SYNTHESIS REPORT

CONTRACT N°: FIKW-CT-2002-20204

Network to review natural analogue studies and their applications to repository safety assessment and public communication (NAnet)

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Consejo de Seguridad Nuclear	**ES**

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CONTENTS

ABBREVIATIONS AND ACRONYMS

CDZ	chemically disturbed zone
EC	European Commission
EDZ	engineered damaged zone
FEPs	features, events and processes
GBIZ	geosphere-biosphere interface zone
HLW	high-level radioactive waste
ILW	intermediate-level radioactive waste
LLW	low-level radioactive waste
NAWG	Natural Analogue Working Group (of the EC)
PA	performance assessment
PCSC	post-closure safety case

EXECUTIVE SUMMARY

Analogue studies are investigations of natural, anthropogenic, archaeological or industrial systems which have some definable similarity with a radioactive waste repository and its surrounding environment.

No natural system is exactly like a repository in all aspects and, thus, there is no complete analogue. There are, nonetheless, many analogue systems which have close similarities to certain components of a repository or to processes that control repository evolution. By careful study of appropriate analogue systems, important lessons can be learnt which may be used to improve our conceptual understanding of short and long-term repository behaviour and our safety assessment modelling capability.

The study of natural analogues is a mature research area and there is a long list of analogue studies which have been undertaken in the last two decades. These have been performed on a wide range of natural systems, such as uranium ore deposits, natural fission reactors, native metal deposits, marine and lake sediments, ancient preserved forests and buried archaeological artefacts.

Many early studies were aimed quite specifically at the provision of numerical data (e.g. corrosion rates or sorption coefficients) that could be fed into safety assessment models. In general, such approaches were not very successful because it proved difficult to extract hard numerical data from complex natural systems subject to uncertain boundary conditions. Most recent analogue studies have taken a broader approach, and it is now generally acknowledged that their primary role in support of safety assessment is to provide qualitative information to help develop or confirm conceptual models by identifying which processes are responsible for the evolution of natural systems, how these processes operate and on what spatial and temporal scales, and how these processes are coupled.

It is clear, therefore, that there exists wide ranging possibilities for the imaginative use of analogues within formal safety assessments and more informal dialogues to help establish consensus and build confidence in disposal options for radioactive waste management. It is in this light that the European Commission launched the NAnet project (*"Network to review natural analogue studies and their applications to repository safety assessment and public communication"*) with a view to help promote more considered applications of natural analogues in future safety assessments and for public communication. The project ran from January 2003 to December 2004 within the 5th Euratom Framework and involved a network of European organisations, including both users and providers of natural analogue information.

The overall aim of the NAnet project was to review the past and present use and understanding of natural analogues, and to make recommendations for their future use. It was intended to derive 'added value' from analogue studies previously undertaken, including some that have been funded by the European Commission. The specific objectives of NAnet were to:

1. Critically review a wide range of analogue studies and their past applications to performance assessments.

2. Critically review a wide range of analogue studies and their past applications to public communication.

3. Consider any potential added value from these past studies that may be applied to future safety cases and stakeholder dialogue programmes.

4. Develop a database of 'quality-approved' (i.e. peer reviewed) analogue information, and identify key areas where further natural analogue research is needed.

5. Host an international workshop to provide a mechanism for soliciting additional relevant analogue information from researchers, safety assessors and representatives from waste management organisations not directly involved in the project.

The international workshop was held at the project half-way stage and was attended by 45 participants, representing 30 separate organisations from 11 different countries. Much of the workshop was taken up with syndicate group debates around questions such as 'How can natural analogues be used to build confidence in our assessment methods and models?' and 'What do you believe are the most important potential applications of quantitative information in a performance assessment?' The syndicate group debates proved to be extremely lively and all participants welcomed the opportunity to debate these issues with a wide ranging group of individuals. Many useful comments and suggestions came out of these debates; these have helped guide the remainder of the NAnet project and are reflected in this report.

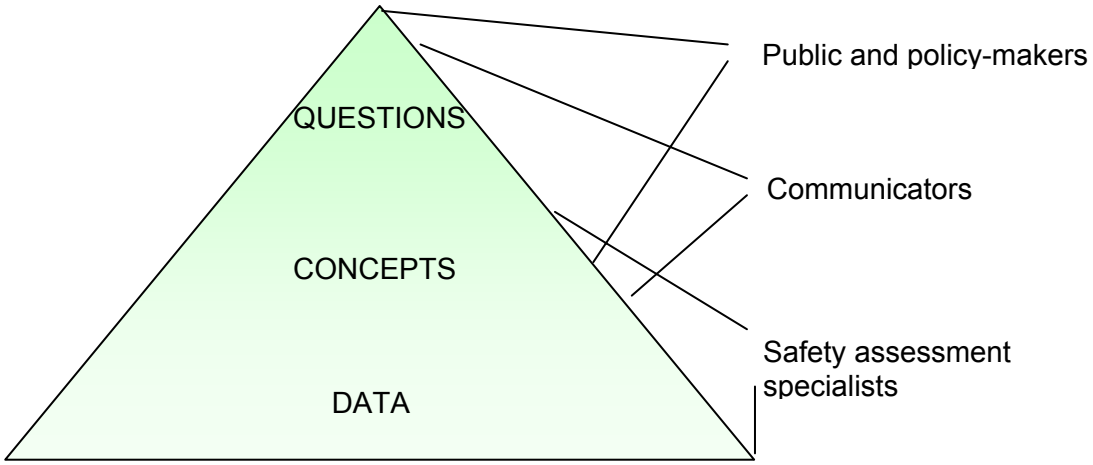
One of the primary outputs of the NAnet project has been the compilation of an extensive suite of reviews of more than 70 individual analogue studies. These reviews cover traditional natural analogue studies, such as large-scale investigations of radionuclide transport around uranium orebodies (e.g. at Alligator Rivers, Oklo, Cigar Lake and Poços de Caldas) and process/mechanistic analogue studies such as those examining natural glass and bentonite clay stability. To complete the picture, a restricted range of other studies of natural systems which employ a similar philosophy to analogues (but which are not usually referred to by that term) were also reviewed. These included studies which have examined radionuclide transport and retardation processes occurring in the geosphere-biosphere interface zone and in the surface environment (e.g. radionuclide migration in the near-surface from uranium mill tailings). This widening of the scope of analogues thus brings together a broad range of investigations that, in concert, can be used to support assessment model chains for the full radionuclide release pathway extending from dissolution of the wasteform to release to the accessible environment. The scope of the project did not extend, however, to analogues of 'biosphere' processes, such as radionuclide uptake, transfer and radiological exposures to humans and other flora and fauna.

Each analogue study review was structured using a standard review template that includes sections concerned with safety assessment relevance and applications, analogue study limitations (e.g. dissimilar materials and environments compared to a repository etc), a summary of any particular quantitative information derived from the study, an assessment of the uncertainties associated with the qualitative and quantitative information, an indication of the time-scales covered by the analogue and reference to any applications in communication with different audiences, including the public, and links to the primary literature.

