NAnet

Network to review natural analogue studies and their applications to repository assessment and public communication

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CEA, CSN, ENRESA, GRS, GTK, NRI, ONDRAF, SKB, UK Nirex
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Historical Perspective

Interest in natural analogue studies commenced some 25-30 years ago and they now form an integral part of all major national programmes for the deep geological disposal of radioactive wastes.

In the early days there was great optimism surrounding the potential of analogue studies and their use in performance assessment.

Historical Perspective

The initial euphoria during the late 1980's and early 1990s, however, became somewhat dampened with the realisation that, from a repository performance and safety analysis point of view, the majority of data produced were only qualitative at best due to the uncertainty in the historical development and previous boundary conditions of the natural geological systems being investigated.

Consequently direct use of quantitative analogue data in performance assessments was limited and mostly applied to the engineered barrier materials (e.g. long-term stability of canister and clay backfill materials), matrix diffusion processes and the checking/testing of geochemical codes and thermodynamic databases.

Historical Perspective

A period of soul-searching followed in the late 1990's.

This reassessment resulted in, for example, the need to integrate analogue studies with controlled experimental conditions, both in the laboratory and under *in situ* conditions in the field when possible.

The approach has helped to provide greater insight into the boundary conditions under which the analogue was or is active. This in turn has helped raise the confidence level and integrity of natural analogue studies, in particular their direct use in repository performance assessments (e.g. Yucca Mt. Peña Blanca analogue).

Historical Perspective

Other issues of importance recognised included:

- The increased awareness of improving dialogue between the geoscientific fraterity involved in the analogue studies and the end-users (e.g. performance assessors; regulators) and not least the general public.

Present Emphasis

- Although direct use of quantitative analogue data has improved, it is still limited in repository performance assessments.
- The indirect use of qualitative analogue data in the form of features, events and processes (FEPs) is being increasingly recognised.

  FEPs are used in the development of scenarios which provide the building blocks to safety and performance assessments (e.g. nuclear criticality; radiolysis; glacial events; radionuclide transport and retention).
- Communication is given greater emphasis.

The NAnet Project (2003-2005)

Prior to 2003 much natural analogue data had been published and several natural analogue reviews had been produced during the years. Some of these were focussed on national disposal concepts, whilst others were more comprehensive and global in approach. Some reviews were restricted to specific areas such as radionuclide transport or waste package materials or analogue application to performance assessment etc.

The overall **aim** of the NAnet project was to review the past and present use and understanding of natural analogues as a whole and to make recommendations for their future use. More active reference to FEPs has also been a feature.

The NAnet Review

NAnet was the first international review project to integrate participants with expertise in:

- conducting analogue field studies
- performing PA and applying assessment models and codes
- regulatory and licencing issues
- public communication

The **scope** of the project was to focus on deep repositories (HLW; ILW) but relevant applications to surface repositories (LLW) were also recognised.

The NAnet Review

Objectives

- Host an international workshop to access additional relevant information from researchers, safety assessors and representatives from waste management organisations not directly involved in the project.
- Critically review a wide range of analogue studies and their past applications to PA and public communication.
- Consider any potential added value from these past studies that may be applied to future safety cases and stakeholder dialogue programmes.
- Develop a database of ’quality approved’ (i.e. peer reviewed) analogue information related to important FEPs, and identify key areas where further natural analogue research is needed.

The NAnet Review

Primary audience

Geared to safety assessment and stakeholder dialogue specialists in disposal agencies, regulatory bodies and related institutions.

Main outcomes

- Input resulting from the international workshop on natural analogues.
- Documenting over 70 peer reviewed natural analogue studies.
- Production of 4 Work Package reports (Near-field, Far-field, Surface environment, Communication).
- Synthesis report (overview and recommendations)
- Project website

Background: Role of analogues and the reasons for their use

The NAnet review presented a very useful state-of-the-art summary chapter addressing issues relating to the derivation and common usage of analogue studies:

- Reasoning by analogy
- Supporting management approaches
- Providing realism in assessment models
- Identification of knowledge gaps
- Confidence building and multiple lines of reasoning
- Dealing with uncertainty
- Repository development programmes

Background: Role of analogues and the reasons for their use

- The application of analogues to safety assessment modelling
  - Conceptual model development
  - Data provision
  - Model, code and data testing and validation
  - Sub-system understanding
    - Near-field issues
    - Far-field processes
    - Near-surface and surface environment processes

Table 1: Factors and criteria to be considered when using an analogue

Factors that strengthen an analogue	**Factors that weaken an analogue**
Relevance – the analogue must be relevant to the issue being considered.	*Dissimilarities ignored* – if obvious dissimilarities are ignored then the value of the analogue can be compromised.
Number of instances – there should be a large number of instances of the analogue, conversely the analogue should not be unique.	*Number of dissimilarities* – large numbers of dissimilarities will weaken the analogue.
Number of similarities – the analogue(s) should show a large number of similarities with the issue being considered.	*Counter examples* – where analogues are ignored that counter the argument.
Variety of instances – a number of different types of analogues should support the issue being considered.	
Familiarity – the analogue should be familiar and easily appreciated by the intended audience	
Modesty of conclusion – the value of an analogue is increased if the strength of the similarity is not over emphasised.	
Integration of lab and in situ experiments – process boundary conditions may be more constrained	

