, Bild 2), die aus amorphem Quarz bestehen und teils über Jahrtausende in chemisch unverändertem Zustand erhalten geblieben sind.

Archäologische Glasfunde

Aus dem östlichen Mittelmeerraum (Ägypten, Griechenland, Mesopotamien) sind bis zu 3500 Jahre alte archäologische Gegenstände aus Glas bekannt. Es handelt sich vor allem um vasen- und krugartige Gefässe (Bild 3).

367 Millionen Jahre alte Glasperlen

Bei Senzeilles in Belgien wurden in einem Tongestein kleinste Glasperlen (0,05 – 1 mm) gefunden, die bei einem Meteoriteneinschlag vor 367 Millionen Jahren entstanden waren. Diese Glasperlen zeigen trotz ihrer Winzigkeit keinerlei Umwandlungserscheinungen.



1

Glas zerbricht muschelartig entlang unebener Flächen.

www.voller-ernst.de



3

The British Museum, London

Glasflasche in Fischform aus El-Amarna (Ägypten, zwischen 1390 und 1336 vor Christus; 14,5 cm lang).

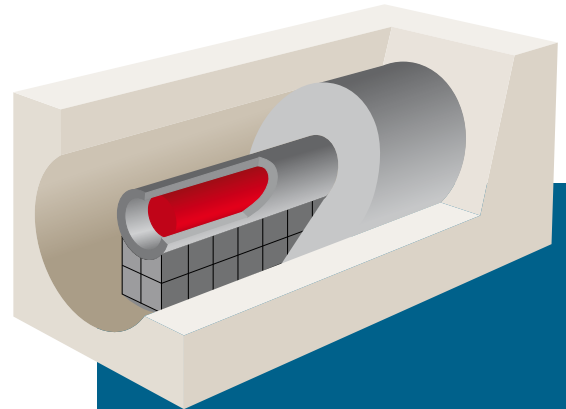
che Barrieren



Comet Photoshopping

2

Der meist schwarze Obsidian entsteht an der Erdoberfläche bei sehr schneller Abkühlung von Lava, zum Beispiel wenn ein Lavastrom ins Wasser fließt.



Frage

Wie lange ist Glas stabil?

Antwort

Beispiele zeigen, dass Glas unter geeigneten Bedingungen viele hunderttausend Jahre überdauern kann.

Einschränkung

Gläser mit viel radioaktiven Stoffen kommen nicht natürlich vor.

Anwendung

Glas bildet die innerste technische Barriere bei einem geologischen Tiefenlager für hochaktive Abfälle. Radioaktive Elemente werden in einer Glasmatrix eingegossen, weil diese sehr schwer korrodiert. Die radioaktiven Stoffe bleiben für lange Zeit sicher in dieser Glasmatrix eingeschlossen.

Metallbehälter

Stahl und Kupfer

Stahl ist eine Eisenlegierung mit einem geringen Gehalt an Kohlenstoff, der den Rostvorgang verlangsamt. Eisen rostet bei Kontakt mit sauerstoffreichem Wasser in Oberflächennähe (Bild 1). Die entstehende Rostschicht bildet jedoch eine Schutzschicht für das darunterliegende Metall und verzögert das Fortschreiten des Rostvorganges (Bild 2). Kupfer ist ein weiches Metall, das in der Natur auch in gediegener, also reiner Form vorkommt (Bild 3); häufiger sind allerdings Kupfererze.

Archäologische Metall-Funde

Unsere Vorfahren haben unbewusst wertvolle Langzeitexperimente gestartet. Archäologische Funde von Metallgegenständen helfen den Wissenschaftlern, die Lebensdauer der Metallbehälter für die hochaktiven Abfälle zu beurteilen. Die Funde zeigen, unter welchen Umständen Eisen und Kupfer

über Jahrtausende erhalten bleiben. In Ausgrabungen hat man bis zu 9000 Jahre alte Kupfergegenstände gefunden, die gut erhalten geblieben sind. Die Herstellung von Stahl ist seit 2700 Jahren bekannt, während Eisen bereits seit 3500 Jahren genutzt wird. Vor allem aus der Römerzeit sind viele Eisenfunde bekannt.

175 Millionen Jahre alte Kupferplättchen

In Littleham Cove (Südwestengland) sickerte vor etwa 175 Millionen Jahren eine kupferhaltige Lösung in Tonschichten. Daraus bildeten sich Plättchen aus gediegenem Kupfer von einigen Millimetern Dicke und Durchmesser bis zu zehn Zentimeter. Tief im Erdboden sind diese unverändert geblieben. Erst nahe der Erdoberfläche verloren die Kupferplättchen später wieder 20 bis 70 Prozent ihrer Dicke infolge Lösung durch Wasser.



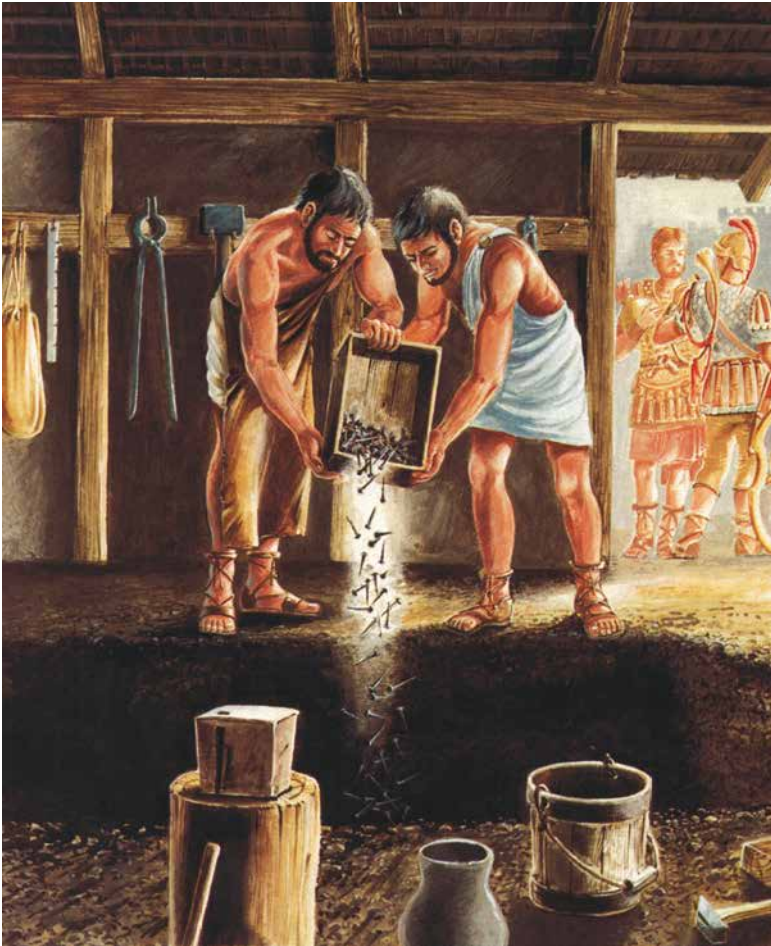
Nagra

1 Dieser römische Helm aus Augusta Raurica (Augst, BL) ist während der vergangenen 2000 Jahre in der Erde nicht durchgerostet, obwohl er nur zwei bis drei Millimeter dick war.



H. Putz

3 Gediegenes Kupfer (Breite 7 cm) fällt aus wässrigen Lösungen in Rissen und Gängen im Gestein aus.

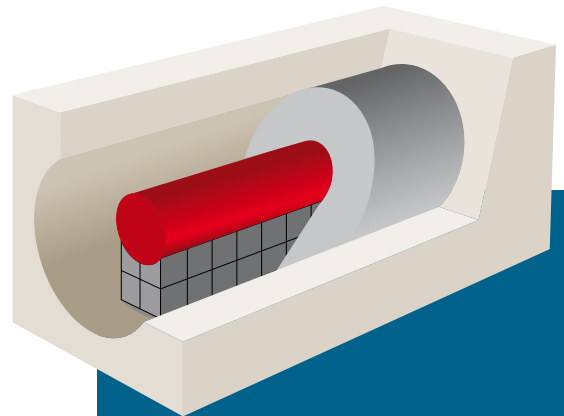


Nagra

2

Römisches Langzeitexperiment

Im Jahre 87 nach Christus vergruben römische Soldaten in Inchtuthil (Schottland) kistenweise Eisennägel vier Meter tief im Boden, um das wertvolle Material dem gegnerischen Zugriff zu entziehen. Die obersten Nägel sind stark korrodiert und bildeten eine feste Rostschicht, welche die darunterliegenden Nägel weitgehend schützte.



Frage

Wie verhalten sich Metalle über lange Zeiträume?

Antwort

In trockenen Bereichen korrodieren Metalle sehr langsam. Die Korrosionsschicht kann auch eine zusätzliche Schutzschicht bilden.

Einschränkung

Antike Beispiele decken nur einen Zeitrahmen von 3000 Jahren (Eisen), bzw. 9000 Jahren (Kupfer) ab.

Anwendung

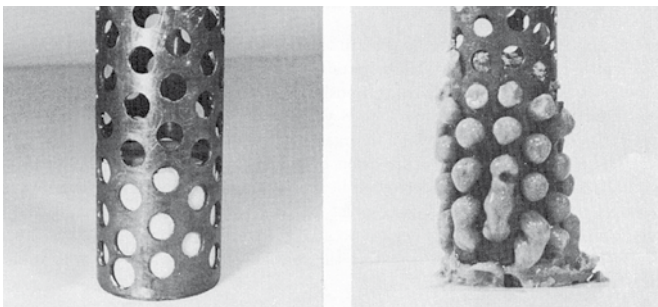
Für den Einschluss der Glasmatrix mit den hochaktiven Abfällen sowie der verbrauchten Brennelemente sind Metallbehälter vorgesehen. Das aktuelle Schweizer Lagerkonzept beinhaltet einen 15 bis 25 Zentimeter dicken Stahlmantel für hochaktive Abfälle und verbrauchte Brennelemente. In Schweden und Finnland sind für die Tiefenlagerung in kristallinen Gesteinen Stahlbehälter mit einer zusätzlichen Kupferummantelung vorgesehen.

Verfüllmaterial

Ton quillt und hält dicht

Das Verfüllmaterial in den Lagerstollen soll eindringendes Wasser von den Lagerbehältern fern- und allfällige austretende Radionuklide aufhalten. Bentonit ist ein Ton, der beides erfüllt. Er vermag viel Wasser zu binden und quillt dabei auf (Bild 1). Zudem besitzt er die Fähigkeit, Radionuklide langfristig zu binden und zurückzuhalten.

Tonminerale entstehen durch Verwitterung oder Umwandlung anderer Minerale und durch Neubildung. Tone bilden eine dichte Isolationsschicht, die für Luft und Wasser so gut wie nicht durchlässig ist (Bild 2). Die geringe Wasserdurchlässigkeit von Ton lernen wir oft schon als Kinder im Spiel kennen (Bild 3).



SKB

Orciatico

Nahe des toskanischen Dorfes Orciatico drang vor etwa vier Millionen Jahren 800 Grad Celsius heißes Magma in eine bereits zwei Millionen Jahre alte Tonschicht (Bild 4). In der 3 bis 12 Meter mächtigen Reaktionszone im Ton veränderte sich der Mineralbestand. Bemerkenswert ist in diesem Fall die Neubildung von quellfähigen Tonmineralien.

Dieses Beispiel zeigt, dass Tone in speziellen Fällen selbst bei Temperaturschock ihr Isolationsvermögen beibehalten oder sogar verbessern können.

1

Das perforierte Rohr ist mit kompaktiertem Bentonit gefüllt. Nach 24 Stunden im Wasserbad quillt der Ton durch die Löcher heraus.



Kalmar Läns Museum

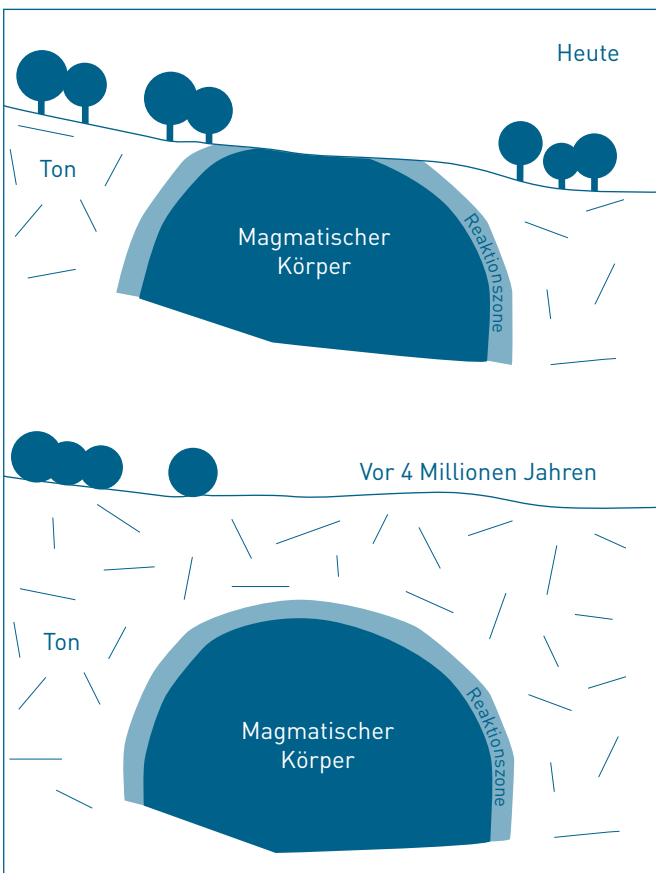
2

Die «Kronan»-Bronzekanone lag 300 Jahre im Schlamm der Baltischen See. Der Kupfergehalt beträgt 96,3 Prozent. Der Kupferkörper stellt ein Analogon dar für die Kupferhülle, wie sie in Schweden und Finnland für hochaktive Abfälle vorgesehen ist. Gleichzeitig demonstriert der marine Schlamm das gute Konservierungsvermögen von Tönen.