After completing these reviews, it was concluded that natural analogues remain one of the most useful tools we have to increase our understanding of the processes that will control the evolution and safety of a repository over time. Analogue studies should, however, be considered as complementary to field, laboratory and modelling studies, rather than as isolated investigations, and implementing organisations should aim to integrate them fully into their research and development programmes. Their primary role is one of helping to understand processes and to develop and challenge conceptual models. Expectations should not be unrealistically high for the acquisition of quantitative data from future analogue studies for input to safety assessment models.

The natural analogue community retains a deeply held belief that analogues contain information that is relevant when making a full safety case that employs multiple lines of reasoning. Whilst this is undoubtedly true, it must be recognised that analogues provide only a sub-set of the complete range of information required for full debate and discussion amongst stakeholders, and that different audiences will require information at different technical levels. Analogues must, therefore, be used within a safety case and in stakeholder dialogue in a complementary manner with other sources of information to address the questions that different audiences may ask.

The concept of an information pyramid was developed as a useful means for considering the likely audiences for analogue information and the types of questions and issues that they may wish to address. This makes clear that members of the public and decision makers may ask high-level 'questions' whilst safety assessors are more likely to ask detailed questions concerning concepts and data.

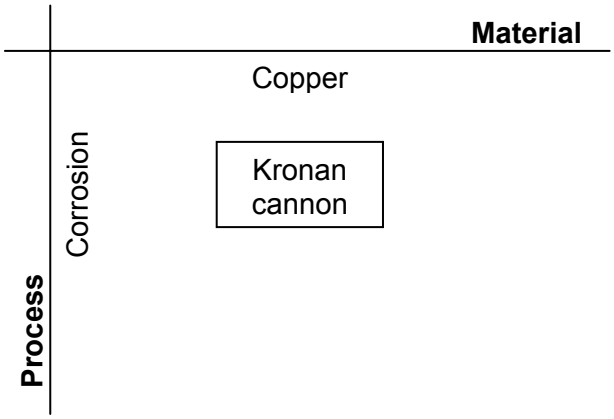


The move to use analogues to help to respond to the questions that people may ask, rather than to promote issues that the analogue researcher thinks safety assessors and others should be interested in, is another key recommendation from this project.

At an early stage in the project, the potential audience for the individual analogue reviews was considered (i.e. the main intended audience for the project). Whilst there was no intention to restrict access to the information to any single group, it was felt that the main beneficiaries for the analogue reviews would be the safety assessors and communication specialists working in the radioactive waste disposal field. The reason for this is that there is a general feeling that natural analogues have not been used to their full potential by these groups. The reason for this may be that they are simply unaware of the extent of analogue information that exists and of its relevance because it is hard to find information that meets their needs from the large body of technical reports and papers that have been published. On the other hand, there has been also a general lack of initiative seriously to evaluate existing information and provide constructive input and recommendations that might raise the value of analogue studies to greater use in safety assessment.

As one result of this conclusion, it was decided that an important outcome from the NAnet project would be a simple referencing system that would enable safety assessors and communication specialists rapidly to find all those analogues that relate to specific issues and interests. The referencing system that was devised is based on a simple matrix that has on one axis the range of materials and on the other axis the range of processes that can occur in the repository system. Intersections of the axes identify unique material-process combinations and analogue studies can be listed at the appropriate intersections. This is

illustrated in the figure below which shows that the 'Kronan cannon' analogue study is relevant to the understanding of copper corrosion.



Two generic analogue matrices have been developed, one for the near-field and one for the far-field. It is recommended, however, that repository specific matrices should be developed by analogue researchers and performance assessors to reflect their own particular repository designs and site characteristics. These matrices can then be populated to indicate how individual analogue studies have been or could be used to inform the development of their own safety assessment models.

The matrices are also useful for identifying gaps in our knowledge. For example, the near-field matrix indicated that analogue studies have examined diffusion through rock and clay but not through some other near-field materials such as cement and concrete. Similarly, there is little available analogue information on certain other transport processes occurring in cement and concrete, including colloid transport and two-phase flow.

Despite these gaps, any new analogue studies should only be undertaken with the specific aim of answering the questions and issues that stakeholders (including safety assessors, decision makers and members of the public) raise. This means that a two-way dialogue is required between the analogue researchers and the user of the information (e.g. the safety assessor). This should help to avoid the expense of undertaking studies that are largely ignored by safety assessors and communication specialists alike.

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 evolved over time in subsequent projects funded by the EC, possibly within the remit of the Natural Analogue Working Group (NAWG). This is important because, without keeping these reviews up to date, the suggested relevance of these analogues to evolving safety assessments will change and the recommendations provided here will become outdated. As several repository development programmes are moving forward and siting decisions are being made, the potential role for natural analogues to support stakeholder dialogue and inform safety assessments is greater than ever.

1 INTRODUCTION

1.1 Background to the project

Analogue studies are investigations of natural, anthropogenic, archaeological or industrial systems which have some definable similarity with a radioactive waste repository and its surrounding environment. No natural system is exactly like a repository in all aspects and, thus, there is no complete analogue. There are, nonetheless, many analogue systems which have close similarities to certain components of a repository or to processes that control repository evolution. By careful study of appropriate analogue systems, important lessons can be learnt which may be used to improve our conceptual understanding of short and long-term repository behaviour and our safety assessment modelling capability.

The study of natural analogues[1] is now a mature research area and there is a long list of analogue studies which have been undertaken in the last three decades. These have been performed on a wide range of phenomena, such as uranium ore deposits, natural fission reactors, native metal deposits, marine and lake sediments, ancient preserved forests and buried archaeological artefacts. Generally, these studies have been of two types, the first are large-scale, multi-disciplinary studies which last several years, often focussed on uranium orebodies and with the objective of characterising radionuclide transport and retardation processes in the field, and the second are small-scale, short duration, tightly focussed process/mechanistic studies with the objective of investigating a single material or process, often examining archaeological or industrial artefacts.

The European Commission (EC) has supported the development of natural analogues and their application to safety assessments through the co-funding of a number of high-profile analogue studies (such as at Oklo, Palmottu and El Berrocal) and through the sponsoring of the Natural Analogue Working Group (NAWG). The NAWG brings together users and providers of analogue-derived information from Europe and further afield, and has held 8 international workshops between 1986 and 1999 [von Maravic and Alexander, 2000].

There has been a considerable evolution in thought regarding the application of natural analogues to safety assessment in the last two decades. Many early studies were aimed quite specifically at the provision of numerical data (e.g. corrosion rates or sorption coefficients) that could be fed into safety assessment models. In general, such approaches were not very successful because it proved difficult to extract hard numerical data from complex natural systems subject to uncertain boundary conditions. Most recent analogue studies have taken a broader approach, and it is now generally acknowledged that their primary role in support of safety assessment is to provide qualitative information to help develop or confirm conceptual models by identifying which processes are responsible for the evolution of natural systems, how these processes operate and on what spatial and temporal scales, and how these processes are coupled. Quantitative information may, in some cases, be obtained from analogue studies but such information is generally used to support or provide bounding limits to other data derived from laboratory or field experiments.