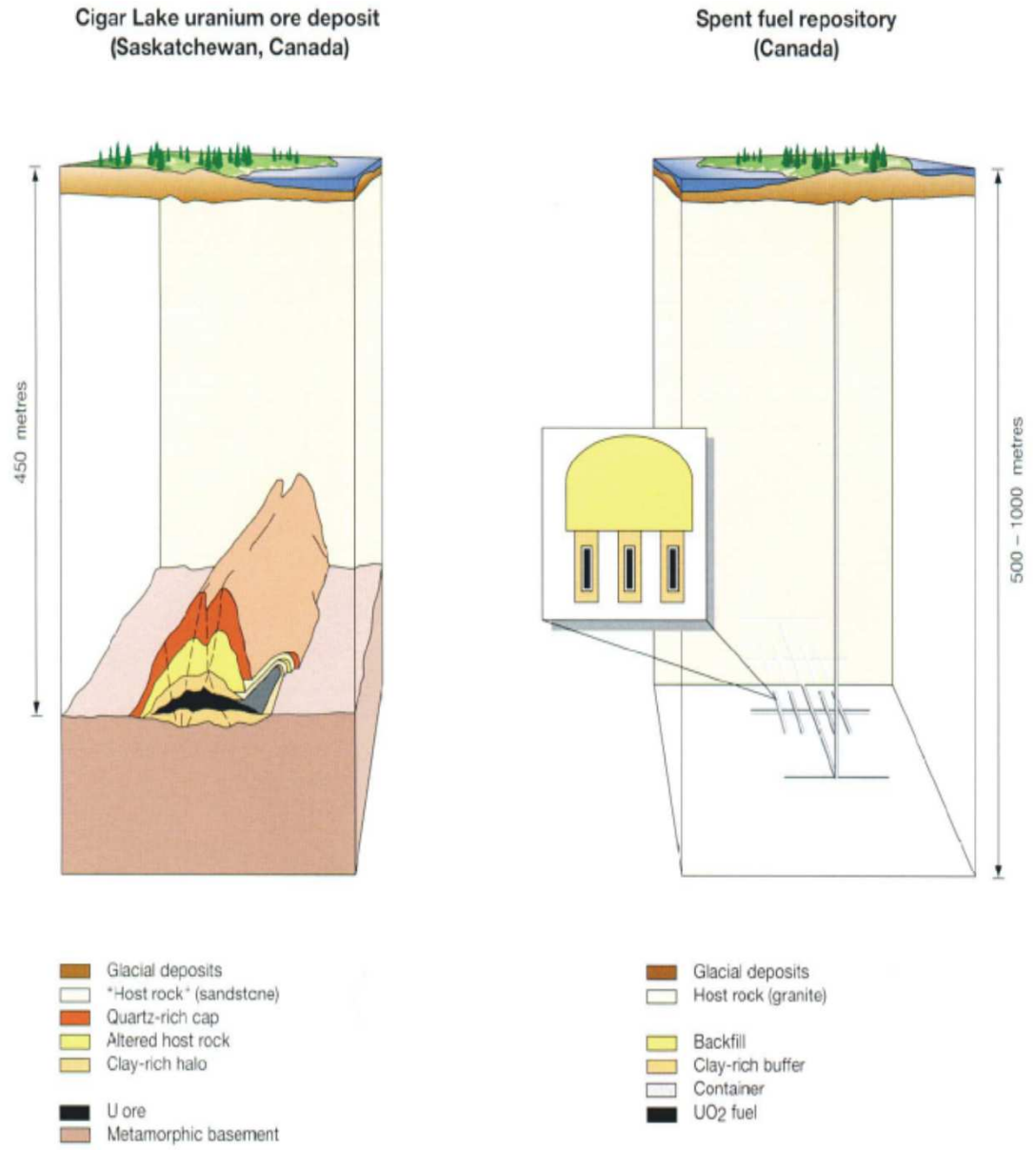


Figure 1: Comparison of the Cigar Lake uranium orebody and the structure of a spent fuel repository, showing the similarities and differences between the two systems