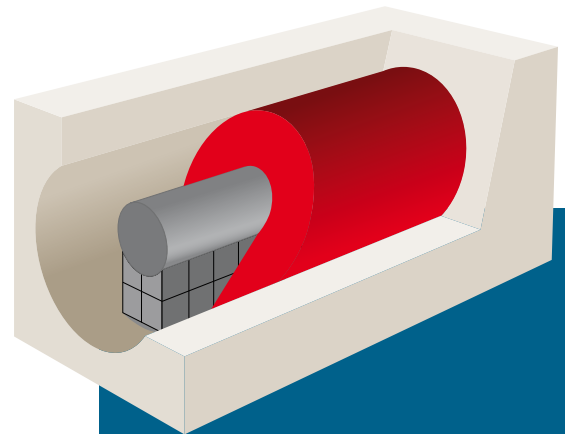


ImagePoint.biz

3 Mit ein paar Steinen und etwas Lehm (Gemisch aus Ton und Sand) ist das Stauen eines Baches ein Kinderspiel.



4 Orciatico. In der Reaktionszone um den magmatischen Körper kam es zur Neubildung von quellfähigen Tonmineralien.



Frage

Wie verhält sich Ton in Kontakt mit Wasser?

Antwort

Bei entsprechender Zusammensetzung quillt Ton bei Wasserzutritt und dichtet Risse ab. Gleichzeitig kann Ton auch Schadstoffe fixieren.

Anwendung

Nach dem Einbringen der Abfallbehälter werden die Hohlräume in den Lagerstollen mit quellfähigem Bentonit komplett verfüllt.

Das Wirtgestein – die geo

Die geologische Barriere umfasst das Wirtgestein und alle darüberliegenden Gesteine bis zur Erdoberfläche. Als Wirtgestein wird jener Gesteinskörper bezeichnet, der unmittelbar das Tiefenlager enthält. Für hochaktive Abfälle werden in Europa als Wirtgestein Kristallingesteine, Ton- und Salzgesteine in Betracht gezogen.

Kristallingestein

Kristallingesteine wie Granit entstehen tief im Innern der Erdkruste aus Magma. Beim Abkühlen entstehen Schrumpfrisse und Hohlräume, in denen sich unter geeigneten Bedingungen schöne Kristalle bilden (Bild 1). Störungen entstehen bei Gesteinsversagen unter unterschiedlichen Gebirgsspannungen. Entlang diesen Störungen und Klüften kann Wasser oft relativ einfach und schnell fließen. Zwischen den ungleichmässig über den Gesteinskörper verteilten Störungszonen gibt es grosse, nur schwach gestörte Bereiche, die wegen ihrer hohen Stabilität für Tiefenlager geeignet wären.

Radioaktive Stoffe in Kristallingestein ...

Kristallingestein enthält bis zwei Prozent radioaktive Elemente (Bild 2), unter anderem Kalium, Rubidium, Thorium und Uran. Viele Mineralien bauen radioaktive Elemente in ihr Kristallgitter ein (Bild 3). Deshalb ist vor allem in Gebieten mit kristallinen Gesteinen an der Oberfläche die natürliche Bodenstrahlung höher. Ein bis zwei Kubikkilometer Granit enthalten soviel Uran, dass damit alle fünf Schweizer Kernkraftwerke während ihrer gesamten Lebensdauer betrieben werden könnten.

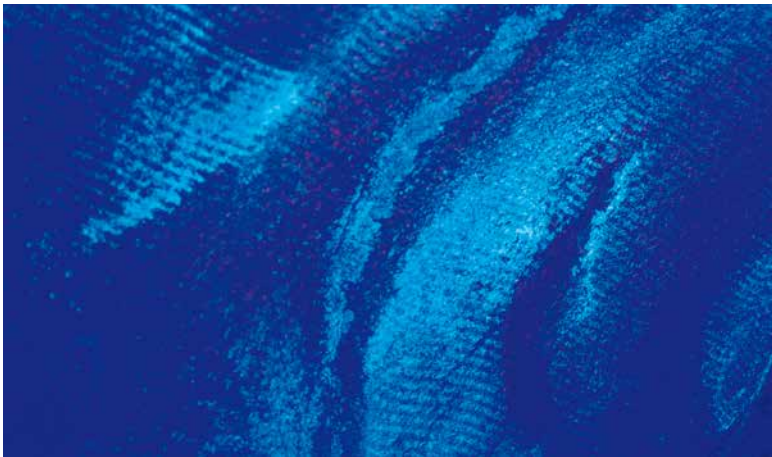
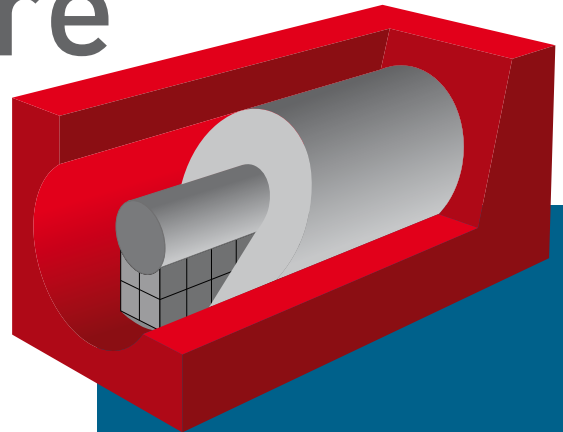
... und in Abfällen

Im Gegensatz zu natürlich vorkommendem Uran in Kristallingestein ist die Radioaktivität in den Abfällen stark konzentriert. Diese Konzentration bewirkt die hohe Radiotoxizität der Abfälle und erfordert die entsprechende Sonderbehandlung.



1 Die geschützte Kristallklüft Gerstenegg auf der Grimsel ist etwa 16 Millionen Jahre alt. Seit ihrer Entstehung hat sie schon über 1,5 Millionen spürbare Erdbeben unbeschadet überstanden, da in der Schweiz etwa alle 10 Jahre Erdbeben dieser Stärke vorkommen.

logische Barriere



Comet Photoshopping

2

Abbild natürlicher Radioaktivität im Felslabor Grimsel. An der Stollenwand durch Verdunstung natürlich konzentriertes Uran wird im UV-Licht sichtbar. Bildausschnitt: ca. 1 m.



D. Seward, ETH Zürich

3

Radioaktiver Zerfall ist sichtbar. Bei spontanem radioaktiven Zerfall von Uran-238 in Mineralien (z. B. Apatit, Zirkon) entstehen Defekte («Spaltspuren») im Kristallgitter. Auf polierten Flächen sind diese Spuren unter dem Mikroskop sichtbar. Dieses Bild zeigt, dass die freigesetzte Energie und der Wirkungsradius begrenzt sind. Bildbreite: ca. 0,7 mm.

Kristallin als Wirtgestein für ein Tiefenlager?

In der Nordschweiz stellen Kristallingesteine ein mögliches Wirtgestein dar. Sie liegen allerdings zum Teil tief im Untergrund unter mächtigen Sedimentschichten, wo sie schwierig zu erkunden sind.

In Schweden und Finnland werden Kristallingesteine als Wirtgesteine für Tiefenlager genutzt. Beide Länder betreiben bereits Tiefenlager für schwach- und mittelaktive Abfälle in Kristallingestein. Im finnischen Olkiluoto befindet sich zusätzlich ein Felslabor in Bau, das später zu einem Tiefenlager für hochaktive Abfälle ausgebaut werden soll.

Salzgestein

Jeder, der schon einmal Spaghetti gekocht hat, weiss, wie leicht sich Salz in Wasser löst.

Trotz wasserführender Schichten im Untergrund besitzt die Schweiz grosse, viele Millionen Jahre alte Salzvorkommen (Bild 1). In Rheinfelden (östlich von Basel) liegt eine 50 Meter dicke und 240 Millionen Jahre alte Salzsicht in nur 100 Meter Tiefe. Eingebettet zwischen Tonschichten ist sie gut geschützt.

Langzeitkonservierung

Salz besitzt gute Wärmeleit- und Konservierungseigenschaften. Durch den Ausschluss von Wasser und Luft erhalten sich im Salz organische Materialien; Metallgegenstände rosten kaum.

Die antiken und mittelalterlichen Gänge in den Salzbergwerken des Salzkammergutes haben sich durch die Kriechfähigkeit (Plastizität; Bild 2) des Salzes verschlossen. Sie wurden erst in moderner Zeit neu entdeckt durch archäologische Funde von zurückgelassenen Werkzeugen, Fackeln und Kleidern aus der Zeit vor 2500 Jahren.



Schweizer Rheinsalinen

1

Die Schweiz deckt ihren jährlichen Salzbedarf aus eigenen Vorkommen. Lagerhalle der Rheinsalinen.



Salinen Austria AG

2

Salz – wie es natürlich im Berg vorkommt. Die Kriechfähigkeit des Salzes spiegelt sich in den Strukturen.



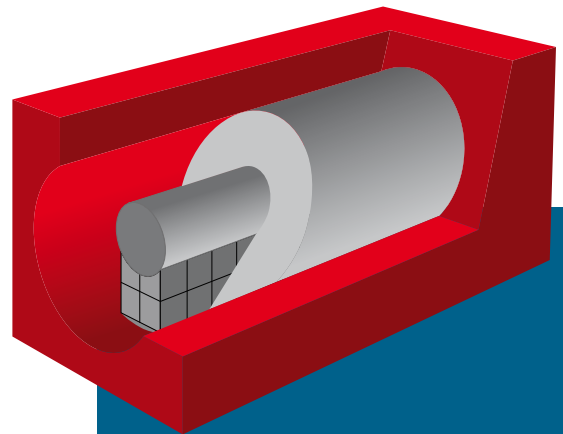
[bab.ch/mauritius images](http://bab.ch/mauritius-images)

Salzgewinnung auf Malta. Steinsalz entsteht durch Verdunstung von Salzwasser in warmen, flachen Buchten.



Nagra

Salzkrusten im Death Valley (Kalifornien).



Salz als Wirtgestein für ein Tiefenlager?

Die Salzvorkommen in der Schweiz sind als Wirtgestein für Tiefenlager nicht geeignet. Die zu geringmächtigen Salzlagen befinden sich zu nahe an der Oberfläche und in Gebieten mit zu wenig stabilen geologischen Verhältnissen.

Deutschland betrieb von 1971 bis 1998 ein Tiefenlager für schwach- und mittelaktive Abfälle im ehemaligen Salzbergwerk Morsleben. Die Einlagerung ist abgeschlossen und das Tiefenlager teilweise mit Salz verfüllt.

Tongestein

Tonformationen zeichnen sich durch ein hervorragendes Isolations- und Abdichtungsvermögen aus, sowie die Fähigkeit, Wasser und gelöste Inhaltsstoffe während geologischer Zeiträume an sich zu binden.

An der Erdoberfläche sind Tone weich und plastisch und reagieren unmittelbar auf Feuchtigkeitsunterschiede. Beim Trocknen zieht sich Ton zusammen und es bilden sich Trockenrisse. Bei erneutem Wasserzutritt quillt Ton wieder auf und die Risse schliessen sich (Bild 1). In grösserer Tiefe bilden Tone festes Gestein (Bild 2). Sie bleiben aber in der Bauphase anspruchsvoll, so dass grössere Hohlräume mit Felsankern oder Betonverkleidungen gestützt werden müssen.

Stauwirkung

Die dichten Tonschichten stauen nicht nur Öl und Gas (Bild 3), sondern auch Wasser (Bild 4). Grosse Grundwasservorkommen entstehen vor allem dort, wo mächtige, durchlässige Formationen von undurchlässigen Tongesteinen begrenzt sind.

Auf Schadstoffe haben Tone eine Art «Bremswirkung». Sie vermögen viele Schadstoffe zurückzuhalten und zu binden.

Uraltes Formationswasser

Bei Millionen Jahre alten marinen Sedimentgesteinen weiss man, dass erhöhte Salzgehalte im Porenwasser in der Regel auf ursprüngliches Meerwasser aus der Ablagerungszeit zurückgehen. Der 180 Millionen Jahre alte Opalinuston enthält in der Tiefe noch 10 bis 20 Gramm gelöste Salze pro Liter Porenwasser. Weil solche Anteile von Meerwasser seit vielen Millionen Jahren im Gestein erhalten geblieben sind, gehen Wissenschaftler davon aus, dass sich die Eigenschaften des Gesteins auch in den nächsten paar 100 000 Jahren kaum verändern werden.



Fotosearch

1

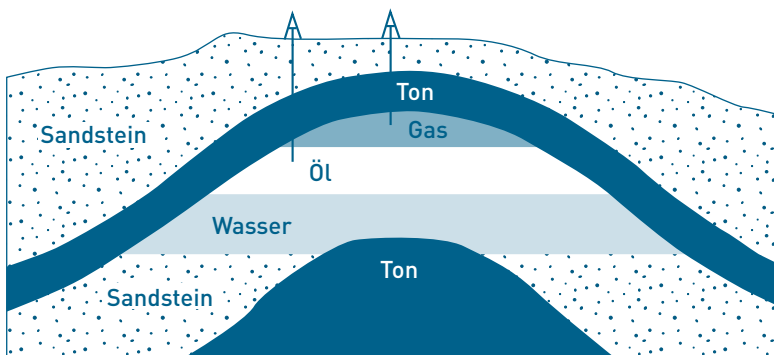
Die Trockenrisse im Boden schliessen sich bei erneutem Wasserzutritt durch Quellung von Ton.



Nagra

2

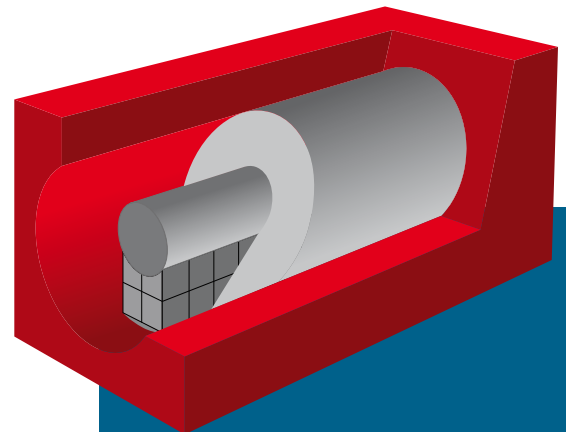
Durch den zunehmenden Druck werden Tone in der Tiefe zu festem Gestein gepresst. Offene Stollenwand im Felslabor Mont Terri.



3 Beispiel einer Erdölfalle. Wegen ihrer geringen Dichte steigen Öl und Gas in den Gesteinsporen auf und sammeln sich im Falten-scheitel unterhalb einer dichten Tonschicht.



4 Sandsteinschichten führen Wasser, welches oberhalb von undurchlässigen Tonschichten austritt und im Winter als kunstvoller Eisvorhang gefriert. R. Kozel



Ton als Wirtgestein für ein Tiefenlager?