[1] The term ‘natural analogue’ is used here and in most of the published literature as short-hand for all types of natural, anthropogenic, archaeological or industrial systems that are considered to be analogous to repository systems.

This move to more qualitative and conceptual applications of natural analogue studies is consistent with the concurrent development in safety assessment methodologies. Most modern safety assessments are 'scenario based' meaning that likely evolution and less likely alternative evolution scenarios are constructed in a bottom-up manner from combinations of features, events and processes (FEPs) which are thought might occur in various parts of the repository during its lifetime and which, in combination, drive repository evolution in particular directions. Natural analogues are proving themselves to be of primary importance in identifying and screening FEPs, and therefore, in defining appropriate scenarios to be assessed.

Similarly, it is now widely recognised that the quantitative end-point of a safety assessment calculation (such as the estimation of radiological dose to members of the public exposed to releases from the repository) is not, by itself, an adequate measure of repository performance. Many regulatory authorities now expressly require safety assessments to be supported by other qualitative and quantitative demonstrations of safety, and presented in a well rounded 'safety case' that employs 'multiple lines of reasoning' that address the issues of importance to all stakeholders, including those of the general public [NEA, 2004].

Natural analogue studies are establishing themselves as one of the most useful forms of 'multiple lines of reasoning' because well chosen and appropriate analogues can provide tangible evidence of system performance that can compare to the day-to-day experiences of different audiences. For example, industrial and archaeological analogues may provide information that relates to materials, timescales and locations that are familiar to many people.

The familiarity and illustrative nature of many analogue systems makes them a useful tool for supporting dialogue and communication with stakeholders, including the general public but extending to other technical specialists and formal decision makers. This application of analogues is of increasing importance as several national repository development programmes are moving towards siting and implementation stages when stakeholder interest is keenest.

It is clear, therefore, that there exists wide ranging possibilities for the imaginative use of analogues within formal safety assessments and more informal dialogues to help establish consensus and build confidence in disposal options for radioactive waste management. It is in this light that the NAnet project[2] was launched with a view to help promote more considered applications of natural analogues in future safety assessments and for public communication.

The project ran from January 2003 to December 2004 within the 5th Euratom Framework and involved a network of European organisations, including both users and providers of natural analogue information.

1.2 Objectives and limitations of the project

The overall aim of the NAnet project was to review the past and present use and understanding of natural analogues and to make recommendations for their future use. It was intended to derive 'added value' from analogue studies previously undertaken, including some that have been funded by the EC. The specific objectives of NAnet were to:

[2] NAnet is short-hand for *"Network to review natural analogue studies and their applications to repository safety assessment and public communication"*.

1. Critically review a wide range of analogue studies and their past applications to performance assessments.

2. Critically review a wide range of analogue studies and their past applications to public communication.

3. Consider any potential added value from these past studies that may be applied to future safety cases and stakeholder dialogue programmes.

4. Develop a database of 'quality-approved' (i.e. peer reviewed) analogue information, and identify key areas where further natural analogue research is needed.

5. Host an international workshop to provide a mechanism for soliciting additional relevant analogue information from researchers, safety assessors and representatives from waste management organisations not directly involved in the project.

Although several reviews of analogues studies have been undertaken before, NAnet was the first international project to involve participants with expertise in undertaking analogue studies in the field; performing safety assessments and the application of assessment models and codes; regulatory and licensing issues; and public communication. The project participants were drawn from repository developers, national licensing bodies and research organisations to ensure a broad range of expertise to the review procedure and when compiling recommendations for improved uses of analogues in the future.

The scope of the project included analogues that are relevant to the most common radioactive waste repository designs and concepts, but was focussed on deep repositories for high-level waste (HLW) and intermediate-level waste (ILW), although it was recognised that many analogues are also applicable to surface repositories for low-level waste (LLW).

The project covered 'traditional' natural analogue studies, such as large-scale investigations of radionuclide transport around uranium orebodies, and process or mechanistic analogue studies such as those examining natural glass and bentonite clay stability. To complete the picture, a restricted range of other studies of natural systems which employ a similar philosophy to analogues (but which are not usually referred to by that term) was also included in the scope. These included studies which have examined radionuclide transport and retardation processes occurring at the geosphere-biosphere interface and in the surface environment (e.g. migration in the near-surface of radionuclides leached from uranium mill tailings). The scope of the project did not extend, however, to analogues of 'biosphere' processes, such as radionuclide uptake, transfer and radiological exposures to humans and other flora and fauna.

The project considered the potential wide ranging applications of qualitative and quantitative analogue information to safety cases which employ multiple lines of reasoning, rather than just to the more restricted scope of mathematically based radiological safety assessments. The project also examined attempts that have previously been made to use natural analogues to engage in dialogue with the public and other stakeholders on radioactive waste management issues.

It was decided that the primary audience for the project would be the safety assessment and stakeholder dialogue specialists in disposal agencies, regulatory

bodies and related institutions because it was felt that the greatest 'added value' would come from their understanding of the potential for analogues in repository development programmes. The deliverables from the project are intended to be focussed on the needs of these groups of people, although it is recognised that the project may be of interest to a much wider range of stakeholders.

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 evolved over time in subsequent projects funded by the EC, possibly within the remit of NAWG.

1.3 Definitions and terminology

During the project, it became clear that a number of technical terms are in wide circulation for which there is no common or agreed definition, and that differing meanings are used by different groups. The working definitions used within the NAnet project for some of the most important terms are as follows:

- ***conceptual model:*** a description of a repository system or subsystem and its behaviour in the form of qualitative assumptions regarding aspects such as the geometry of the system, boundary conditions, time dependence, and the nature of any relevant physical, chemical and biological processes that operate;

- ***mathematical model:*** a set of mathematical equations designed to represent a conceptual model;

- ***numerical model:*** a computer code designed to solve the problem defined by the mathematical model;

- ***performance assessment:*** an evaluation (usually quantitative) of the performance of a repository in part (e.g. the near-field barriers) or as a whole, and its implications for protection and safety;

- ***safety assessment:*** an evaluation of the safety performance of the entire repository system involving calculation of radiological impacts to people (usually radiological dose or risk);

- ***safety case:*** a collection of arguments and evidence to demonstrate the safety of a repository that includes a safety assessment and other supporting information that describes the robustness and reliability of the safety assessment and the assumptions made therein, as well as other related information such as a description of the site and the reasons for it being chosen.

2 THE OUTCOMES OF THE PROJECT

The NAnet project resulted in the following deliverables and outcomes:

- the completion of peer reviews of over 70 individual analogue studies;
- the hosting of an international workshop on natural analogues;
- the production of 4 Work Package reports on specific work areas within the project;
- the project website; and
- this Synthesis Report that provides an overview of the project and makes recommendations on future best uses of analogues in repository development programmes.

Each of these deliverables is described below.