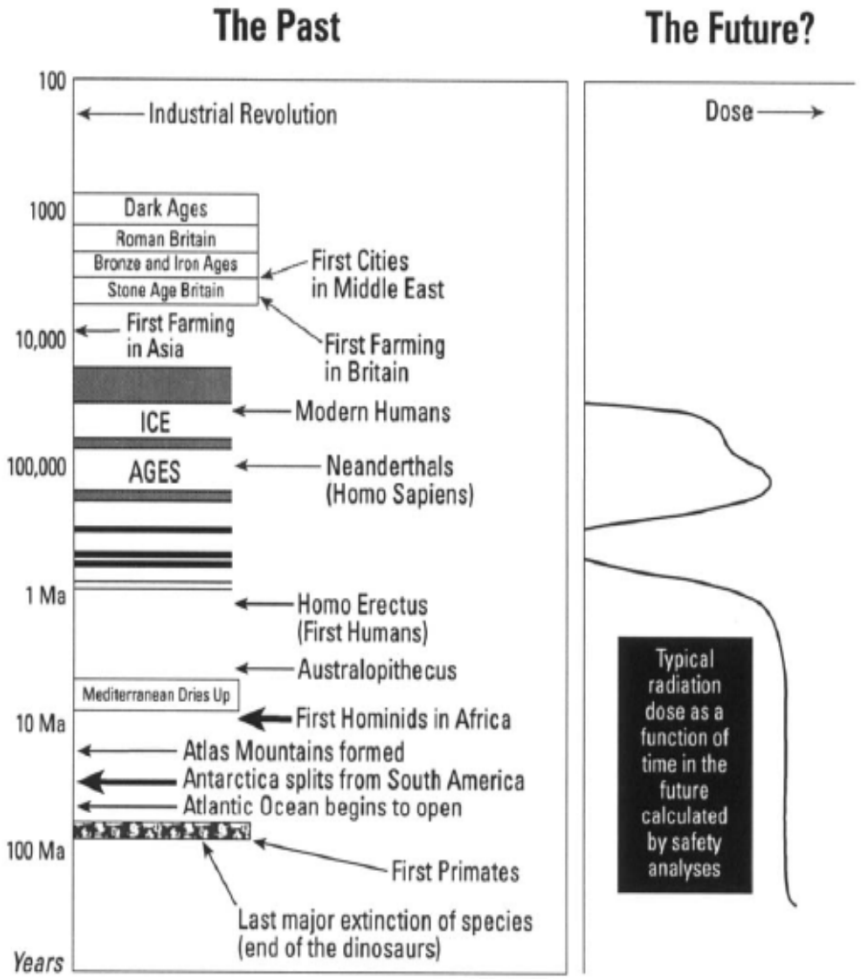


Figure 2: Comparing future assessment time periods with past history. Analogues help to put these timeframes into human context. The vertical axis is time (past and future) on the same scale

Table 2: The advantages and disadvantages of analogue studies compared to field and laboratory experiments. In reality, both are required and should be seen as complementary to each other

Analogue studies	**Field and laboratory experiments**
Operate over very long time periods, typically thousands or millions of years	Short-term experiments, lasting weeks to a few years at most
The boundary conditions of the analogue system are often poorly constrained	Well defined boundary conditions for the experiment that are set by the researcher
The materials in analogue systems only approximate the nature of repository materials	Can use the technological materials which will actually be used in the repository design
Natural systems are complex and involve coupled processes, so are realistic but hard to model	Very simple experimental systems which facilitate modelling of the results but may be unrealistic
Processes take place at natural reaction rates and under natural conditions in analogue systems	Reactions are often accelerated by raising the temperature or using aggressive reagents
Reactions in analogue systems can demonstrate inherent kinetic constraints	Thermodynamic assumptions allow little consideration of reaction kinetics, and accelerated studies may exceed kinetic constraints

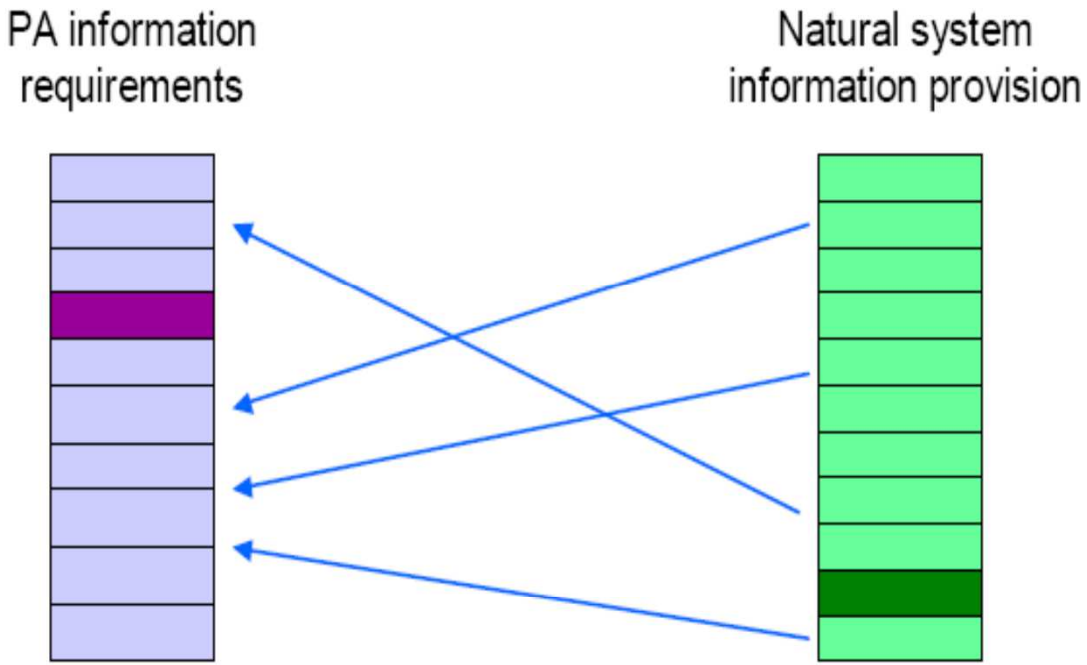


Figure 3: Mapping analogue information onto the requirements of the assessment models to identify knowledge gaps