Tongestein ist derzeit in der Schweiz das bevorzugte Wirtgestein für ein geologisches Tiefenlager für hochaktive Abfälle. Der marine Opalinuston gilt wegen seiner Ausdehnung und sehr geringen Wasserdurchlässigkeit als besonders geeignet.

Mehrere andere Länder bevorzugen tonige Gesteinsformationen ebenfalls als mögliche Wirtgesteine für ihre Tiefenlager.

Isolation und Abdichtung: Fossilien

Fossilien sind Zeugen der Vergangenheit. Unter optimalen Bedingungen bleiben nicht nur Knochen oder Abdrücke und Reste von Schalen (Bild 1) erhalten, sondern in seltenen Fällen auch Abdrücke von Weichteilen, also der Körpermasse. Der Erhalt von organischer Substanz (Bild 2) ist nur möglich, wenn der Kadaver sofort weitgehend luftdicht eingeschlossen wird und sich nicht zersetzt.

Zwei Millionen Jahre altes Holz

In der Tongrube von Dunarobba (Umbrien, Italien) im Tiber-Tal wurden zwei Millionen Jahre alte Baumstämme gefunden (Bild 3), deren organische Holzsubstanz erhalten geblieben ist. Durch seine Wasser- und Luftundurchlässigkeit verhinderte der Ton sowohl die Zersetzung als auch eine Versteinerung der Holzsubstanz.

Die Sequoia-ähnlichen Bäume waren vor zwei Millionen Jahren von Tonschlamm überschwemmt und in Lebendstellung eingeschlossen worden.



Messelforschung

2

Diese Reste eines Hirschkäfers aus der Tongrube Messel (Deutschland) sind fast 50 Millionen Jahre alt. Die erhaltene organische Materie (Chitin und Farbpigmente) ist ein seltenes aber besonders schönes Beispiel für das dauerhafte Isolationsvermögen von Tonschichten.



Comet Photoshopping

1

Der schillernde (opalisierende) Glanz der Ammonitenschale war namensgebend für den 180 Millionen Jahre alten «*Leioceras opalinum*», welcher wiederum dem Opalinuston seinen Namen verlieh.



N. Chapman

3

Die fossilen Einzelstämme in Dunarobba sind bis zu acht Meter hoch mit einem Durchmesser von über 1,5 Meter.

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Links

Eine Zusammenstellung interessanter Links im Zusammenhang mit diesem Themenheft finden Sie im Internet auf unserer Webseite www.nagra.ch.

Nationale Genossenschaft
für die Lagerung
radioaktiver Abfälle

Hardstrasse 73
5430 Wettingen
Schweiz

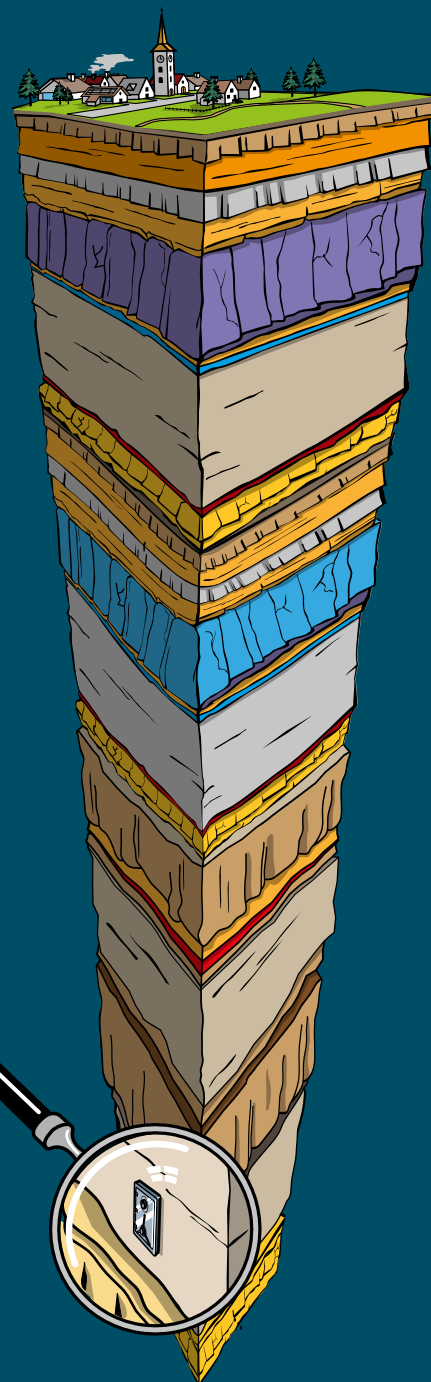
Tel. 056 437 11 11
Fax 056 437 12 07

info@nagra.ch
www.nagra.ch

nagra ● **aus verantwortung**

long-term safety

the main goal of deep
geological disposal of
radioactive waste



About this brochure

This brochure looks at disposal systems, engineered barriers, the host rock and natural analogues of a deep geological repository for high-level waste arising from the operation of a nuclear power plant.

Visitors attending exhibitions, presentations or other events have questions regarding the long-term safety of a deep geological repository. They are particularly interested in the long-term protection from radioactive substances. Geological challenges such as earthquakes and long-term measures to ensure the safety of future generations are also discussed. This brochure explains the most important aspects of these questions.

A selection of the terminology used in this brochure is explained in the Glossary starting on page 32.

Long-term safety – the main goal of deep geological disposal of radioactive waste

Nagra publishes special brochures on nuclear waste disposal at irregular intervals
December 2018

Print

Köpfl & Partner AG, Neuenhof

The most important points at a glance	4 – 7
▪ Long-term safety – an introduction	4 – 7
Long-term safety – why?	8 – 11
▪ The impact of radioactivity on humans Why are radioactive substances dangerous?	8 – 11
Today, tomorrow and thereafter	12 – 29
▪ Deep geological repositories for long-term protection Opting out of deep disposal means permanent monitoring	12 – 15
▪ Deep geological disposal – safety over long time periods Components of a deep geological repository	16 – 17
▪ The future evolution of a deep geological repository Fast-forwarding through the future	18 – 25
▪ What can nature teach us about waste disposal? The geological past as a guide	26 – 27
▪ How can safety be demonstrated? Safety analyses are an important element	28 – 29
Passing on messages over millennia	30 – 31
▪ How can information about a deep geological repository be preserved for future generations?	
Glossary	32 – 35

The most important poi

Long-term safety – an introduc

Switzerland’s radioactive waste must be disposed of safely, which means isolating it from the human environment for a very long period of time.

Protection against radioactivity

Natural radiation is part of our habitat (see Figure 1). Humans must be protected against excessive exposure to radiation because it can damage their health. It is easy to protect against a radiation source outside the body (external radiation) by using suitable shielding, keeping a safe distance or by limiting the exposure time. Internal radiation is caused by absorbing radioactive substances (radionuclides) that decay inside the body. It is possible to protect against this radiation type by avoiding the ingestion of radionuclides.

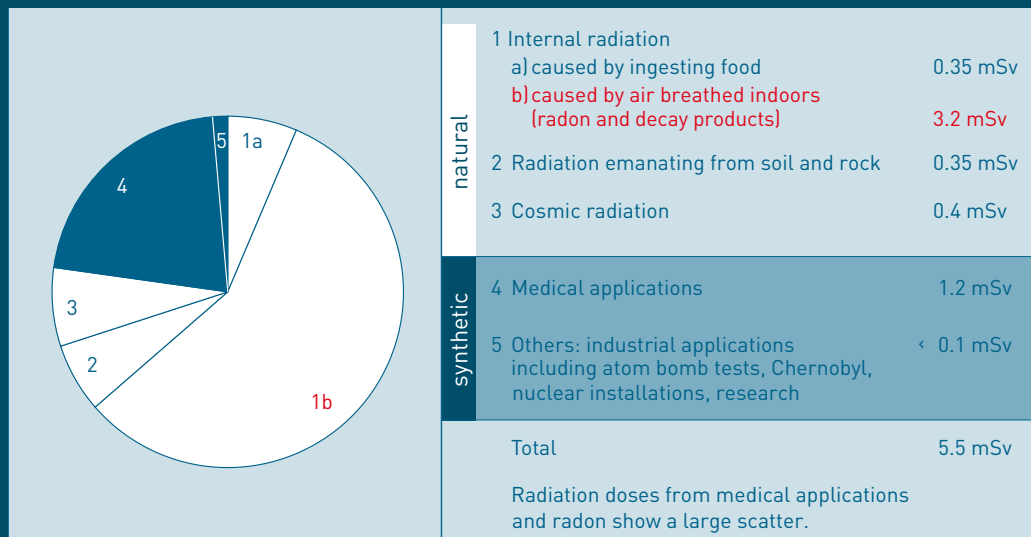
Consensus on deep geological disposal

As opposed to chemical waste, the toxicity of radioactive waste decreases with time due to decay. However, long containment periods are needed until the radiation level of radioactive waste has decreased to a level equivalent to that found in nature (see Figure 7, pages 12-13).

At the earth’s surface, within the sphere of human influence, conditions do not remain stable over long periods of time. World history is marked by social and political upheavals. A repository at the surface would have to be actively monitored the entire time. Safe containment would depend on a well-functioning society.

Underground geological processes occur extremely slowly and are unaffected by what is happening at the earth’s surface. Earth’s history shows us that many rock formations can remain stable over millions of years and barely alter their properties. Compared to the timescales over which these geological processes occur, the necessary contain-

Radioactive waste must be safely confined and isolated from the human habitat to prevent radionuclides being taken up into the human body.



© Nagra

Figure 1
Average annual radiation exposure for a Swiss resident according to the Swiss Federal Office of Public Health (2014): Further data are available in Figure 6 on page 11.

nts at a glance

tion

ment period for high-level waste is relatively short. In a deep geological repository, impermeable rock formations confine the waste passively – without human intervention. Today, there is international consensus that high-level waste should be disposed of in stable underground rock formations. The waste solutions discussed have not only included deep geological disposal or disposal at the earth's surface. Other options that have been considered and, in some cases, even carried out include dilution, deep sea disposal or even disposing of radioactive waste in outer space. However, some of these concepts carry high risks for humans and the environment and they have been abandoned. The Swiss Nuclear Energy Act stipulates deep geological disposal (see text-box below). The radioactive waste must remain retrievable after emplacement.

Barriers provide safety

In deep geological repositories, the radioactive substances are safely enclosed by containers, tunnel backfill, repository installations and by the surrounding rock. These engineered and natural barriers (so-called safety barriers, see page 17) prevent unacceptable amounts of radioactive substances from being dissolved by water and migrating through the surrounding rock to the earth's surface where they can reach our habitat. They ensure that the strict protection objectives for humans and the environment will be reliably complied with over long time periods.

Scientists around the world agree that deep geological disposal of high-level waste is the safest solution. Underground, the waste can decay over millennia until it has reached a harmless level.

Several engineered and natural safety barriers in a deep geological repository ensure that the high-level waste is isolated from the human habitat at the earth's surface for a very long period of time.

Nuclear Energy Act

The Swiss Nuclear Energy Act stipulates deep geological disposal for all types of radioactive waste:

Art. 31 Obligation to manage and dispose of radioactive waste

- 1 Anyone who operates or decommissions a nuclear installation is obliged to safely manage all radioactive waste arising from that installation at their own cost. The obligation to manage and dispose of radioactive waste shall encompass the necessary preliminary activities such as research and geological investigations, as well as the timely provision of a deep geological repository.

Art. 37 Operating licence

- 1 An operating licence for a deep geological repository is granted if [...]:
 - a. the findings obtained during construction confirm the suitability of the site;
 - b. it is possible to retrieve the radioactive waste without undue effort until closure of the repository.

Safe containment in the future

While the radioactivity is decaying, slow processes are taking place inside the deep geological repository: The bentonite backfill becomes saturated with water and the disposal canisters corrode. The behaviour of the bentonite and the Opalinus Clay host rock has been thoroughly researched. It is thus possible to make detailed statements about the future evolution of the repository until the radioactivity has decayed to natural levels (see pages 18-25).

By conducting experiments in underground rock laboratories in Switzerland and using models, scientists investigate the future behaviour of the safety barriers in a deep geological repository.

Learning from nature

The materials intended for use in the engineered barriers of a deep geological repository can be found in similar form either as natural ore deposits or as archaeological relics, or even both. These “natural analogues” can be regarded as a type of long-term experiment and offer valuable examples of the long-term behaviour of deep geological repositories (see pages 26-27).

Studies on natural processes that extend over very long periods of time help us to understand the long-term evolution of deep geological repositories.



© Comet Photoshopping, Dieter Enz

Figure 2

More than 100 people are working for Nagra on radioactive waste disposal in Switzerland.

Safety has the highest priority

The correct site selection and layout of the repositories ensure long-term safety. Nagra conducts extensive safety analyses to investigate the functioning of the engineered and natural barriers after the repository has been properly sealed. Increasingly detailed safety analyses are stipulated in all stages of the Sectoral Plan for Deep Geological Repositories, as well as for the following licensing procedures. These analyses must demonstrate that the population at the earth's surface is not exposed to potential additional radiation doses exceeding a specified level, namely the protection criterion of 0.1 Millisievert annually.

Nagra conducts extensive safety analyses and models the performance of the engineered and natural barriers after the closure of a deep geological repository.

This is equivalent to one fiftieth of the average annual radiation exposure of a resident of Switzerland.

Information for the future

The topic of how to mark a deep geological repository is frequently discussed. The purpose is to avoid unintentional intrusion into the repository. There are different options for preserving information on a repository over long periods of time.

Many countries around the world are occupied with the question of how to safeguard knowledge about deep geological repositories for future generations. One possibility is to keep the information in several archives.

Long-term safety – why?

The effect of radioactivity on hu

Radioactive waste must be safely confined and isolated from the human habitat to prevent the radionuclides contained in the waste from entering the human body.

Radiation is a natural component of our environment, coming mainly from soil and rocks. This includes the radioactive noble gas radon that can escape from below ground and accumulate in basements and cellars. Various other sources also contribute significantly to natural radiation exposure (see Figure 1, page 4, and Figure 6, page 11).

Radioactive substances emit ionising radiation. There are three types: alpha, beta and gamma radiation. All of these have the ability to expel electrons from the atomic shell. This can lead to the breaking up of chemical compounds, which is why these radiation types are termed ionising. Alpha and beta radiation consists of particles. They are made up of helium nuclei and electrons. Like light

or radio waves, gamma waves are electromagnetic waves, but their wavelengths are much shorter, and they therefore have higher energy.