2.1 The suite of analogue reviews

One of the main objectives of the NAnet project was to review a wide range of analogue studies and their past applications to performance assessments and public communication.

Well over 100 studies have been described as 'analogues' – some of these were undertaken with the primary purpose of providing information to support safety assessments (these include the large international projects such as Alligator Rivers, Oklo, Cigar Lake and Poços de Caldas) but many others were undertaken with some other primary purpose and subsequently have been considered to have had analogue relevance (these include many of the archaeological examples such as the Inchtuthil nails).

The analogue literature is extensive, comprising several thousand journal papers, conference proceedings and technical reports. A first task in NAnet was to sift the known literature and identify the most important analogue studies for the review. For the sake of completeness, small studies with related themes were often grouped together than reported separately: for example all of the studies on natural glasses were grouped together into one review. The result of the sifting exercise was the compilation of the following list of over 70 analogue studies.

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)
Kinnekulle (Sweden)
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

Each analogue study review was structured using a standard review template that includes sections concerned with safety assessment relevance and applications, analogue study limitations (e.g. dissimilar materials and environments compared to a repository etc.), a summary of any particular quantitative information derived from

the study, an assessment of the uncertainties associated with the qualitative and quantitative information, an indication of the time-scales covered by the analogue and reference to any applications in communication with different audiences, including the public, and links to the primary literature. These individual analogue reviews accompany this main report.

Although this suite of reviews represents one of the main outcomes of the project, it was not the goal of NAnet to provide an exhaustive overview of every study undertaken. Instead the intention was to give an introduction to the analogue literature and to provide suggestions and examples for how analogues may best be used to support repository development programmes. This report and the individual analogue reviews should thus be seen as complementary to other reviews of the analogue literature that are available [e.g. Miller et al., 2000; Lopez et al., 2004].

2.2 International workshop

One of the planned objectives of NAnet was to host an international workshop at the project half-way stage. This workshop was held over two days in May 2004 at the Château de Cadarache, France and was attended by 45 participants, representing 30 separate organisations from 11 different countries. Much of the workshop was taken up with syndicate group debates on the following themes and questions:

1. How can natural analogues be used to build confidence in our assessment methods and models? How can natural analogues be used to build confidence amongst the many stakeholders? Is building confidence in our assessment methods and models using natural analogues the same as building confidence with stakeholders or are different approaches needed?

2. Natural analogues are often unacknowledged in top-level performance assessment reports. Why do you think this is the case? Should natural analogues have a higher profile in these reports and, if so, how can natural analogues best be integrated with field, laboratory and modelling studies within a repository development programme to ensure this happens?

3. What do you believe are the most important potential applications of qualitative information in a safety case that employs multiple lines of reasoning? Have you any recorded examples of the explicit application of qualitative analogue information used in a safety case? How can the application of natural analogues to safety cases best be improved in the future?

4. What do you believe are the most important potential applications of quantitative information in a performance assessment? Have you any examples of the provision and application of quantitative data derived from natural analogues in a performance assessment? How can the application of natural analogues to performance assessments best be improved in the future? Do you consider there is a fundamental difference in the application of qualitative rather than quantitative information in a performance assessment or safety case?

5. Natural analogue studies frequently are subject to uncertainty, particularly with respect to the boundary conditions of the analogue system. How should these various types of uncertainty be assessed and managed in a safety case or performance assessment, and does this restrict the potential application of analogue information? Are there any other limitations of natural analogues and how should these be addressed?

6. Do you consider that natural analogues are equally applicable to all future assessment time periods? If not, how should the treatment of analogues vary for different assessment time periods and how would this be balanced with other lines of reasoning? Are there any regulatory requirements that control the consideration of time in a licensing situation?

7. Many different safety cases and performance assessments will be required during a repository development programme (e.g. at concept design, design optimisation, siting and licensing). Do you consider that natural analogues are equally applicable to the safety cases undertaken at these different stages? If not, how should the treatment of analogues vary with the different stages?

The syndicate group debates proved to be extremely lively and all participants welcomed the opportunity to debate these issues with a wide ranging group of individuals. Many useful comments and suggestions came out of these debates and these informed the remainder of the NAnet project and are represented in this report. The full record of the workshop and the written responses to the discussion themes are given in Appendix A.

2.3 Work Package Reports

The main bulk of the work in the project was undertaken in 4 work packages:

1. the ***near-field*** work package which had the objective of reviewing analogue studies of relevance to the near-field and critically reviewing the qualitative and quantitative information derived from these studies;

2. the ***far-field*** work package which had the objective of reviewing analogue studies of relevance to the far-field (geosphere) and critically reviewing the qualitative and quantitative information derived from these studies;

3. the ***surface-environment*** work package which had the objective of reviewing a restricted range of studies which have investigated processes of significance to safety assessment which occur in the near-surface/surface environment (excluding biosphere processes); and

4. the ***communication*** work package which had the objective of reviewing the application of natural analogue information to public communication and stakeholder dialogue.

Separate reports were written that provide a commentary of the work and conclusions from each of these work packages, and complement this Synthesis Report. The main findings from each of these work packages are summarised in later sections of this report.

2.4 Project website

A website was been created to provide a summary of the objectives and outcomes from the project, and to enable downloads of the project reports. The website can be accessed at http://www.enviros.com/zztop/nanet/nanetmain.htm.

2.5 Synthesis Report

This report (the Synthesis Report) builds on the work package reports and provides the overall conclusions and recommendations of the NAnet project.

3 THE ROLES OF ANALOGUES AND THE REASONS FOR THEIR USE

Reasoning by analogy is a powerful tool that can provide a unique window, albeit an imperfect one, onto the very long timescales and the complex processes that will control the behaviour of a repository.

Analogue thinking can potentially bring about several important benefits in repository development programmes and some of the most important ones are discussed below. The actual application of analogues will vary from programme to programme and there are no 'rules' that must be followed. There are, however, some examples of good practice in the use of analogues that may benefit most repository developers, regulatory bodies and other stakeholders.

3.1 Reasoning by analogy

The reasoning behind the development and application of natural analogues grew out of the thinking that has been employed in the science of geology for over 200 years.

Geology is unusual among the sciences in that it is an investigation with the goal of developing a description of those Earth processes that have led over time to the disposition of rocks as seen today. Frodeman [1995] emphasised that geology is an *historical science* in which large timescales, coupled with the complexity and singularity of geological events, renders laboratory experiments of only limited relevance and reasoning by analogy becomes fundamentally important. This contrasts markedly with a *hard science* such as physics where the testing of hypotheses by laboratory experiment under controlled conditions plays a pivotal role and reasoning by analogy is considered of only limited value.

Analogy between present-day processes and those processes that operated in the past forms the basis of the 'principle of uniformitarianism' [Hutton 1785] and is one of the few basic tenets of geology – *the present is the key to the past*. The term 'analogy' is relatively rarely mentioned explicitly in the geological literature; perhaps because the methodology is so ubiquitous that it does not require to be specifically stated.