Table 3: An example of the differences between modelling assumptions and analogue observations that may lead to over-conservatism in safety assessment

Process	Normal assessment assumption	Analogue observations		Benefit to assessment
Steel canister corrosion	The canister is not considered to be a barrier. May be implicit in a delay release factor.	Canister delays released by 50 to 300 y after closure	Corrosion rate data from iron analogues	Prolonged life of waste package
Degradation of cement wasteform	Assumes instantaneous saturation and leaching of cement	Degradation takes place slowly over thousands of years after closure	Analogue cement leach rate data; rates are slow and diffusion is controlled	Slower release of nuclides from the waste to the host rock
Chemical conditions	pH evolves rapidly over time due to rapid leaching of cement	Very slow evolution of pH buffered by mineral-water interactions	Maqarin studies reveals cement leach rates are slow	Longer radionuclide retention times

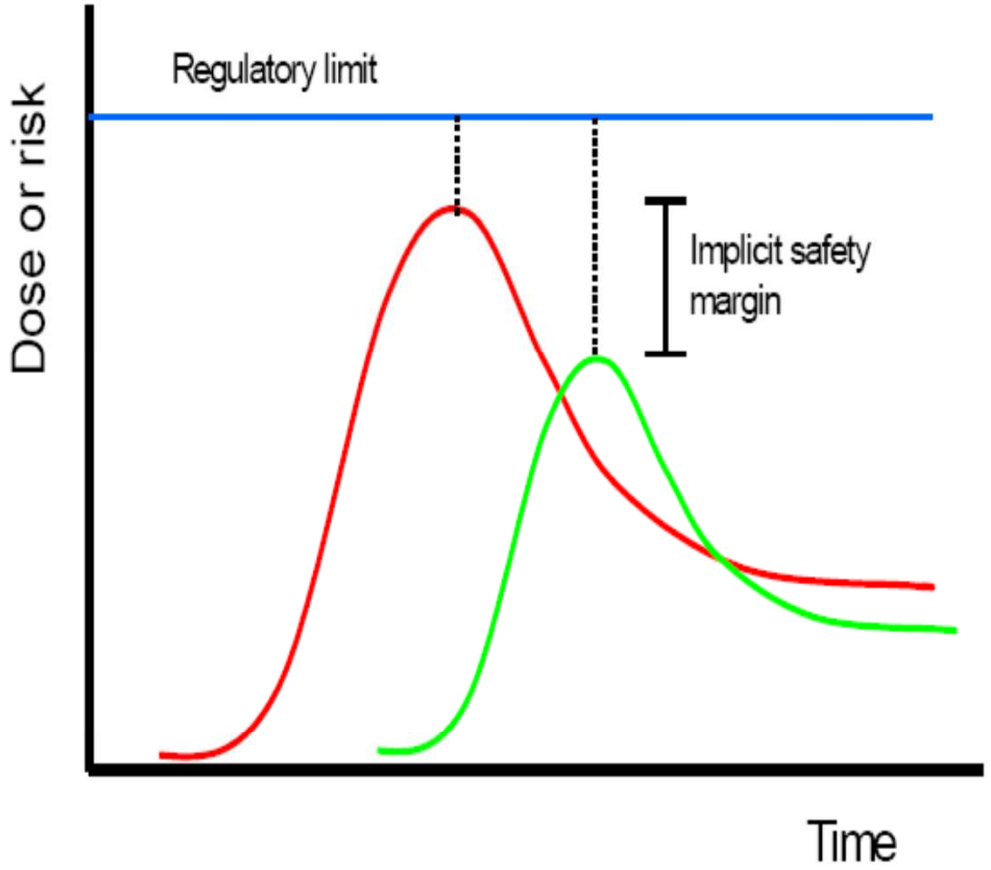


Figure 4: Idealised dose-time curves for a safety assessment that makes conservative assumptions (left-hand, red curve) and an assessment that makes realistic assumptions supported by analogue information (right-hand, green curve)