How to protect against radiation?

Three principles apply to protection against external radiation:

- Using shielding
- Maintaining a safe distance
- Limiting exposure time

It is possible to shield radiation sources. Depending on the radiation type, materials of differing thickness are needed. To retain alpha rays, a piece of paper or a few centimetres of air already suffice. Alpha rays do not penetrate the body's uppermost layers of skin. To shield beta rays, a sheet of aluminium with an approximate thickness of two millimetres is needed. This radiation type can



© SKB

Figure 3

Spent fuel assemblies in the Swedish interim storage facility CLAB in Oskarshamn: The radiation from the spent fuel assemblies is shielded by water.

mans

penetrate human tissue. Dense materials are needed to stop gamma rays. For example, to halve the gamma radiation emitted from the radionuclide caesium-137 (unstable isotope of the element caesium), seven millimetres of lead or 1.5 centimetres of iron are needed (see Figure 4). In nuclear power plants, water is used to shield against the radiation emitted by spent fuel assemblies (see Figure 3).

The effect of radioactive substances on human health is greater when they are ingested than when they impact the body externally.

Unit

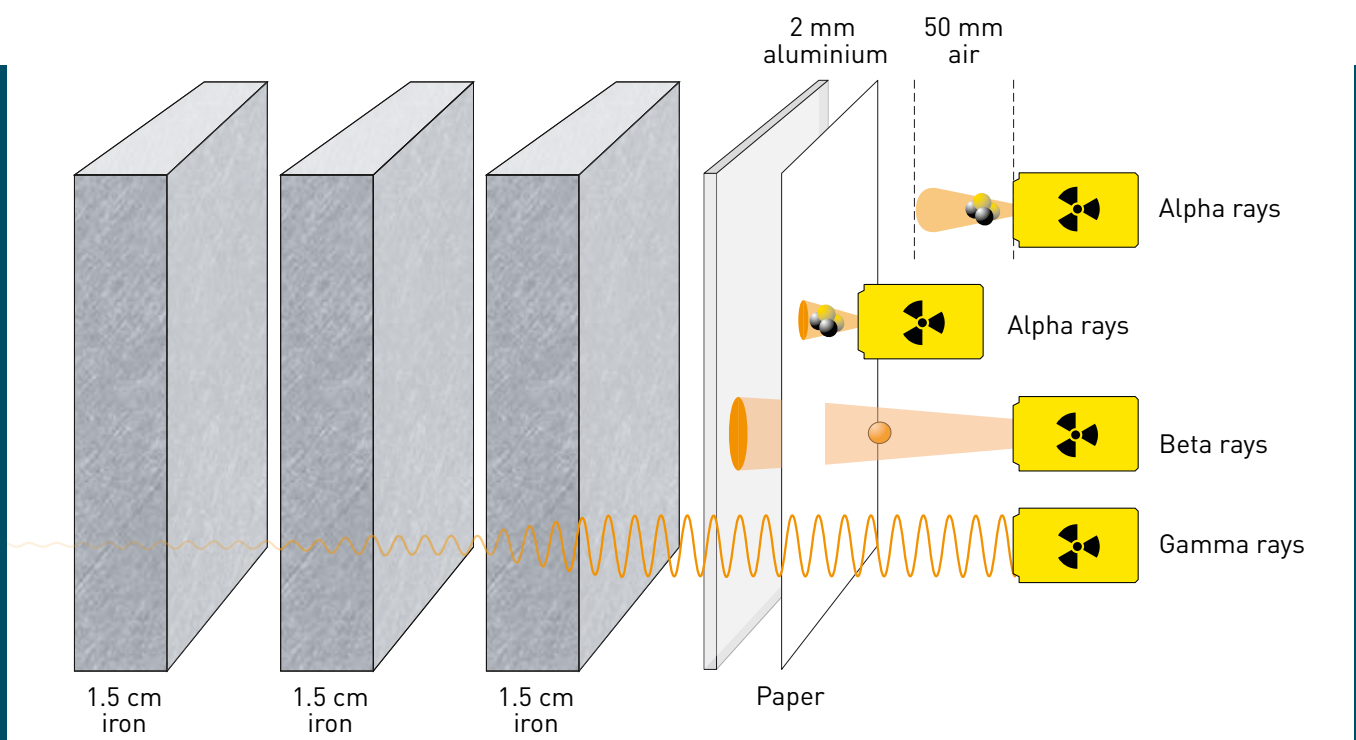
Sievert (Sv)

The dose caused by ionising radiation (alpha, beta, gamma and X-rays) is measured in Sieverts (so-called dose equivalent), which is a measure of the biological effect of radiation. The same dose in Sieverts represents an equivalent radiation dose.

$$1 \text{ Sv} = 1\,000 \text{ mSv (Millisievert)}$$

Figure 4

Shielding of different radiation types



Avoiding radiation exposure

It is possible to protect against internal radiation by avoiding the ingestion of radioactive substances through food, drinking water or air (see Figure 5). Filter masks, for example, are a possible protective measure when working with volatile radioactive substances in research or industry. In a private environment, it can be useful to air out the basement regularly to avoid exposure to radon. Surface contamination with radioactive substances can be washed off.

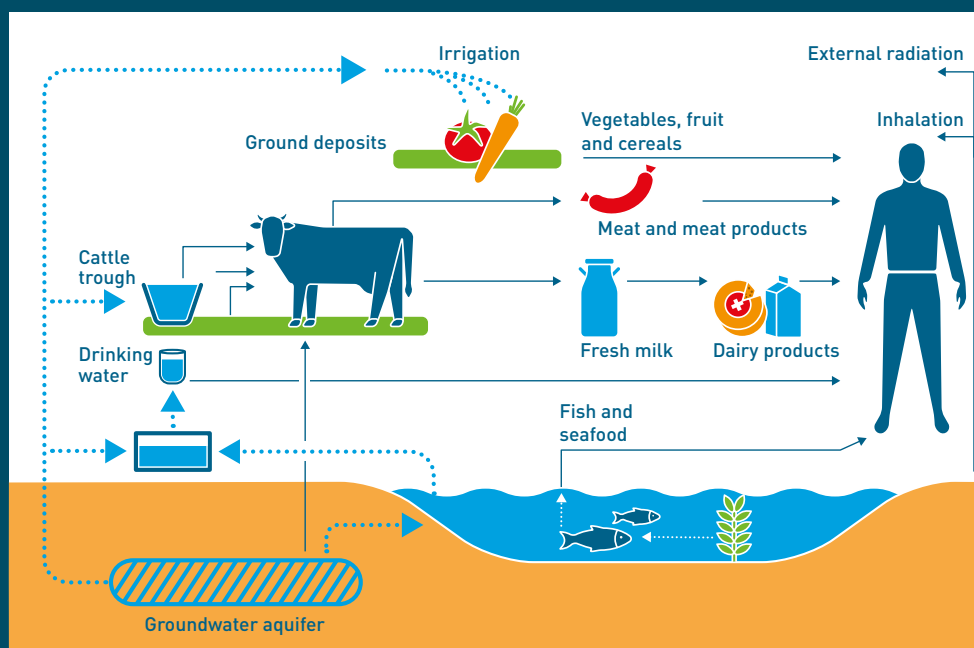
Inside the body, ingested radioactive substances decay, which can directly damage cells, tissue or organs. The duration of the radiation exposure depends on the half-life and the biological residence time of the radionuclides in the body.

Dose: a measure of effect

The effects of radiation depend on the ingested dose. If a dose of approximately 250 Millisieverts is ingested within a short period of time, the first signs of radiation sickness appear. This amount is more or less equivalent to the radiation exposure of 20 computer tomography scans from stomach to pelvis (see Figure 6). If the dose increases further, nausea, vomiting and headaches can occur. Excessive radiation exposure can lead to long-term damage such as cancer.

Ensuring safe containment

Radioactive waste must be safely enclosed and isolated from the human habitat (biosphere) to avoid the uptake of radionuclides into the body. To ensure this, Switzerland's radioactive waste will be disposed of in a deep geological repository.



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Figure 5
Absorption of radionuclides by the human body

Radiation doses from natural and artificial sources

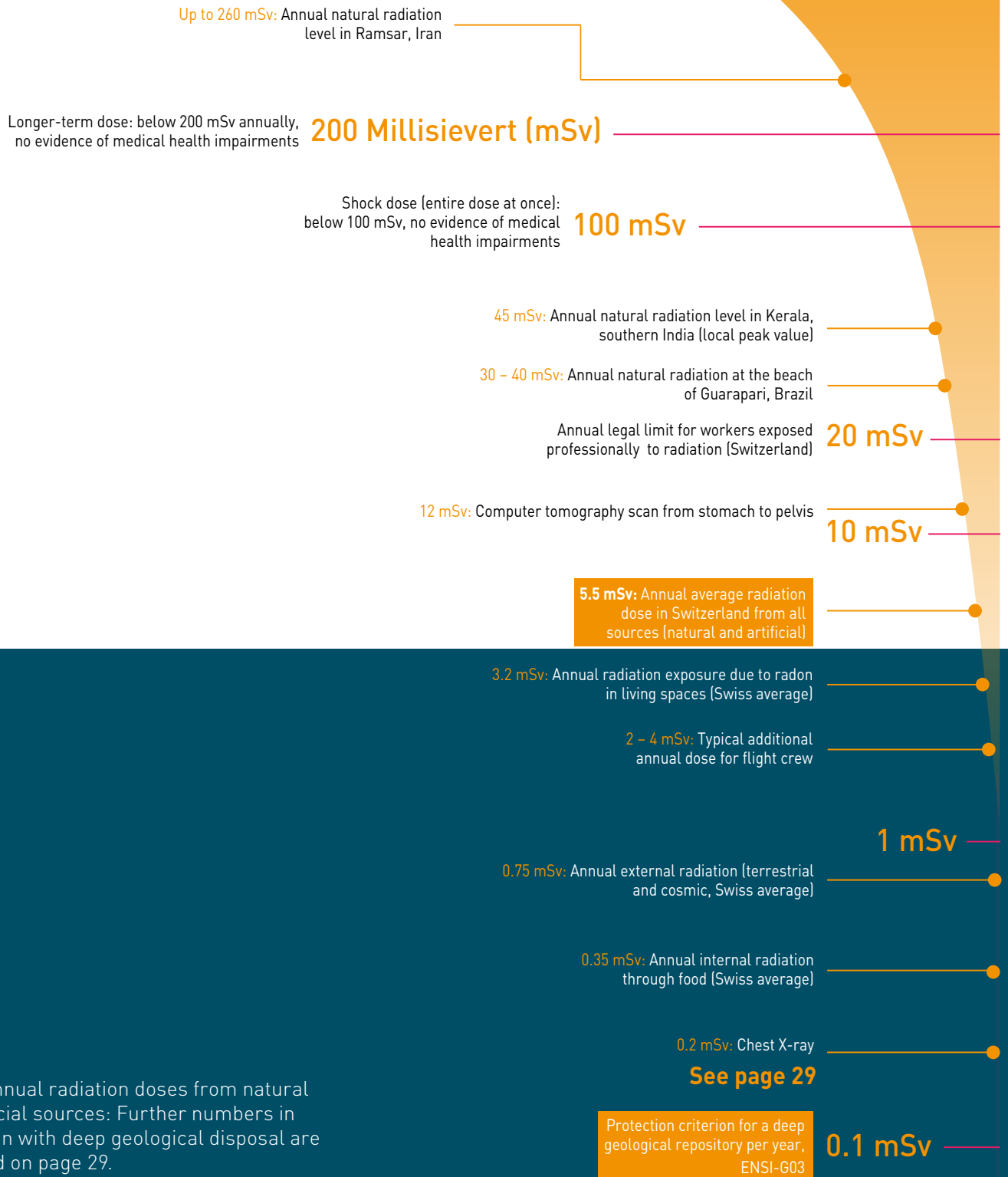


Figure 6
 Typical annual radiation doses from natural and artificial sources: Further numbers in connection with deep geological disposal are presented on page 29.

Today, tomorrow and th

Deep geological repositories fo

Scientists around the world agree that deep geological disposal of radioactive waste is the safest solution. Underground, the waste can decay over millennia until it has reached a harmless level comparable to that of natural radiation.

Radioactive waste must be disposed of in a way that ensures the permanent protection of humans and the environment. To achieve this goal, it must be kept separate from our habitat. Numerous geological investigations have shown that the underground in different areas of Switzerland has remained undisturbed over very long periods of time. It can be shown that rock formations remain stable and retain their properties over many millions of years, allowing for the safe containment of radioactive waste over long timescales. Deep underground and unaffected by occurrences at the earth's surface, time essentially comes to a standstill.

How long must the waste be contained?

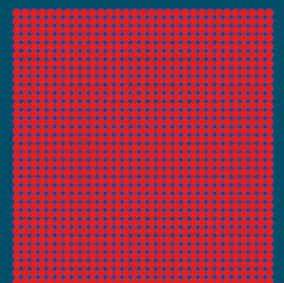
Most of the radioactive waste decays quickly (see Figure 7). After around two hundred years, the radiation level of the waste in a deep geological repository amounts to only a few per cent compared to its level at the time of emplacement. The proportion of radioactive substances with long half-lives radiates less strongly but over a longer period of time.

After 200 000 years, the high-level waste (HLW) is about as radiotoxic as the corresponding amount of natural uranium ore that was mined to make fuel assemblies. For the safety analyses, a time period of one million years is considered.