The relevance of analogues to radioactive waste management stems from the long timescales that have to be considered. Periods up to a million or more years into the future need to be considered and these are beyond experimental investigation and human experience. Except for the need to look forward instead of backwards, the issues are similar to those encountered in geology. Thus the use of analogues to help understand and illustrate the future development of a deep repository for radioactive wastes is an appropriate methodology – *the past is the key to the future*.

A number of researchers have been concerned with the philosophical aspects of reasoning by analogy as applied in the field of radioactive waste disposal. On the basis of early thinking, Chapman et al. (1984) developed a set of guidelines for selecting appropriate natural analogues for investigation:

1. The process involved should be clear-cut. Other processes which may have been involved in the geochemical system should be identifiable and amenable to quantitative assessment as well, so that their effects can be subtracted.

2. The chemical analogy should be good. It is not always possible to study the behaviour of a mineral system, chemical element or isotope identical to that

whose behaviour requires assessing. The limitations of this should be fully understood.

3. The magnitude of the various physico-chemical parameters involved (pressure, temperature, pH, Eh, concentration etc.) should be determinable, preferably by independent means and should not differ greatly from those envisaged in a repository.

4. The boundaries of the system should be identifiable (whether it is open or closed, and consequently how much material has been involved in the process being studied).

5. The timescale of the process must be measurable, since this factor is of the greatest significance for a natural analogue.

These guidelines still hold true, although it is recognised that is difficult to find natural systems that meet all of these requirements. More generally, for an analogue to be useful there must be quantitative or qualitative resemblances between the situations being considered and these must be relevant to the purpose for which the analogue is being used. It is possible to recognise criteria that should be considered when using an analogue, and which can strengthen or weaken an analogue, and these are listed in Table 1.

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	

3.2 Supporting management approaches

In the early stages of a waste management programme, the primary objective is usually to decide upon the preferred management option and prove its viability. This

means that the issues of importance tend to be broadly generic. Several programmes have undertaken detailed assessments of alternative management options but, for the higher level radioactive wastes, geological disposal in deep engineered repositories is the most widely adopted management method internationally.

It can be argued that the geological disposal concept (at least for spent nuclear fuel) was initially analogue led because it was a logical conclusion from the observation that certain stable geological environments have isolated uranium orebodies from the surface environment for millions of years by purely natural processes. Put simply, the concept involves placing the uranium-rich spent fuel back into similar geological environments from which the original uranium ore was extracted. Of course, spent fuel is not identical to uranium ore (and other radioactive wasteforms are even less so) and the host rocks around an orebody do not contain the engineered barriers that are present in a repository. Nonetheless, in very broad terms, observations of uranium orebodies and other natural geological systems can provide a helping hand in building confidence in the fundamental concept of geological disposal.

Surprisingly, despite the obvious analogy between repositories and uranium orebodies, very few examples of the use of this 'global analogue' came to light during the NAnet project to support geological disposal as a viable management approach. It appears that most literature (both technical safety assessments and more generic 'communications' brochures) puts more emphasis on the engineered barriers than the natural barriers to provide for safety. The one exception to this is the Cigar Lake uranium orebody in Canada which has been used by several organisations to make broad comparisons between natural and repository systems (Figure 1).

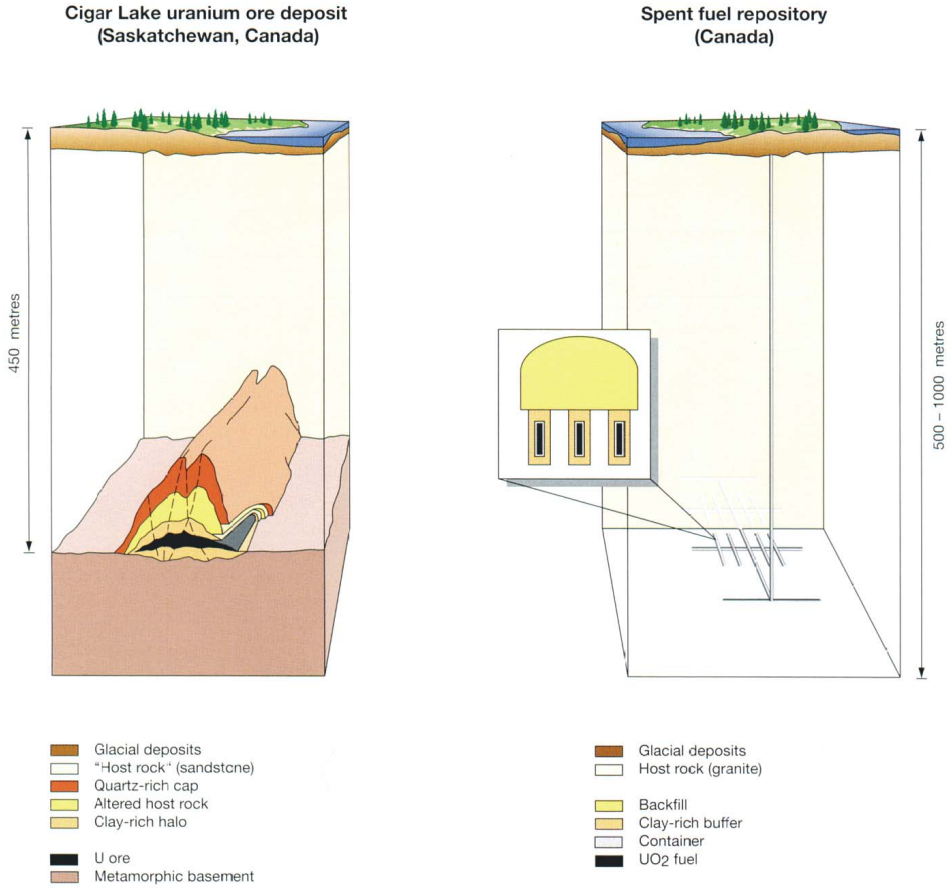


Figure 1: Comparison of the Cigar Lake uranium orebody and the structure of a spent fuel repository, showing the similarities and differences between the two systems

We would recommend that greater use is made of analogues to explain the fundamental role of the natural barriers to protect and isolate the repository because the original concept of geological disposal is that the natural and engineered barriers would be complementary to each other and work in concert to ensure safety – this is the essence of the multibarrier system.

Another example of geological observation (analogue thinking) leading to the development of a waste management approach, but this time of a sub-system level, is that of research into Synroc [Ringwood et al., 1979]. Mineralogical and geochemical studies indicate quite clearly that some naturally occurring minerals concentrate and retain radioelements such as uranium, thorium, caesium and rubidium. It was this observation that led to the development of a number of mineral-based wasteforms (Synroc and its derivatives) that have been proven in pilot-scale tests to be robust and effective in incorporating HLW. Despite its analogue heritage, Synroc has not been adopted at the industrial scale as an immobilisation matrix.