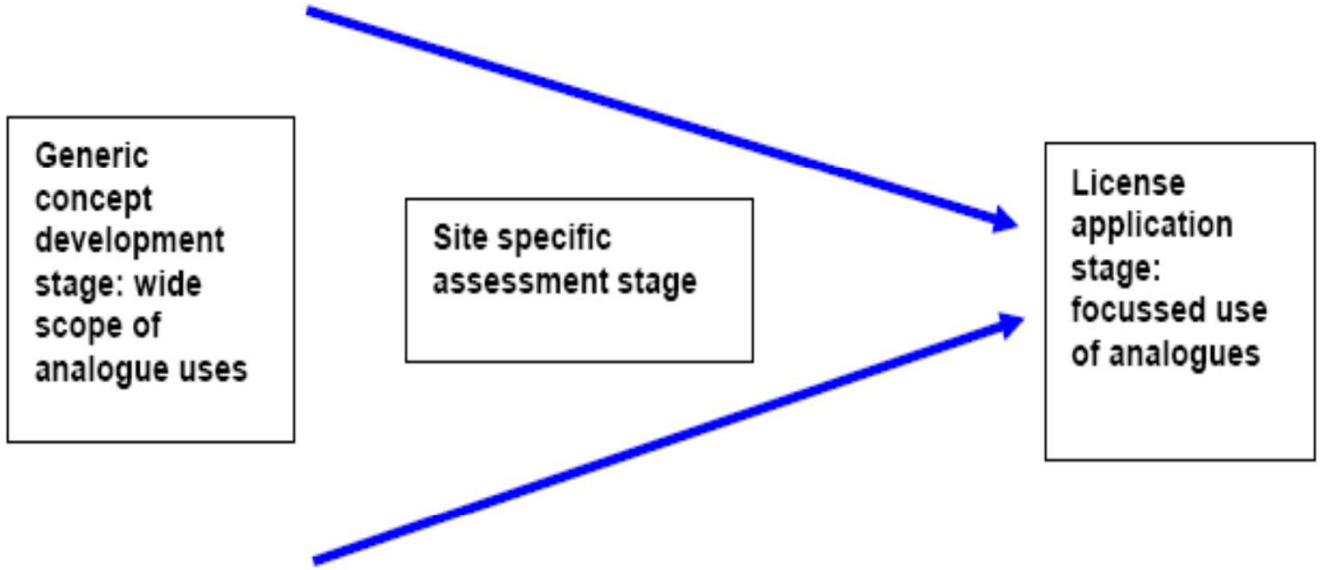


Figure 5: Changing use of analogues throughout a repository development programme

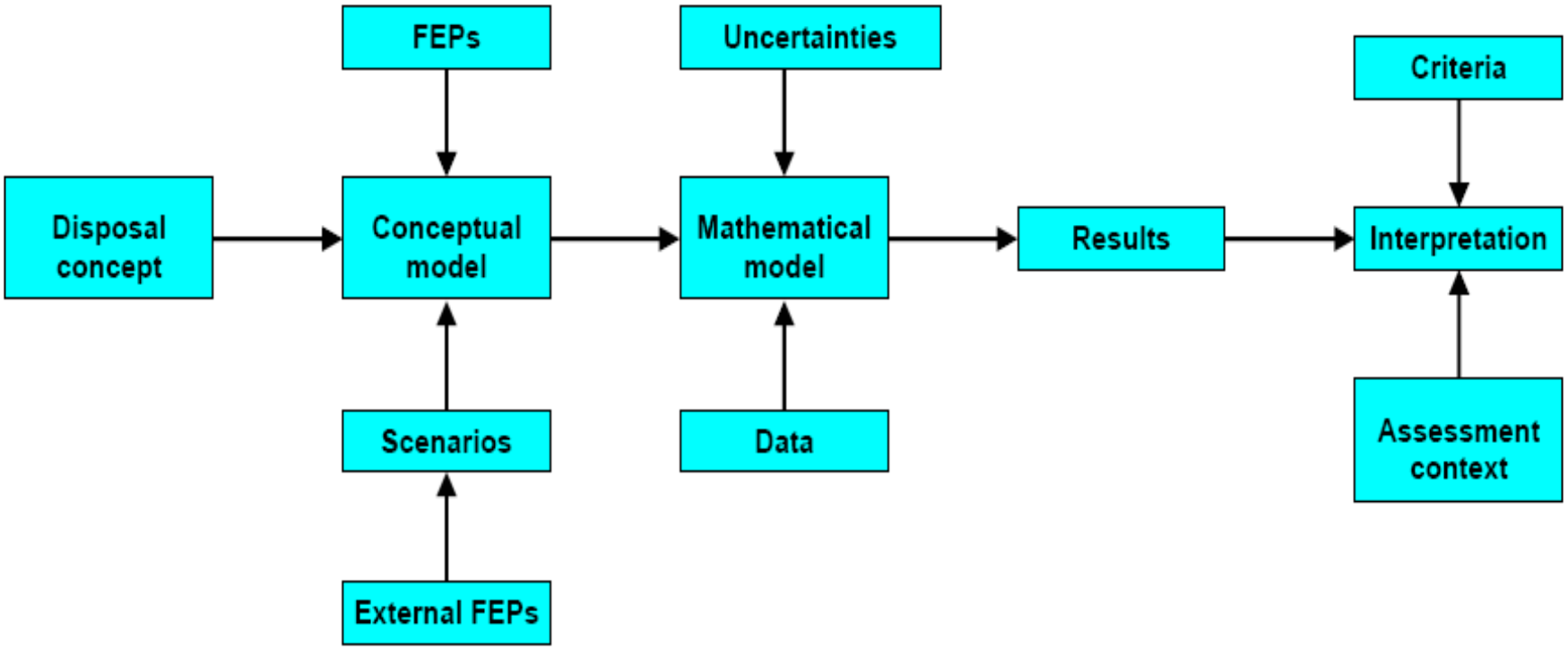
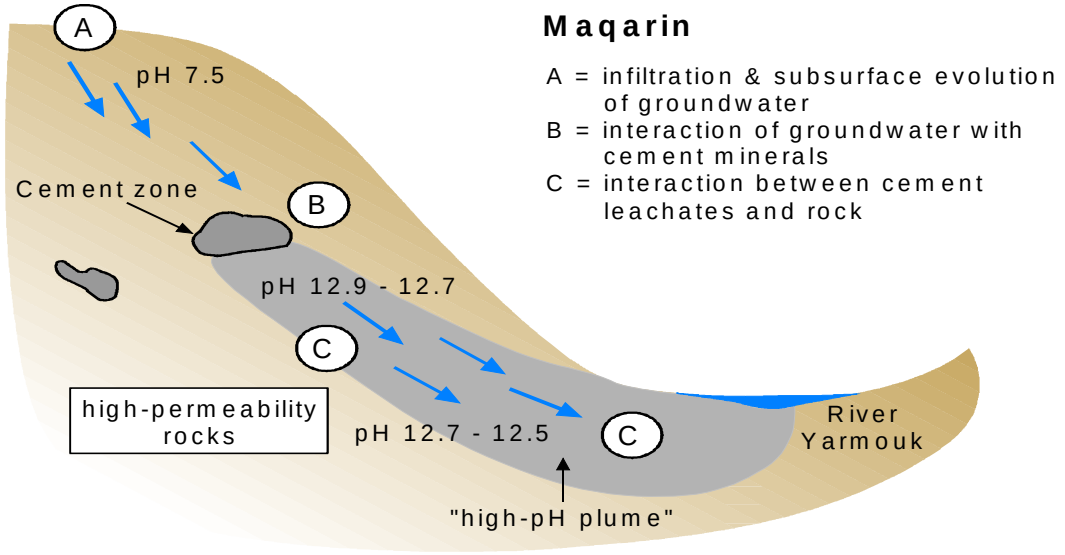