Waste in interim storage facilities

Figure 7

Decay of high-level waste over a time period of one million years



Cumulated activity of all fuel assemblies 1 month after removal from the reactor

100%

ereafter r long-term protection

Other concepts rejected

Aside from deep geological disposal, other waste solutions have been examined. These include:

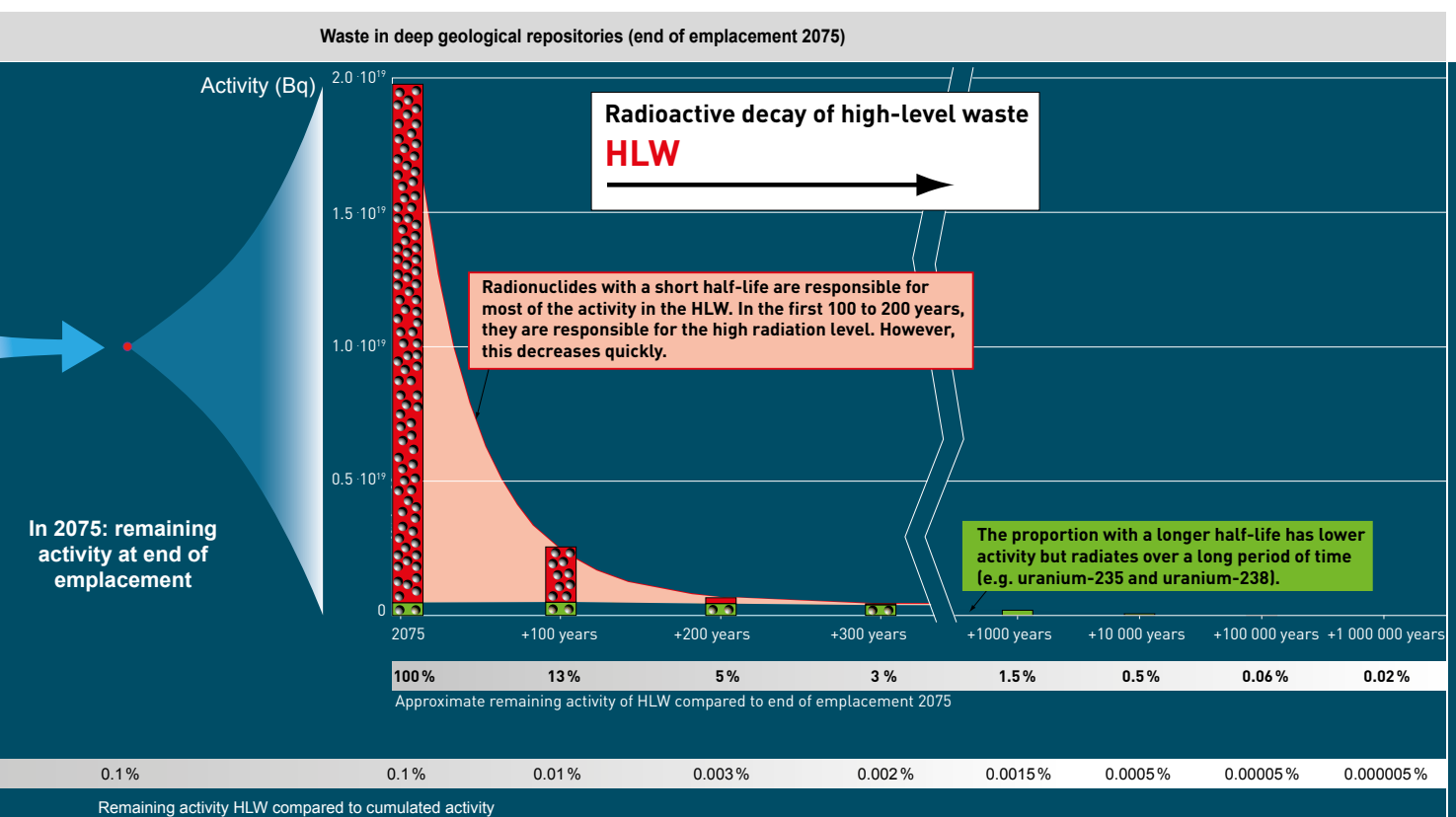
- Diluting the radioactive waste in the environment
- Disposal in undisturbed marine sediments
- Disposal in Antarctic ice-sheets
- Disposal in outer space

These concepts are no longer pursued. Disposing of waste in the sea, for example, is highly disputed and legally prohibited today. Using rockets to aid in disposal is too risky in case of explosions on take-off.

In Switzerland, the Nuclear Energy Act stipulates the disposal of radioactive waste in deep geological repositories. This is considered the safest method not just in Switzerland but is recognised by experts worldwide.

Long-term safety from the very beginning

Measures for the long-term safety of a deep geological repository already begin during site selection, layout and the construction of underground installations. During the site selection process, zones with deformed rock layers (fault zones) are avoided. The repository must, on the one hand, be constructed at sufficient depth to be protected from glaciers and erosion. On the other hand, excessive depth can compromise the engineered barriers and the host rock. The layout of the emplacement drifts in the host rock is important for the optimised emplacement of the radioactive waste. This ensures the best conditions for the permanently safe containment of the wastes.



Opting out of deep disposal means monitoring

Should a deep geological repository not be constructed, the waste would have to be permanently stored at the earth's surface. This would present society with an unsolvable task. Monitoring and maintaining such surface facilities would have to be ensured over many millennia. Societal developments are not foreseeable over such long time periods. Wars, revolutions, but also epidemics, could disrupt the continued monitoring of the waste, and there would be a risk of letting it fall into the wrong hands.

Sealed, but monitored

The Nuclear Energy Act stipulates the monitoring of radioactive waste. In the pilot repository (see page 16), the behaviour of the different safety barriers can be monitored after closure of the emplacement drifts. During this period, it must be possible to retrieve the waste without significant effort.

The monitoring results must be applicable to the processes occurring in the main repository as they form the basis for the decision to close the deep geological repository (Nuclear Energy Act, Article 66).

The duration of the monitoring phase is not stipulated. Future generations must decide themselves if and when they want to implement the final closure of the repository.

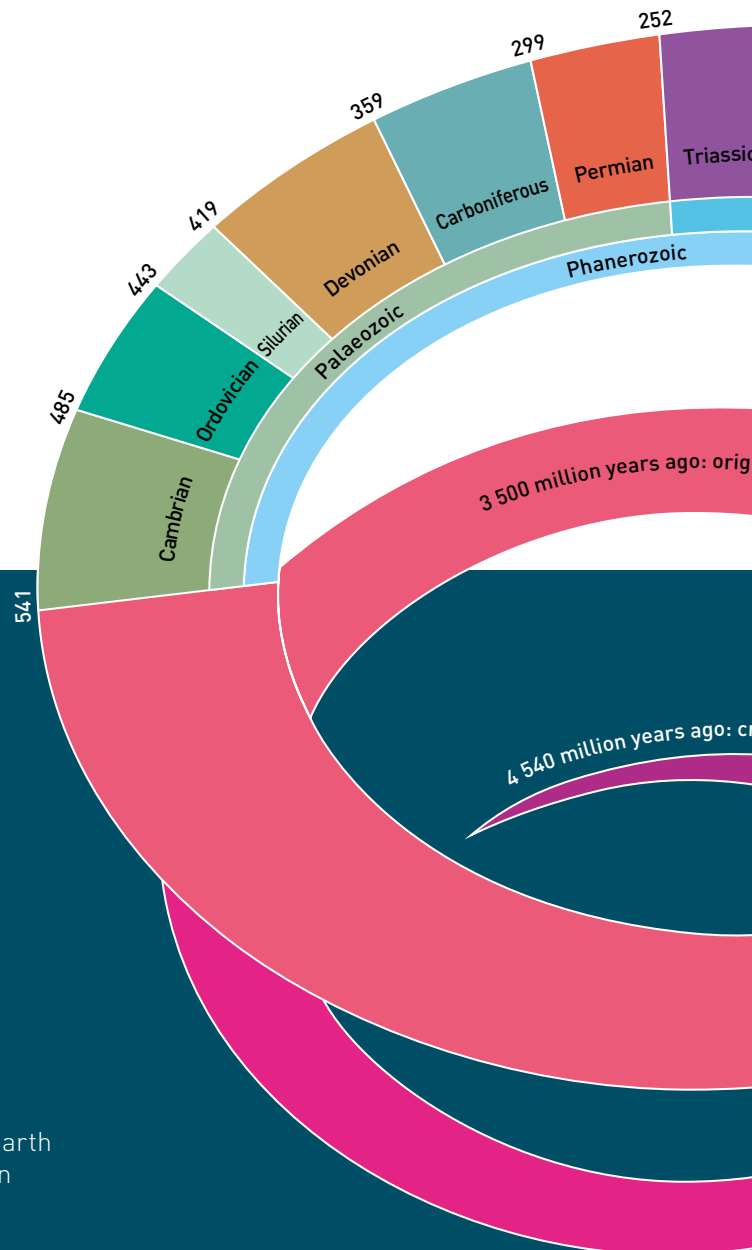
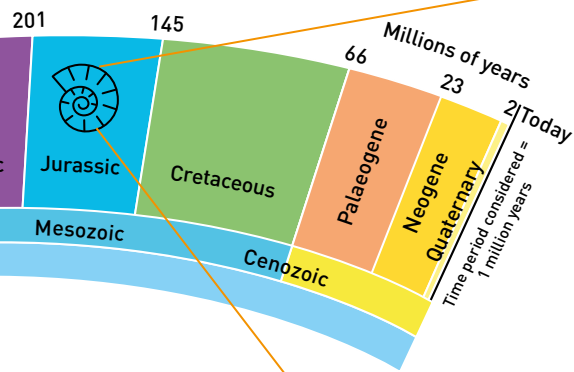


Figure 8
By the standards of human history, one million years is an inconceivably long time period. Compared to the age of the Earth (4.54 billion years) or the age of the Opalinus Clay (175 million years) proposed as the host rock for radioactive waste in Switzerland, it is only a short amount of time.

Barriers provide safety

In accordance with the Swiss disposal concept, a deep geological repository can be left unsupervised once it has been permanently closed. This means that it is passively safe during the entire containment period and does not require monitoring in the

long term. The repository is robust against future developments at the earth's surface or underground – with no need for human intervention. This is made possible through different engineered and natural barriers that reliably contain the radioactive waste.



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Opalinus Clay as the host rock

The argillaceous rock Opalinus Clay was formed in a shallow sea approximately 175 million years ago during the Jurassic period. Properties such as self-sealing and good radionuclide retention make the Opalinus Clay an ideal host rock for deep geological repositories. The Opalinus Clay was named after the fossil shells of the ammonite "Leioceras opalinum". Its name is derived from the iridescent (opalescent) sheen of its shell.



Deep geological disposal – safe

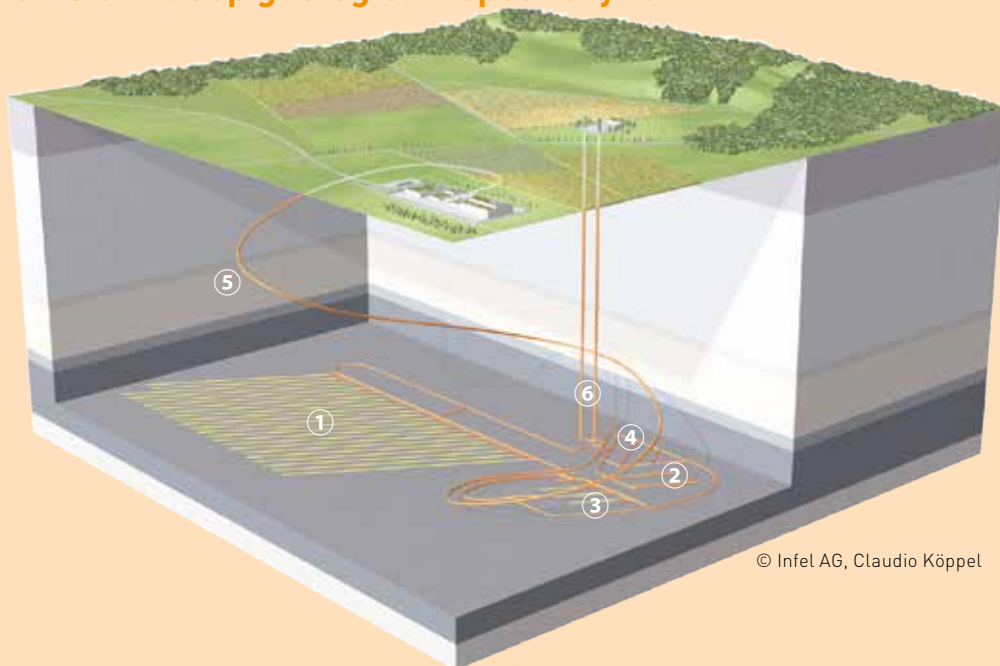
High-level waste must be isolated from the human habitat and thus also from the earth's surface for a very long period of time. This can be ensured by multiple safety barriers.

The safe containment of radioactive waste in a deep geological repository over long timescales (see text-box) can be ensured through a combination of engineered and natural barriers (see page 17).

Every individual barrier has the task of protecting the waste from disturbances and retaining the radioactive substances until they have decayed to natural levels.

The next pages provide a brief insight into how these safety barriers work.