3.3 Providing realism in assessment models

A geological repository designed for long-lived wastes will need to provide isolation from the human environment for time periods of up to one million years before the hazard posed by the waste diminishes (via radioactive decay) to levels equivalent to that posed by uranium ore. These time periods are far in excess of human experience and, indeed, are equivalent to the period since Homo sapiens evolved as a species. This is indicated in Figure 2 which compares future times with past history.

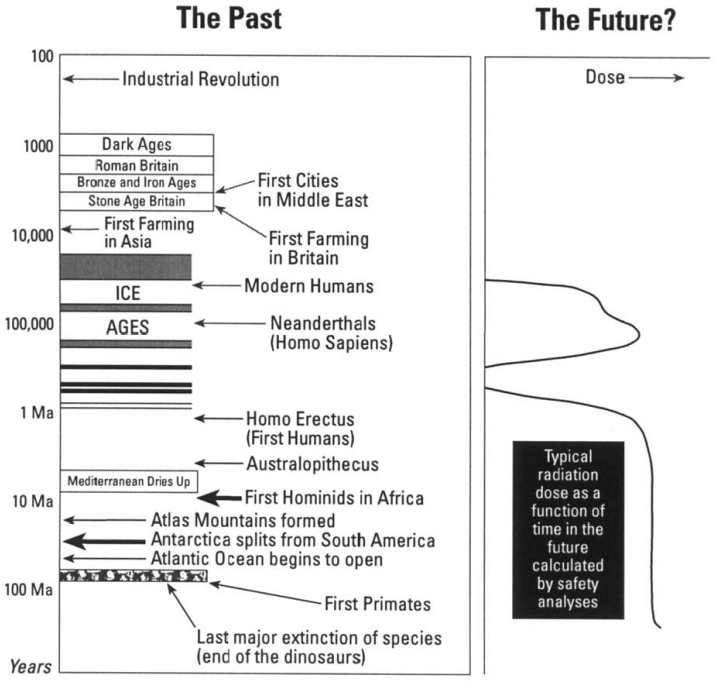


Figure 2: Comparing future assessment time periods with past history. Analogues help to put these timeframes into human context. The vertical axis is time (past and future) on the same scale

When predicting the safety of a repository over these time periods, it is inevitable that the conceptual and mathematical models used in safety assessments must grossly simplify the complex and coupled processes that will control repository performance.

Abstraction and simplification in modelling should not mean that the calculated consequences are under-estimated, provided that conservative assumptions are made in the simplification and parameter setting stages. Abstraction and simplification does, however, mean that the assessment models become progressively less realistic and, for many stakeholders, this may mean a loss of confidence in the model results.

Analogues can provide a means to maintain a degree of reality in the assessment process, literally by providing 'ground truth', for the conceptual models and parameter values used. The specific applications of analogues to conceptual model development and to the provision of numerical data are discussed in Section 4.

Although analogues are important for providing realism, it is important to recognise that they do not have a unique role in this regard and should be seen as complementary to other forms of investigations such as field and laboratory experiments. Combining analogue studies with field and laboratory investigations provides a powerful means of investigating the natural processes which will occur in the repository environment because the disadvantages of one method are balanced by the advantages of the other. This is seen from a simple comparison of the characteristics of field and laboratory experiments with analogue studies listed in Table 2.

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

As a result, natural analogues should not be viewed in isolation and their key role is to be complementary to other confidence and knowledge building methods such as laboratory studies and modelling exercises. This is one of the main messages from the NAnet project: that natural analogue studies should be fully integrated into the mainstream scientific and engineering developmental work in a repository programme, rather than being treated as a separate discipline.

3.4 Identification of knowledge gaps

It is important that our current understanding of repository behaviour is continually tested and challenged so that we can make progressive improvements in our safety

assessment capability. One important aspect of challenging our models is to identify any knowledge gaps and inadequacies in our conceptual models, numerical models, codes, databases and parameter values.

It is the combined role of all of our research tools (laboratory and field investigations, and analogues) to challenge but, because of the nature of analogue studies, they have the greatest opportunity to test our conceptual models to ensure they remain fit for the purpose.

One possible approach for testing and challenging conceptual models (and databases) is to perform a simple audit of our analogue knowledge against those processes explicitly represented in assessment models and their data requirements. This is illustrated figuratively in Figure 3 which shows the extent of current analogue knowledge on the right and the requirements of the assessment models in the left. In some cases we can see that analogue information maps to an assessment model (i.e. a process observed in an analogue study is simulated explicitly in a model or data measured in an analogue study is input to a model). However, we can also see that:

– there is information from analogues that does not feature in our assessment models, indicating a potential gap in the modelling capability; and

– there are information requirements from the models that are not satisfied by the analogue studies, indicating a potential gap in our data provision.

These two types of knowledge gaps need to be examined to see whether or not they are significant. If they are, then further development work is required to ensure the gaps are filled.

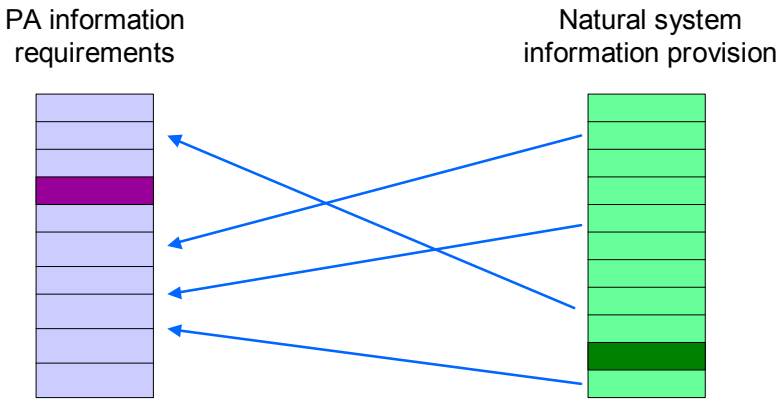


Figure 3: Mapping analogue information onto the requirements of the assessment models to identify knowledge gaps

Within the NAnet project we did not identify any programme that had undertaken such an audit in a rigorous manner but several safety assessments have done something similar by screening lists of FEPs to determine which processes should be explicitly addressed in scenario analysis. FEP list screening adopts something of the audit principle but it does not usually delve into the details of assessment conceptual models and, therefore, does not challenge them at a fundamental level.

Considerable effort is required to develop new, more realistic modelling tools. In reality, assessment models can only evaluate those processes that codes are capable of simulating, which is not necessarily the same as those processes that are considered to

be significant. We recommend, however, that safety assessments should include a fundamental audit of conceptual models at the process level, using relevant available analogue and other information, to ensure that the models reflect the current state of system understanding and that all significant processes and data are addressed. So doing will help to meet the expectations of safety cases to justify all assumptions made in the assessment models.

Another important role of analogue studies is to explore alternative analogues that would help to demonstrate that conceptual models, data or codes are either incorrect or incomplete or non-conservative. The concept of alternative analogues is not widely promoted but is fundamental to testing the validity of our modelling approaches.