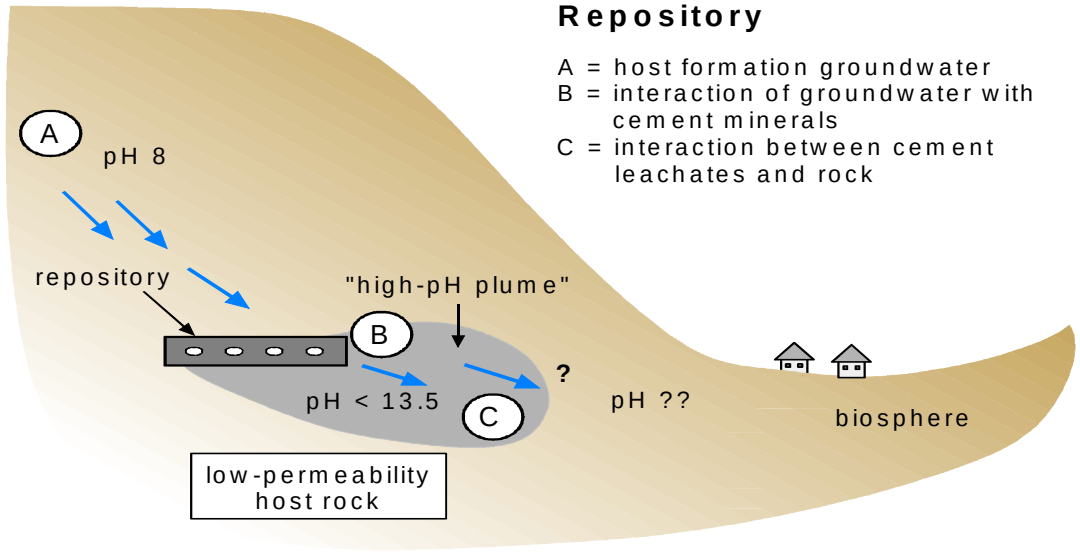
Figure 6: The various stages in a safety assessment modelling approach

Safety Case	Conceptual model development	Data provision	Model validation
(Switzerland, 1985)	➢ Stability and instability of concretes and mortars ➢ Stability of bitumen ➢ Radionuclide release concepts against Oklo observations	➢ Constrain illitisation of bentonite	
SKB-91 (Sweden, 1991)	➢ Support of bentonite stability from observations at Gotland ➢ Redox front model supported by Poços de Caldas observations ➢ Inclusion of matrix diffusion	➢ Limit relevance of colloid transport by using data from Poços de Caldas ➢ Demonstrate conservatism in estimating radiolytic oxidation by using information from Cigar Lake	➢ Radionuclide solubility model testing and comparison with observed solubilities at Poços de Caldas and Cigar Lake
TVO (Finland, 1991)	➢ Use of palaeohydro-geological data in the development of Ice-age scenarios ➢ Observations from Cu-deposits and Kronan canon to support corrosion estimates ➢ Use of colloidal and microbial information from Poços de Caldas and Palmottu to develop models	➢ Matrix diffusion profiles surveyed from various natural analogues	➢ Testing of UO_2 spent fuel dissolution models using information from Cigar Lake



Maqarin

A = infiltration & subsurface evolution of groundwater
B = interaction of groundwater with cement minerals
C = interaction between cement leachates and rock



Repository

A = host formation groundwater
B = interaction of groundwater with cement minerals
C = interaction between cement leachates and rock

International Workshop

The international workshop was held in May 12/13, 2004 under the auspices of the CEA in Cadarache, France. The first day concerned the introduction and background to the workshop, and included an update on some past and on-going analogue studies and presentations of recent national review documents (e.g. Germany, Japan, Spain and the USA).