Components of a deep geological repository for HLW



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1 Main repository for SF/HLW

Emplacement drifts for spent fuel assemblies and high-level waste

2 Repository for long-lived ILW

Emplacement rooms for long-lived intermediate-level waste

3 Pilot repository

Short emplacement drift in the deep geological repository where a representative volume of radioactive waste is disposed of. The pilot repository will be observed during the entire operating and monitoring period

4 Test area

This area is used for collecting data required for the operation of the facility

5 Access tunnel

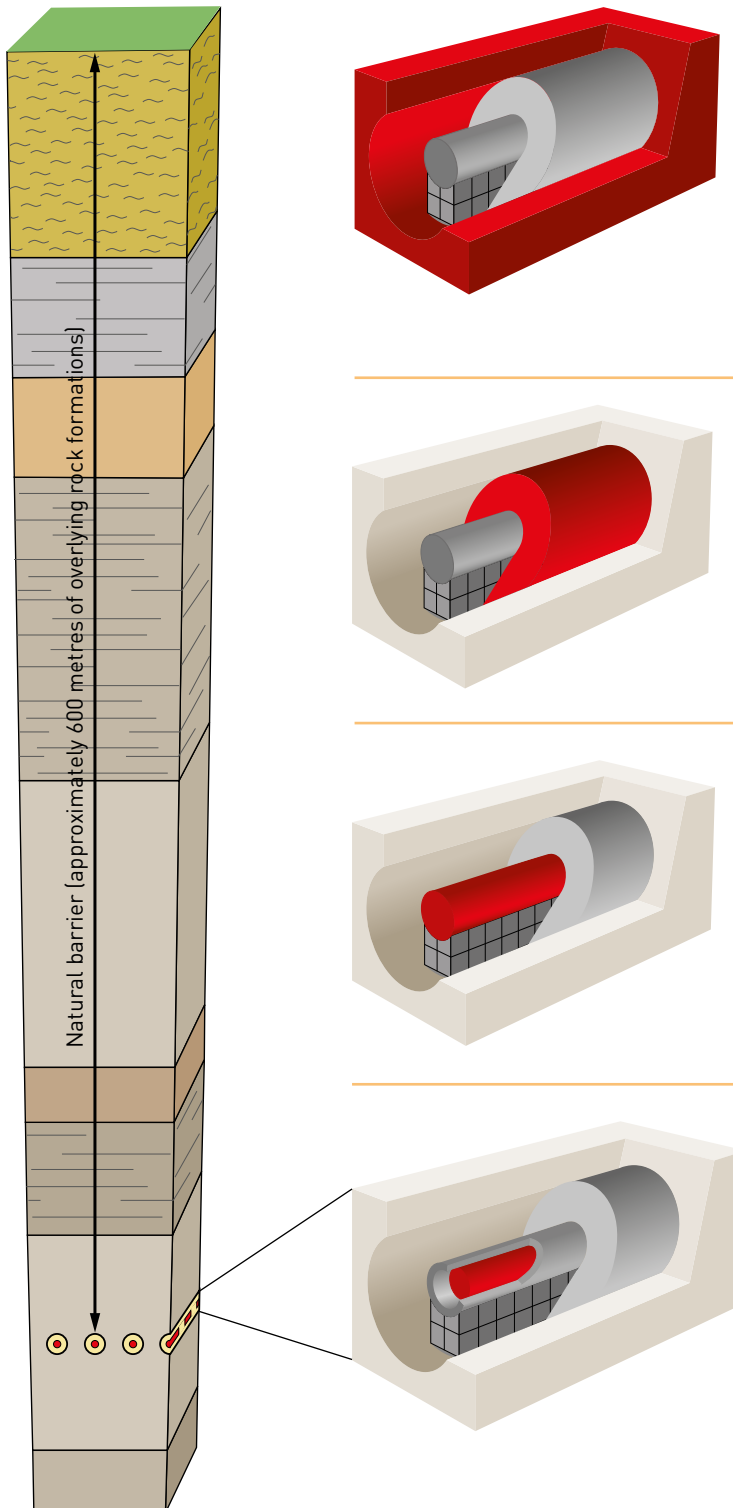
Access from the surface facility to the deep geological repository; access through shafts is also possible

6 Ventilation shaft and construction shaft

Shafts for the construction and ventilation of the deep geological repository

ty over long time periods

Safety barriers in a deep geological repository for high-level waste (HLW) and spent fuel assemblies (SF)



Natural barrier

- The emplacement drifts are constructed in the **host rock** (Opalinus Clay). The permeability of the rock is very low. Like bentonite, Opalinus Clay can bind radionuclides and thus retain them. The host rock and the rock layers above it protect the waste and the engineered barriers (e.g. against glaciers and erosion).

Engineered barrier

- The **bentonite** (clay) tunnel backfill has a very low permeability and swells on contact with moisture, thus sealing fissures and fractures. The clay minerals bind radionuclides.

Engineered barrier

- The thick-walled **disposal canisters** prevent the release of radioactive substances for at least 10 000 years.

Engineered barrier

- The **glass matrix** or the **fuel assemblies** and the radionuclides they contain have a very low solubility. This means that even when water enters the disposal canisters, radionuclides are dissolved in the water at a very slow rate.

The future evolution of a deep g

By conducting experiments in underground rock laboratories in Switzerland and using models, scientists investigate the future behaviour of the safety barriers in a deep geological repository.

 **0 to 100 years**

Bentonite slowly saturates

After the emplacement of the disposal canisters, the voids in the drifts of the main repository are backfilled with bentonite (see Figure 9). The bentonite slowly saturates with porewater that gradually diffuses from the surrounding Opalinus Clay host rock into the bentonite around the canisters. No free water flows through Opalinus Clay but it is still contained in its pore spaces. The water volume bound in the rock is approximately 120 litres per cubic metre of Opalinus Clay. By absorbing water, the bentonite begins to swell and thus forms a

practically impermeable homogeneous mass. The swelling bentonite also closes fissures generated during the construction process. The bentonite thus supports the self-sealing capacity of the Opalinus Clay.

Waste remains under control

Approximately 20 years after the start of emplacement, all the drifts are backfilled and sealed. Accesses to the deep geological repository remain open during the entire monitoring phase. The waste is monitored in a pilot repository (see page 16). It is important that the sensors used for monitoring have a long operational lifetime as they have to work properly for decades. At present, for example, scientists at the Mont Terri Rock Laboratory are examining fibre-optic cables for measuring temperature. These sensors may be suitable for future use in a pilot repository.



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Figure 9

At the Mont Terri Rock Laboratory, an experiment is already being conducted to test the backfilling of the emplacement drifts on a 1:1 scale.

eological repository

100 to 1000 years

Once the monitoring phase has ended, the deep geological repository is closed and all underground installations and access structures that are still open are backfilled and sealed. Monitoring can then be continued from the earth's surface.

Canister as a strong barrier

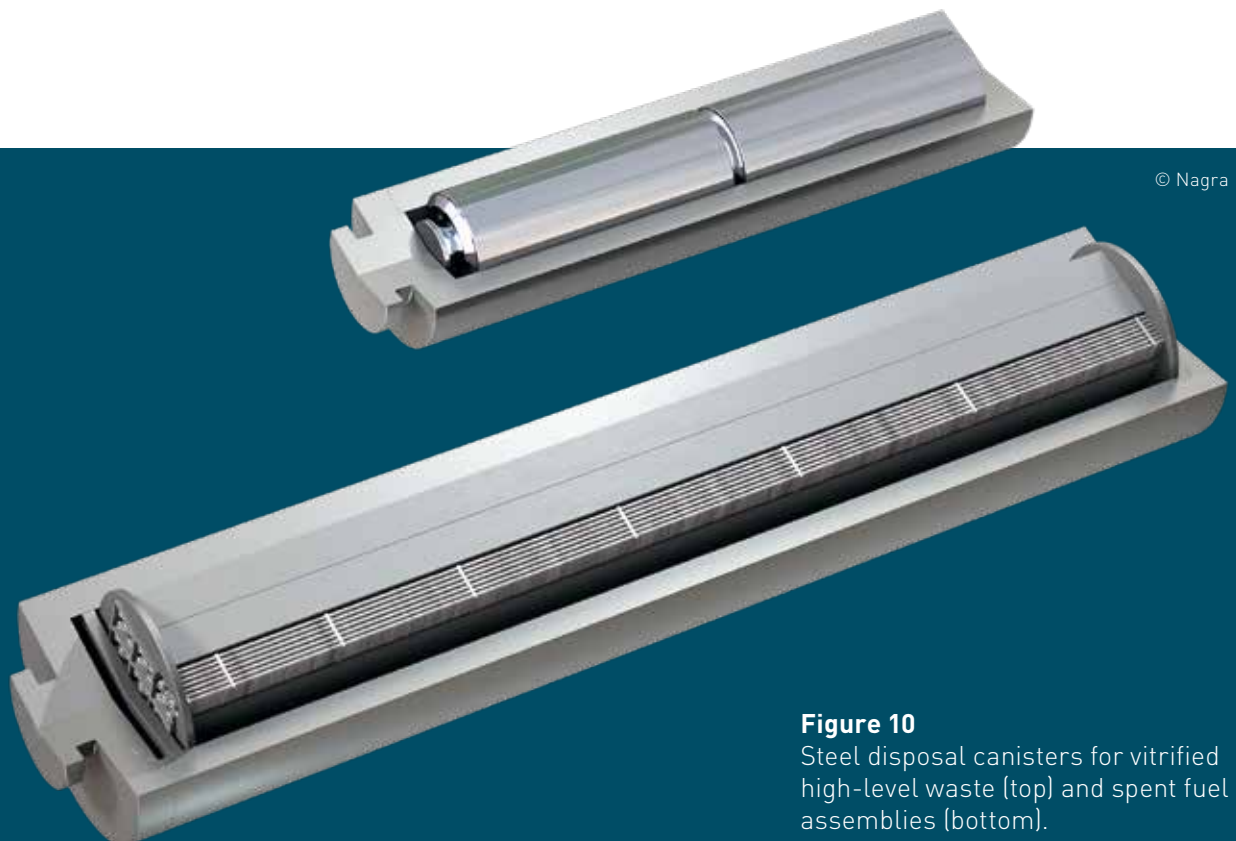
The current reference concept foresees the use of steel disposal canisters with a wall thickness of at least 15 centimetres. They must effectively contain the radioactive waste during the first thousands of years (see Figure 10). Alternative materials include copper or ceramics; Nagra is currently investigating these in cooperation with international research partners. The disposal canisters are expected to have a minimum lifetime of 10 000 years.

Radiation shielded

Direct radiation is shielded by the canisters, the tunnel backfill, the repository installations and the host rock. At a distance of just one to two metres from the tunnel wall, the radiation level of high-level waste is already below that of the rock's natural radiation level.

Conflicts of use can be ruled out

Potential conflicts of use are taken into consideration when selecting the siting regions. Of particular importance is whether economically exploitable raw materials exist in or close to the host rock. These include petroleum, natural gas or a potential geothermal energy source. Avoiding these regions reduces the risk of future generations looking there for these types of raw materials.



© Nagra

Figure 10

Steel disposal canisters for vitrified high-level waste (top) and spent fuel assemblies (bottom).

1000 to 10 000 years

Bentonite is saturated with water

By now, the bentonite is completely saturated with water and its properties resemble those of the surrounding host rock. It is practically impermeable and has the ability to bind radionuclides. This means that most of the substances remain attached to the clay minerals and are prevented from migrating further.

Waste cools down

The heat generated by the decay of the radionuclides in the high-level waste decreases continually over time. After approximately 1000 years, the thermal output of the fuel assemblies amounts to only roughly eight per cent of the value at the time of emplacement. The temperatures of the waste and the surrounding host rock have equalised.

Effects of gas formation can be controlled

The disposal canisters begin to corrode on contact with porewater. As part of the reaction between water and iron, hydrogen gas is produced. This non-radioactive gas must be allowed to escape or its volume reduced to avoid any unacceptable increase in the pressure in the emplacement drifts. Gas production could otherwise lead to the formation of fissures in the host rock and create pathways that could accelerate the migration of radionuclides. Experiments in the Mont Terri and Grimsel rock laboratories (see Figure 11) as well as calculations show that, even when steel disposal canisters are used, the gas pressures in the emplacement rooms remain below the point where the formation of fissures in the host rock is expected. The gas can be released at the interfaces between the host rock and bentonite.



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Figure 11

Numerous experiments are being conducted in the Mont Terri Rock Laboratory, including some on gas transport.

🕒 10 000 to 100 000 years

The disposal canisters are designed to remain absolutely tight for at least 10 000 years. Later, when they may have corroded through, the waste can come into contact with the surrounding porewater from the bentonite.

Radioactive substances can now dissolve very slowly from the spent fuel and the vitrified waste from reprocessing. Both are only poorly water-soluble. As there is no flowing water surrounding the waste canisters, the dissolved radionuclides can only move through the bentonite very slowly by diffusion.

What is diffusion?

Diffusion is a passive equilibrium of the concentration of dissolved substances between areas with higher and lower concentrations. A simple example is when a sugar cube is dropped into a cup of coffee. After a while, the coffee becomes sweet even if it has not been stirred. The sugar molecules diffuse until the level of sweetness in the coffee is the same everywhere, in other words until the concentration of sugar molecules has equalised in the coffee.

The host rock becomes the most important barrier

Radionuclides that have not yet decayed in the canister or during diffusion through the bentonite are retained by the Opalinus Clay as an additional natural barrier (see Figure 12).



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Figure 12

Nagra has evaluated the Opalinus Clay as a host rock for the deep geological repository for high-level waste and spent fuel assemblies.

Like bentonite, the Opalinus Clay has the ability to retain radionuclides. In addition, it is practically impermeable. Material transport is mainly by diffusion, as in bentonite.

Keeping radionuclides away from the human habitat

To keep radionuclides away from the human habitat, the deep geological repository must limit the transport of radionuclides with groundwater by means of a system of safety barriers. Even if faults

are present in the rock formations, groundwater cannot penetrate into the repository via these disturbances and enable the transport of radioactive substances. This is due to a further characteristic of the host rock: its self-sealing capacity. When Opalinus Clay comes into contact with water, its clay minerals begin to swell. Any fissures that formed are closed again and potential water flow-paths are sealed (so-called self-sealing). This has been demonstrated in numerous experiments and can be directly observed in outcrops (see Figure 13).



Legend

- Fault zone
- ← Shear direction

Figure 13

A fault zone runs through the Opalinus Clay in the photo, but the rock remains dry (Mont Terri Rock Laboratory).

Up to 1 000 000 years

No climate model can offer a reliable forecast over such a long time period. Within one million years, climate conditions will probably change several times and extensive glaciation cannot be ruled out. For this reason, different climate scenarios are considered for site selection.