For example, there are numerous archaeological analogues to demonstrate that iron and steel can be preserved for hundreds of years or longer (e.g. the Inchtuthil Roman nails) – *this is a positive analogue approach*. Our general knowledge and everyday observations, however, point to the fact that iron and steel can corrode away completely in only a few years (e.g. as seen in any car scrapyard) – *this is an alternative analogue approach*. It would be short sighted to take in isolation the example of the Inchtuthil Roman nails and from it develop a conceptual model for slow iron corrosion in a repository. It would, however, be scientifically valid to look at the extent of decay and preservation of iron artefacts in different environments to determine empirically those chemical conditions under which corrosion is observed to be slow, compare this to the anticipated conditions in a repository, and use this information to develop a conceptual model that is specific to repository conditions.

Such an approach is rarely adopted, perhaps because there is a psychological tendency to focus on studies which promote a positive result. Indeed, within the NAnet project we found no recorded information on alternative analogues being used constructively in support of safety assessments. We recommend, however, that safety cases should focus equally on both types of analogues when possible to ensure that they can be robustly defended against a challenge of being too narrowly focussed.

3.5 Confidence building and multiple lines of reasoning

International guidelines [e.g. IAEA, 1994; NEA, 1999, 2004] indicate that safety cases need to employ multiple lines of reasoning, both quantitative and qualitative, to demonstrate the performance and safety of a repository. In addition to building a more robust case, the use of multiple lines of reasoning should also help to ensure accessibility for a wider range of audiences. There are no rules on what should be provided in a safety case as multiple lines of reasoning but it is important that the requirement to use them is not interpreted too narrowly and, in particular, should not be restricted only to consideration of radiological issues.

Analogue studies can provide a major input to defining and evaluating multiple lines of reasoning in a safety case. In particular, analogues and wider 'natural systems' thinking can help to provide approaches based on the following key areas of repository performance that are addressed in safety assessment calculations:

- ***concentrations*** (mass or activity) as comparisons between abundances of repository releases and naturally-occurring chemical species in various environmental compartments, such as soils, surface waters etc.;

- ***fluxes*** (mass or activity) as comparisons between the movement of repository releases and naturally-occurring chemical species across various interfaces, such as between the geosphere and the biosphere; and

– ***time*** as a measurement of the longevity of the repository barriers, such as the duration of transport through part or all of the repository system, the time for failure of the canister, the time for contaminants to return to the surface environment or the time taken for decay to reduce the inventory to that of a uranium orebody or to other simple yardsticks such as proposed clearance levels for removal of radioactive material from regulatory control.

This approach to the use of natural analogues is beyond the scope of the NAnet project but has been examined in other national and international projects, including a co-ordinated research project undertaken by the IAEA [IAEA, 2005].

It is recommended that future projects work to combine 'traditional' analogue studies with more recent developments in 'natural safety indicators' to meet the regulators' requirements for comprehensive safety cases.

3.6 Dealing with uncertainty

It is recognised that safety assessments have to adopt a series of conservative assumptions in order to calculate the radiological consequence that may arise from certain scenarios. To counter the problems associated with compounded conservatism in assessments, and to evaluate the different types and degrees of conservatism applied, natural analogues can be used to help define uncertainty and conservatism in a safety assessment, and hence the overall repository 'safety margin'.

As an example, Table 3 lists some of the conservative modelling assumptions that typically would be made in a safety assessment for an ILW repository together with some of the more realistic observations that can be made through natural analogue studies, and identifies possible benefits to the assessment that could be gained if the analogue observations were used to constrain the assumptions.

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

Over-conservative assumptions that are not supported by analogue information (and information from laboratory and field studies) can lead to a safety assessment

calculation that may grossly under-estimate the actual safety margin for a repository and lead to unnecessary lack in confidence in repository performance. Figure 4 graphically shows the difference that adopting 'realistic' assumptions compared to 'over-conservative' assumptions could have on the outcome of a safety assessment.

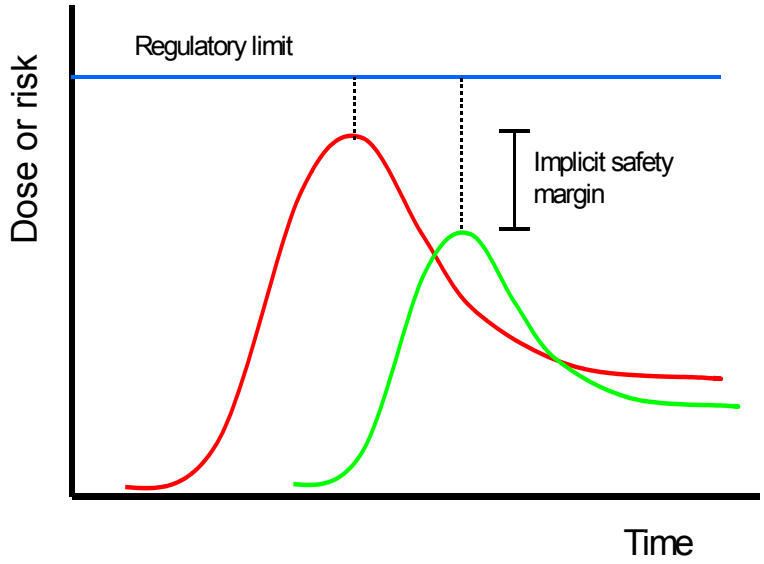


Figure 4: Idealised dose-time curves for a safety assessment that makes conservative assumptions (left-hand, red curve) and an assessment that makes realistic assumptions supported by analogue information (right-hand, green curve)

Analogues can assist in constraining the use of data from different sources, often subject to varying uncertainty and levels of interpretation. They can also highlight areas in particular process models that are not so well grounded in real physical measurements and are, therefore, prone to generalization in model development.

Analogues provide a means of checking the reality of the conceptual models used in the safety assessment models. All safety assessments need to manage a number of types of uncertainty, including conceptual uncertainty. Analogues can help us address uncertainty and questions such as "When do we know enough?" and "Are the data fit for purpose?" by providing opportunities to test and validate our concepts, models and data.

3.7 Repository development programmes

Different countries are currently at different stages in their repository development programmes. This, along with the fact that each country has specific disposal concepts and licensing approaches, means that analogues are used in different ways in various national programmes.

Examination of how natural analogues have been used to date indicates that there is a spectrum of analogue applications from the generic research-based studies during the early stages of a repository development programme through to the process and data-specific stages of a mature programme (e.g. in the US where analogues are highly focused on specific technical issues and uncertainties). Figure 5 depicts this spectrum in a schematic way showing how the analogue applications may become more focussed as the programme moves forwards.