International Workshop

The second day was organised around group discussions and their reporting. Each group addressed a list of key questions and issues related to natural analogues (NAs). Questions included:

- What makes a good or bad analogue study?
- Is the list of approx. 70 NA studies considered by NAnet adequate?
- Is the matrix approach to ordering the NA studies on the basis of FEPs and host rock type useful?
- Are the near- and far-field matrices correct?
- Are there any other sources of information that could be used in NAnet or future similar projects?

Reviews of Natural Analogue Studies

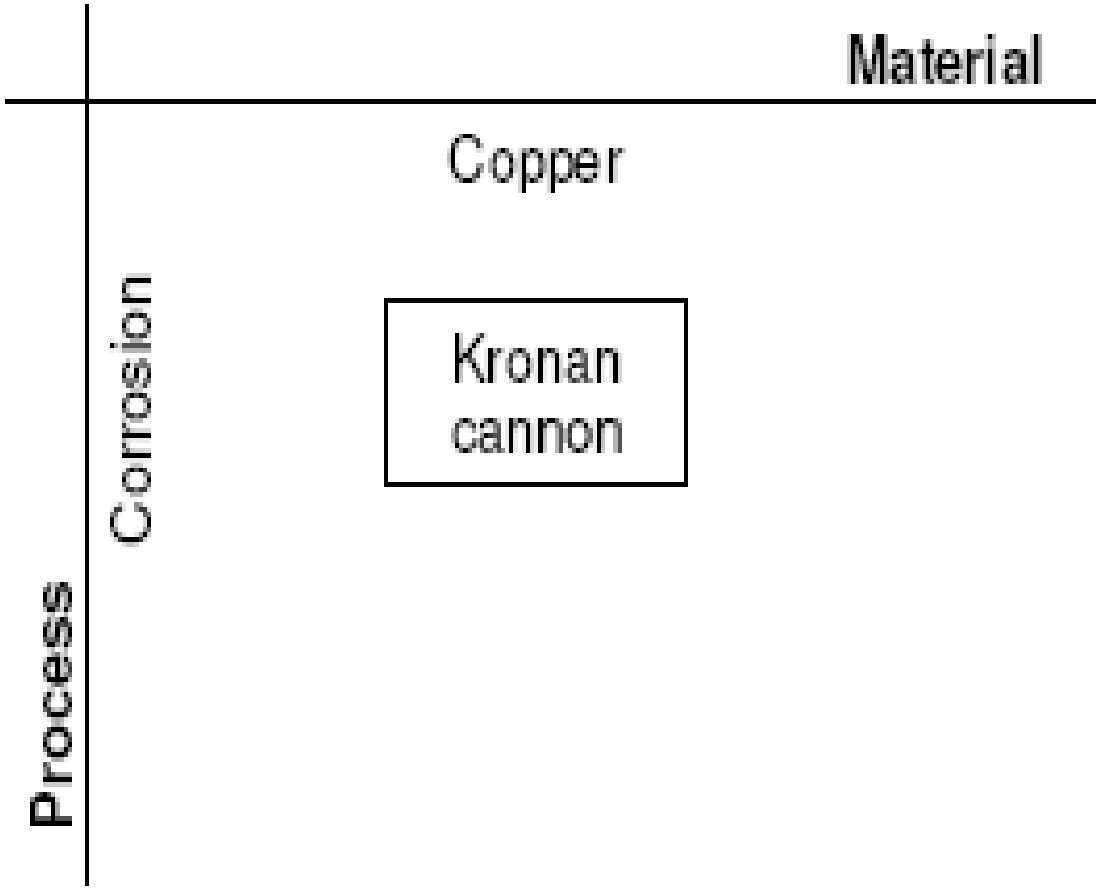
The review studies were organised as follows:

- Title of analogue study
- Description (including participants and time frame)
- Relevance
- Position(s) in the matrix tables
- Limitations
- Quantitative information
- Uncertainties
- Time scale
- PA/safety case applications
- Communication applications
- References

Generic Natural Analogue Matrices

An attempt was made to present the various natural analogue studies in the context of near- and far-field FEPs.

For the far-field exercise different host rock environments (mudrock, crystalline rocks, salts, sandstones, limestones and tuffs) were also integrated.