Deep beneath the glacier

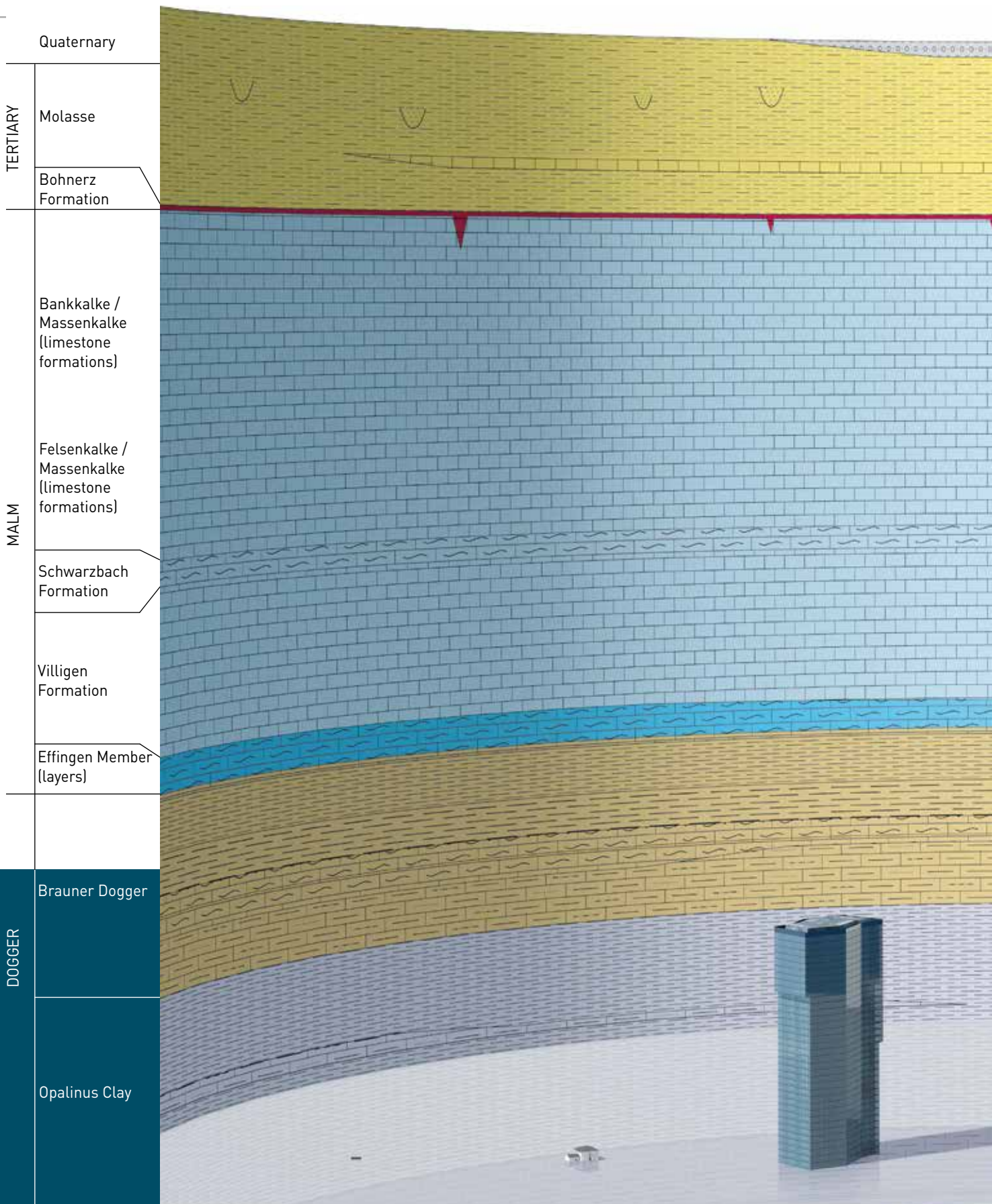
Geological processes such as erosion occur very slowly. However, to reliably prevent the exposure of the repository through glacial impacts or through uplift of the earth's surface (with erosion occurring

simultaneously), it must be constructed at a suitable depth. A HLW repository should be constructed at a depth of approximately 600 metres below the earth's surface depending on the site (see Figure 14, pages 24-25). Past geological developments provide clues about future erosion rates. It is thus possible to predict the future based on past events.

Nature also shows us how natural disposal systems, barriers or the host rock behave over very long periods of time. Examples of this are presented in the following section on natural analogues. They provide parameters and important indications for the model calculations.

Earthquakes – a danger for deep geological repositories?

Strong earthquakes cannot be ruled out during the long time period under consideration. Deep geological repositories are thus constructed away from known underground fault zones, avoiding faults where stress can build up and suddenly be released. Within the disposal zone, a safe distance is maintained from faults. This prevents the disturbance of disposal containers and engineered and geological barriers due to movements at such zones. Fractures newly formed by earthquakes are quickly closed due to the swelling of the clays. This prevents radioactive substances from migrating with the water in the fracture.



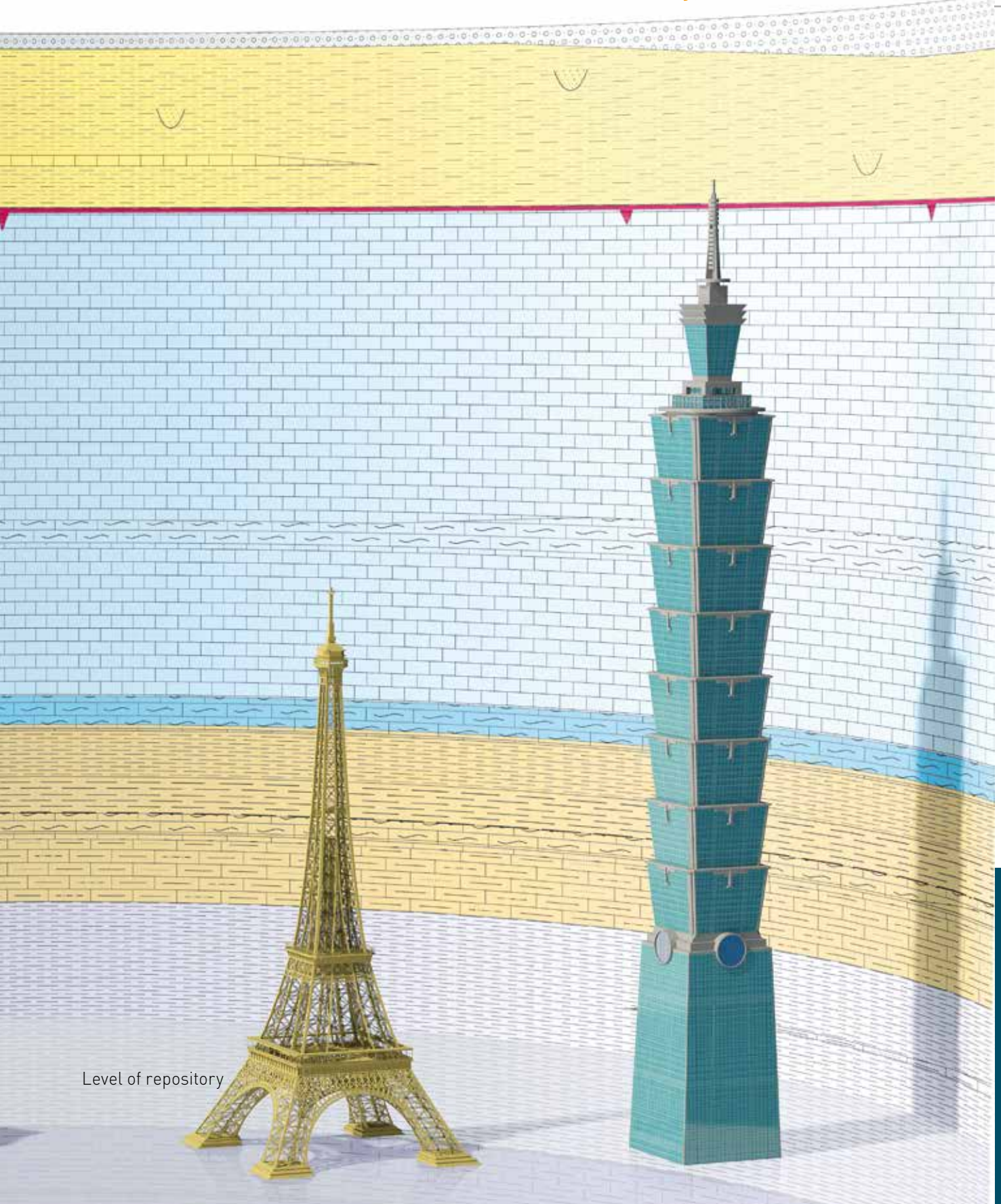
Disposal container
Diameter: 1 metre

Single-family home
Height: 6 metres

Prime Tower, Zürich
Height: 126 metres

Figure 14

This graphic illustrates the depth of a deep geological repository compared to the height of various structures.



Level of repository

Eiffel Tower, Paris
Height: 324 metres

Taipei 101, Taipei
Height: 508 metres

What can nature teach us about

Studies of natural processes that occur over very long time periods help us to understand the long-term behaviour of deep geological repositories.

It is not possible to conduct experiments over thousands of years. How can one then be sure that a deep geological repository will retain radionuclides over very long time periods?

Processes and phenomena can be found in nature that are similar to those occurring in the environment of a deep geological repository. These so-called natural analogues deepen our understanding of how repositories will evolve over long timescales. As opposed to short-term laboratory experiments, it is possible to observe processes and phenomena that have been ongoing for many millions to billions of years.

Natural reactor as an example

The natural reactors in Oklo (Gabon, Africa) are an important natural analogue. Approximately two billion years ago, natural nuclear chain reactions took place, resulting in the formation of several tonnes of highly active fission products under very high pressure and high temperatures (up to 600 °C) that continuously decayed over time. These figures are not the most important lesson for deep geological disposal of high-level waste. The key fact is that, over a time period of two billion years, the fission products were transported only a few metres. Nature has thus already created a deep geological repository at Oklo (see Figure 15).

Glass serves as a barrier

Lava erupting from a submarine volcano alters to volcanic glass because it cools off very quickly (see Figure 16). The best-known example of volcanic glass is obsidian. Stone Age cultures favoured it due to its properties for making tools and weapons.



© Nagra

Figure 15

The natural reactor in Oklo is a good example of a natural repository and the retention of radionuclides in rock.

disposal?

These tools are very well preserved to this day. Investigations of volcanic glass that formed in the sea show a corrosion rate of only a few micrometres over 1000 years. The very slow rate at which this process occurs means that glass is an excellent barrier for the containment of radionuclides.

Waste products are generated during the reprocessing of spent fuel assemblies. These are solidified in a vitrification process and transported to the repository in welded steel containers.

Steel corrodes slowly underground

Steel is used for disposal canisters in deep geological repositories. The corrosion rate of steel can be estimated using archaeological artefacts. Humans have been able to make steel for approximately 3 500 years. How well these steel artefacts have been preserved provides information on their

corrosion rates. In environments low in oxygen – as in a planned repository – metals corrode very slowly. The corrosion layer itself functions as an additional protective layer against further corrosion.

Opalinus Clay contains seawater

The Opalinus Clay host rock is also a type of natural analogue. The approximately 175 million-year-old rock still contains 10 to 20 grams of dissolved salt per litre of porewater. This salt comes from the ancient sea in which the Opalinus Clay was originally deposited. The seawater contained in the rock over many millions of years demonstrates how well Opalinus Clay can retain substances over millions of years.

Further reading

Nagra special issue number 1: “Spuren der Zukunft” (in German)



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Figure 16

Volcanic glass is formed when lava cools off very quickly.

How can safety be demonstrated

The site selection and conceptual design of a deep geological repository ensure its long-term safety. Nagra conducts extensive safety analyses that illustrate the performance of the engineered and natural barriers after the repository has been properly closed.

Deep geological repositories have to meet the highest safety requirements. From the start, the primary goal of the selection process for potential geological siting regions has focused on long-term safety. The law and regulatory requirements call for the long-term safety of deep geological repositories to be demonstrated in safety analyses. These are conducted in several steps and become increasingly detailed. The knowledge gained is used to modify the conceptual design of the repository if necessary.

The legally permitted additional maximum radiation dose for the population is 0.1 mSv annually. This is roughly equivalent to one fiftieth of the average radiation exposure (see Figure 1, page 4). The analyses must demonstrate that the protection objective is met.

Various scenarios examined

Nagra conducts extensive safety analyses to investigate whether the deep geological repositories will exceed the specified maximum dose. These analyses form the base for evaluating whether a repository is acceptable from a safety perspective.

In the safety analyses, the potential release of radionuclides present in a deep geological repository and their potential migration pathways from the repository to the human habitat are assessed quantitatively. The calculations are based on the waste inventory as well as on scientifically underpinned data on the properties of the planned engineered and natural barriers. These properties include: location, geometry and properties of the rock, structural design, retention capacity of the barriers and the regional hydrological situation. All these factors are input into the model calculations. They also take uncertainties into account, which means that unfavourable conditions are also analysed when evaluating safety. The results are compared to the protection criterion (see Figure 17).

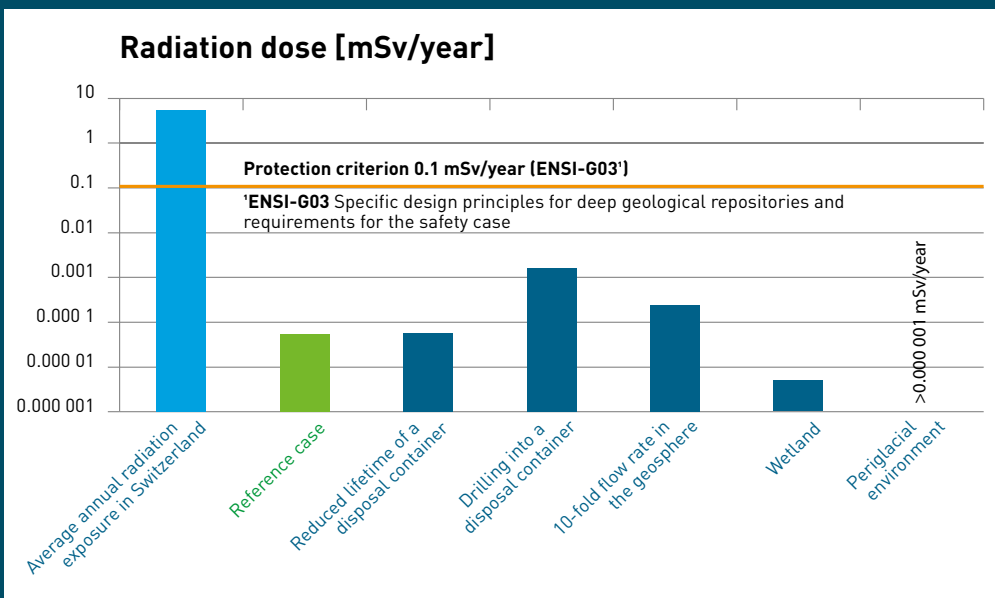


Figure 17
The safety analyses have to demonstrate that the dose values remain below the protection criterion (simplified, source: NTB 02-05, Table 8.2-2).

ed?

Scenarios covering all eventualities

Nagra looks at many different scenarios when conducting safety analyses. These include:

- Increased movement of water through the disposal zone
- Unfavourable diffusion values
- Increased solubility of radionuclides
- Elevated dissolution rate of emplaced fuel assemblies
- Reduced lifetime of disposal containers
- Decreased retention capacity (sorption) of the engineered barriers and the host rock
- Alternative climate variants

Protection criterion is met

Safety analyses to date have shown that, even under pessimistic, partly hypothetical assumptions about the behaviour of the engineered barriers and the host rock, the protection criterion of 0.1 mSv annually is met (see Figure 17). Human intrusion is considered in the safety analyses so that the possibility of directly drilling into a disposal container is also taken into account. Even in this case, the maximum radiation dose to the population remains below the officially stipulated protection criterion.