Material
Copper
Corrosion
Kronan
cannon
Process

		Wasteform				Waste package				Buffer		Near-field rock
		Glass	SF	Cement	Others	Copper	Steel	Titanium	Concrete	Bentonite	Concrete	
Degradation of the engineered barriers	Mechanical	Glasses: archaeological Glasses: natural	Bangombe Cigar Lake Oklo Shinkolobwe	Hadrian's Wall	Bitumen studies Resin studies SYNROC studies	Hyrkkölä Keweenaw Kronan Cannon	Inchtuthil Disko Island	Josephinite	Beziers Hadrian's Wall	BARRA Boom Clay Busachi Col du Perthus Dunarobba Isle of Skye Kinnekulle	Beziers Hadrian's Wall	Asse Mine Borehole depths Caves and caverns Salt domes Salt mines Krasnoyarsk
	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	Akrotiri Hyrkkölä Keweenaw Kronan Cannon Littleham Cove	Inchtuthil Disko Island	Josephinite	Hadrian's Wall Khushaym Matruk Maqarin Scawt Hill	BARRA Orciatico Busachi Col du Perthus Dunarobba Isle of Skye Kinnekulle Murakami	Hadrian's Wall Khushaym Matruk Maqarin Scawt Hill	Salt domes Salt mines Caves: seepage Khushaym Matruk
Radionuclide transport	Advection (flow)			Beziers Maqarin Khushaym Matruk Hadrian's Wall					Beziers Maqarin Khushaym Matruk Hadrian's Wall	Dunarobba	Beziers Maqarin Khushaym Matruk Hadrian's Wall	Björklund BORIS Caves: seepage Caves: preservation El Berrocal Geothermal systems Morro do Ferro Osamu Utsumi
	Diffusion									Loch Lomond Bangombe Boom Clay Cigar Lake Dunarobba Kinnekulle		Akrotiri Bangombe BORIS
	Colloid transport									Bangombe Cigar Lake		Alligator Rivers Bangombe BORIS El Berrocal Menzenschwand Morro do Ferro
	Two-phase flow									Gas studies		Gas studies Geothermal systems
Radionuclide retardation	Sorption, precipitation and physical retardation	Glasses: archaeological Glasses: natural	Bangombe Alligator Rivers Cigar Lake El Berrocal Mina Fe Oklo	Maqarin		Hyrkkölä Littleham Cove			Semail Ophiolite Maqarin Khushaym Matruk	Cigar Lake Boom Clay Bangombe	Semail Ophiolite Maqarin Khushaym Matruk	BORIS El Berrocal Morro do Ferro Oklo Alligator Rivers Osamu Utsumi

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

Near-surface/surface environments

- Traditionally biosphere studies have focussed on providing a discharge-to-dose conversion factor for radionuclides of concern and have not been considered under natural analogues.
- In addition, the biosphere represents a highly complex environment, more challenging than the near- and far-field systems.
- Furthermore, the use of different PA models and codes also differentiate the biosphere systems.
- NAnet took the view that the definition of analogues should be widened to include the near-surface/surface biosphere systems, but excluding biologically-influenced surface processes (i.e. radionuclude uptake and transfer and exposure to flora and fauna).

Near-surface/surface environments

- Much anthropogenic data exist of surface contamination (e.g. Chernobyl; mine drainage etc.), but migration of toxic species tends to be downwards to the water table rather than discharging upwards from repository release.
- More promising was to understand specific examples of different classes of interaction between surface waters and groundwaters under varying climatic, topographic, geologic and soil/ecosystem conditions.
- Three categories of near-surface analogue information were proposed to identify the main factors determining radionuclide behaviour (e.g. exchange mechanisms controlling the advection and/or diffusion (also dispersion) of groundwaters across the geosphere/biosphere interface).

Near-surface/surface environments

- ***System Context Studies***: Factors concerned with regional or super-regional scales (i.e. climate; landscape topography).
- ***Whole System Studies***: Discrete hydrogeological settings within which the effects of numerous transport-related processes of contaminant migration have been studied.
- ***Sub-system Studies***: Analogues of detailed contaminant transport-related processes (e.g. physical and geochemical features and mechanisms).

Communication

- ***Benefits:***
  - Directly observable in the environment
  - Offer tangible links to personal experience
  - Inherent attractiveness of nature to most individuals
  - Obvious channel of communication to the general public
- ***Difficulties:***
  - Qualitative nature of analogues coupled to complex integrated environmental processes
  - Therefore analogue are open to a wide range of interpretations which can be used to support different agendas.
  - Thus hesitancy in their use by experimental scientists, modellers, communication specialists and physical scientists.

Communication

- ***Recommendations:***
  - Emphasis on safety assessors, communication specialists and other scientists to raise awareness of analogues and their usefulness.
  - In this respect, safety assessors should be involved from the outset in the planning of future analogue studies to ensure that the derived data and concepts can be used to develope credible models for safety assessments.
  - The ability of analogues to readily respond to questions about radioactive management posed by the different stakeholders (i.e. an initial two-way dialogue).
  - Future focus of analogue communication should be based on the expressed needs of specific audiences.
  - NAnet suggests an indexing system hosted on a website based on frequently asked questions which would be regularly updated.

Communication

It is obvious that analogue studies alone cannot answer all the questions that people will ask. Four key themes are possible:

- Time: How can you be sure that the repository will work over the timescales involved?
- Depth: How do you know that you can build something so deep underground?
- Process: How do you know what processes will operate in the repository?
- Precedence: Has this ever been done before and how successful has it been?

Figure 8: Analogue representation of the near-field materials planned to be used in the Swedish concept for a deep spent-fuel repository

THE Definition

’An analogue is a natural, historical or anthropogenic system that permits a study of repository-related processes, including its surrounding environment and the processes that control its evolution’.