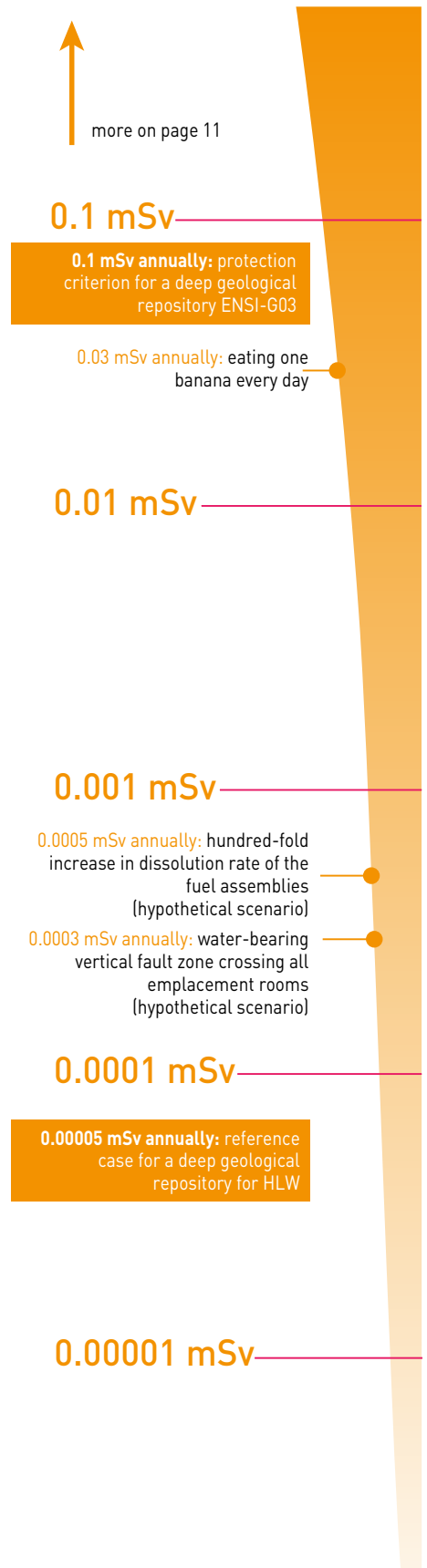


Figure 18

The safety analyses calculate the annual individual dose for a human. The diagram shows the maximum values for a time period of one million years. A diagram comparing these figures to natural levels can be found on page 11.

Passing on messages ov

Many countries around the world are considering the question of how to preserve knowledge about deep geological repositories for future generations. One possibility is to keep the information in different archives.

Knowledge about the site and the waste inventory of a deep geological repository must be preserved for as long as possible. Erecting warning signs to prevent inadvertent human intrusion is under discussion. The Swiss Nuclear Energy Act stipulates the permanent marking of a deep geological repository. The Nuclear Energy Ordinance calls for documentation that preserves all knowledge of the repository. After closure, the Federal Government must ensure that the information is preserved. How can this knowledge be maintained and passed on over very long time periods?

Preserving knowledge

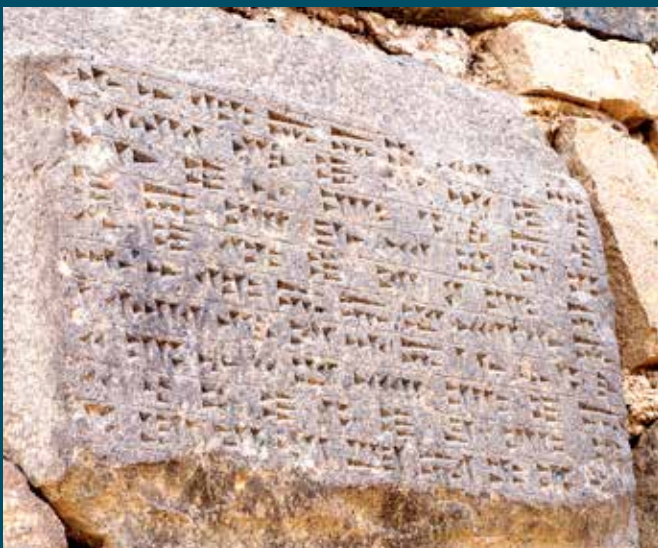
An international expert group of the Nuclear Energy Agency (NEA) of the OECD is looking at possibilities and strategies for solving this problem in its project

“Preservation of Records, Knowledge and Memory across Generations”. The group is developing strategies for preserving information and knowledge about deep geological disposal of radioactive waste over long time periods. The core issue is the idea of not just collecting knowledge in one place, but preserving information on the waste inventory, construction and location of the deep geological repositories in archives belonging to national and international government authorities. This measure should prevent all knowledge being lost at once.

If future societies go through major upheavals, the responsible authorities must still be able to make well-informed decisions based on all available knowledge. The primary goal of passing on information is to avoid an inadvertent intrusion into the repositories.

Messages for 100 generations?

None of the scientific studies and none of the countries dealing with the issue of marking deep geological repositories expect the marking to last



© Shaun Dunphy

Figure 19

Cuneiform inscription on a wall of the ancient fortress Erebuni located in present-day Armenia (approximately 800 B.C.)

for a million years, but rather for several thousand years. The radiotoxicity of the waste will have decreased significantly after this time.

Marking deep geological repositories

Research on passing on knowledge over generations and marking deep geological repositories is still in its infancy. Languages and symbols change constantly. What should unambiguous symbols look like that will still warn people if scripts and symbols change in the future (see Figures 19 and 20)?

The durability of the information medium is also important. Various ideas are under discussion for marking the site of a repository: on-site structures or clay fragments buried in the ground bearing information about the repository.

Long-term information

The safety of a deep geological repository depends on its location and design. The radioactive waste must be safely enclosed until it has decayed to a harmless level, and without the need for human intervention. Preserving knowledge about a repository is beneficial even when it is not a prerequisite for long-term safety. Passing on the information to several national and international authorities and archives is a good approach to preserving knowledge.

Passing on and preserving knowledge for future generations is not just a challenge in radioactive waste disposal. Preserving knowledge is a recurrent, major challenge for society.

Figure 20

These international hazard symbols warn of ionising radiation. The symbol to the right is supplementary and illustrates the correct behaviour when exposed to strong sources of radiation.



Glossary

Atom

(Ancient Greek: atomos “indivisible”) Atoms are made up of a positively charged nucleus (consisting of protons and neutrons) and a shell consisting of negatively charge electrons. In their normal state, these atoms are electrically neutral. They are charged by removing or adding an electron. This process is called ionisation and the resulting particle is an ion.

Bentonite

Bentonite is a rock consisting of several clay minerals with a strong ability to absorb water. It is formed by the weathering of volcanic ash and is used to seal structures. It is considered as a potential barrier in the deep geological disposal of radioactive waste. Bentonite is also found in other products such as cat litter.

Caesium (Cs)

Silvery in its pure state, this extremely reactive alkali metal melts at body temperature. The natural isotope Cs-133 is stable. All other caesium isotopes

are radioactive and occur only as synthetic fission products of nuclear reactions.

Conceptual design

The arrangement of building components to ensure that they meet their defined purpose. This can relate to all aspects of designing, constructing, manufacturing, operating and terminating a project.

Corrosion

The gradual transformation of a substance through the impact of other substances. One example is the corrosion of iron when it comes into contact with air and is exposed to moisture. This process is more commonly known as rusting.

Fault (geology)

A tectonically generated discontinuity where blocks of rock are moving or have moved against each other. Faults can vary in length between millimetres and kilometres (fault zone).

Fuel assembly

A fuel assembly consists of a bundle of fuel rods. These contain fissile material in the form of fuel (usually uranium). Fuel assemblies are used in the reactor of a nuclear power plant for the production of energy through nuclear fission. The primary sources of the radioactivity of a spent fuel assembly are uranium, neptunium, technetium, iodine and caesium.

Half-life

The amount of time it takes a specific radionuclide to decrease its amount and thus also its radioactivity to half of its original value. For example, the half-life of caesium-137 is approximately 30 years (see Figure 21).

High-level waste (HLW)

Waste that emits strong radiation and consists of fission and activation products separated from spent fuel during reprocessing and then immobilised with glass. In Switzerland, spent fuel assemblies that are not reprocessed are also considered high-level waste.

Natural analogues

Natural analogues are geosystems, materials and processes occurring in nature whose behaviour over long periods in the past is relevant for deep geological repositories. They include materials manufactured by humans.

NTB

Nagra technical report

Pilot repository

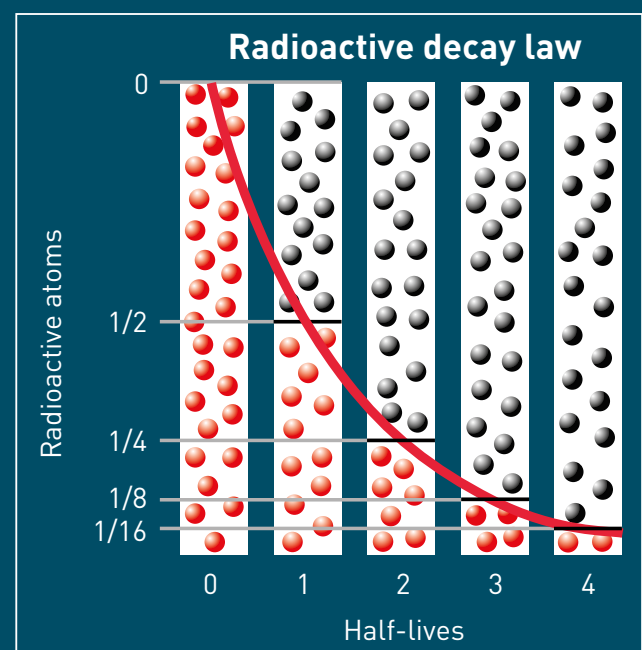
In a pilot repository, the behaviour of the waste, the backfill and the host rock is observed until the end of the monitoring phase. The resulting knowledge forms the basis for the decision to close the deep geological repository. The processes and systems monitored (e.g. safety barriers) must be transferable to the main repository.

Porewater

The water present in voids in soils and rocks.

Figure 21

The half-life is the amount of time it takes half the nuclei of a radioactive isotope to decay. The half-life varies from isotope to isotope and can range from fractions of a second to billions of years.



Protection criterion

For every future evolution considered likely, the release of radionuclides may not at any point exceed an annual individual dose of 0.1 mSv at the earth's surface (Guideline ENSI-G03).

Radionuclide

Unstable atomic nucleus that spontaneously decays while emitting ionising radiation. There are naturally occurring and artificially produced radionuclides.

Radiotoxicity

Term describing the damage radioactive substances can cause when they enter the human body.

Radon (Rn)

A radioactive noble gas that is a component of the air. It is responsible for the largest proportion of natural radiation occurring at the earth's surface. It is produced by the decay of uranium underground and then rises to the surface by migrating through

rock fissures. In Switzerland, the average effective dose per person caused by radon is approximately 3.2 Millisieverts annually. This amounts to roughly 60 per cent of the average annual radiation exposure.

Reference case

The reference case represents the most plausible situation and its evolution in a simplified manner. Safety analysis shows the effects of alternative scenarios compared to the reference case.

Reference concept (canister)

The thick-walled steel canister assumed in safety analyses.

Reprocessing

A chemical process whereby fissionable substances are separated from spent fuel. Residual uranium and plutonium are recovered from the spent fuel and used for the production of new fuel assemblies.

Underground rock laboratory

An underground laboratory constructed directly in rock where experiments can be conducted under realistic conditions on a 1:1 scale (e.g. to examine the properties of rocks or the construction of a repository).

Waste inventory

All of Switzerland's radioactive wastes are recorded in an inventory containing data on the origin and activity of the materials.

National Cooperative for the Disposal
of Radioactive Waste

Hardstrasse 73
Postfach 280

5430 Wetingen Switzerland
Tel. 056 437 11 11
Fax 056 437 12 07

info@nagra.ch
www.nagra.ch/

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Appendix 5: Radio – examples of programmes produced by the BBC in the late 90s

The BBC has specialist teams producing science programmes for TV and radio. The BBC also produces science programmes of its work for worldwide sale and also maintains comprehensive science web pages as part of its website (www.bbc.co.uk). The style and content of its TV and radio programmes depend on their intended destination and audience. The examples described here are of programmes broadcast on Radio 4 - the domestic speech channel. In April 1998 the then Radio 4 Controller changed the scheduling of many programmes causing much consternation amongst its conservative listeners. Radio 4's main coverage of science was rescheduled to a special 'science slot' at 21:00 from Mondays to Thursdays with occasional short pieces at other times in the week.

1. Frontiers: Nature's nuclear dumps

This 30 minute programme was broadcast in April 1998 at 21:00 on a Wednesday in the first week of BBC Radio 4's new schedules. 'Frontiers' was advertised as one of the new 'cutting edge' science programme for the network. Thus it had to have a good science base, be suitably 'high tech', have an appeal to their old science programme audience – scientists and interested public and hopefully attract new, younger listeners. A tall order – but the BBC chose to cover NAs in their new flagship programme.

The programme:

Presenter is Peter Evans – a much respected voice of science on Radio 4. Tone is serious, considered but willing to be controversial discussing issues.

Based on the UK perspective and was made after the enquiry into UK Nirex's application to site a GDF in the Sellafield area. It contained the following topics:

Nuclear energy and nuclear power

Radioactive waste

Fears about radiation

Natural analogues – Loch Lomond, Roman nails, Maqarin, Oklo

Greens suspicions and views of nuclear industry

Views of Nirex etc

Voices used include: Ian McKinley (Nagra), Gus McKenzie (SURRC) and Alan Hooper (UK Nirex).

Sites visited were all in the UK

A balanced discussion is attempted in the programme about radioactive waste disposal.

2. Postmarks: Bugs and radiation

Postmarks was an infrequent series of programmes where working scientists sent 'postcards' back to the UK whilst working abroad. This particular series was also broadcast on the BBC World Service Radio. This 15 minute programme was broadcast in June 1999 at 21:45 on a Saturday evening. It followed an arts review programme (film, theatre and book reviews) and preceded the Saturday evening play. The programme had to be entertaining and light with science as the 'filling in the sandwich'. Audience research also suggests that many of the listeners at this time are preparing to go out for the evening or are preparing for an evening at home with friends.

The programme:

Presenter was Julie West (BGS).

Story – A woman scientist working in Japan. Topic – microbiology in a uranium prospect (Tono) – a natural laboratory. It covers the following topics:

Preparations for the trip

The JNC guest house bedroom

The Tono mine discussing lack of uranium movement

A Japanese bath

Conversation about working women in Japan.