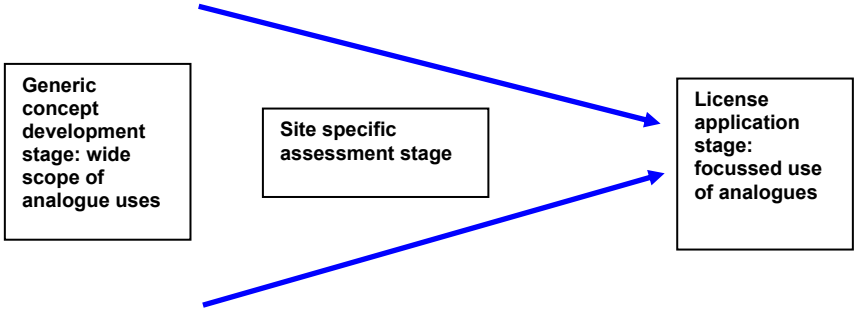


Figure 5: Changing use of analogues throughout a repository development programme

During the entire repository development programme there should be a continual use of analogue information in communication and confidence building. In particular, non-technical audiences may seek analogue information (and other types of information) to help them understand the issues involved in geological disposal (see Section 5).

Similarly, during a repository development programme, there should also be a continual demand for analogue information to help develop and challenge the safety assessment models. This can happen in many different ways, and can be driven by the needs of the safety assessor or by the findings of the analogue researcher. A simplified representation of a safety assessment modelling approach is given in Figure 6. This is generic but many of the elements would be common to most assessment. The approach begins on the left-hand side with the identification of a disposal concept and leads through the development of conceptual and mathematical models to simulate the evolution of the repository, to the calculation of results and their interpretation on the right hand side. Natural analogues may be used to support most, if not all, of these stages, as discussed below.

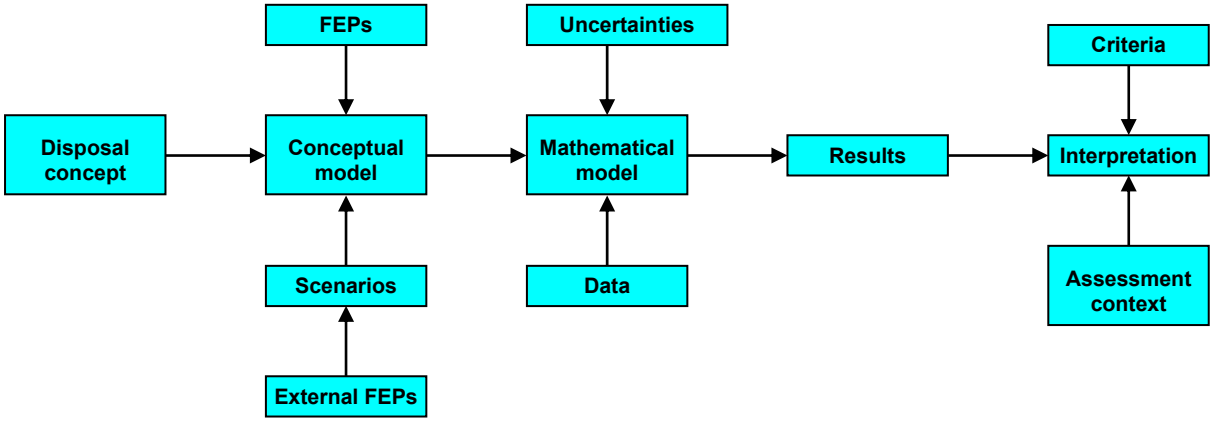


Figure 6: The various stages in a safety assessment modelling approach

Disposal concept: As discussed in Section 3.2, it can be argued that the entire geological disposal concept is analogue led because it is observations of the persistence of ore bodies at depth that suggests the disposal of spent fuel in similar geological environments could be feasible. Other analogues can be used to support other concepts, such as the development of the Synroc wasteform.

Concept model development: The development of a conceptual model that describes the expected evolution of the repository provides the basis for a safety assessment. Conceptual model development can be informed by analogue studies that indicate which processes operate in the natural environment, which of these processes is of significance and needs explicitly to be included in the assessment model, which processes are coupled and what the spatial and temporal variations in these processes are. Analogue studies (in collaboration with field and laboratory studies) are the key tools for developing adequate and appropriate conceptual models by providing this information.

FEPs and scenarios: Conceptual models need also take account of FEPs that are internal to the repository system (such as groundwater flow, radionuclide transport and retardation processes) or external to the repository system (such as climate change events, tectonic activity or the actions of humans) that may influence the evolution of the repository. Internal and external FEPs are usually grouped in such a way as to define sets of 'scenarios' that may control the repository evolution. A key task in a safety assessment is to identify and screen FEPs and scenarios that are relevant to the repository system and site. This is a further task that may be usefully supported by analogues. Indeed, it can be argued that this, together with conceptual model development, is the primary role for analogues in safety assessment because it defines our understanding of all of the effects and impacts the surrounding natural system could have on a geological repository and vice versa.

Mathematical model development and results calculation: These tasks are largely desk-based and do not directly require the support of analogue studies.

Data provision and uncertainty: The provision of numerical parameter values for input to safety assessment models was one of the drivers for many early analogue studies, but few useful data were actually derived from these studies. The main reason for this is the difficulty associated with defining the boundary conditions of analogue systems precisely, meaning that many measurements are associated with a large degree of uncertainty. This remains that case today and expectations should not be unrealistically high for the acquisition of quantitative data in future analogue studies. Nonetheless, there have been some studies in which the analogue system has been characterised with sufficient precision to allow numerical data to be acquired. More commonly, analogue derived data can be used to provide bounding limits to parameter values acquired from laboratory studies.

Interpretation, assessment context and criteria: Once the safety assessment results are calculated, they are interpreted in the light of the assessment context (i.e. why the assessment was undertaken), and a set of assessment criteria (such as formal dose or risk limits) to determine whether the calculated results relate to 'acceptable' repository performance or not. Usually the criteria are defined in regulations but in some cases it is possible to define criteria on the basis of analogue information. For example, analogue type performance measures are used in some regulations such as in the UK where there is a requirement for repository releases not to significantly alter the background radiation environment.

Finally, because the safety assessment method should be an iterative one, there is the opportunity to evaluate the results via sensitivity analysis, which may open up additional questions regarding uncertainties in the model that may require further analogue studies to help understand them.

4 SPECIFIC APPLICATIONS OF ANALOGUES TO SAFETY ASSESSMENT MODELLING

As discussed in Section 3, natural analogues have a number of important applications, alongside other types of investigations such as laboratory and field studies, to the development of performance and safety assessment models. In this section, we review the specific application of analogues to some of the key aspects of performance assessments, namely:

- conceptual model development,
- data provision, and
- model, code and data testing and validation.

Each of these aspects can be applied to the repository system as a whole but are more usually considered within the context of repository sub-systems, which are generally considered to be the:

- near-field,
- the far-field (geosphere), and
- the biosphere (surface environment and upper layer of soil including the root zone).

The reason for this division is largely one of convenience in that separate numerical models are generally applied in safety assessments to simulate the performance of each of these sub-systems.

The various ways in which natural analogues can be used to help in each of the various aspects of safety assessment and for sub-system understanding, are described in the following sections.

4.1 The application of analogue information in published safety assessments

It is generally acknowledged that the supporting role of natural analogues in safety assessment often goes unacknowledged in published assessment reports. A review of a number of assessments completed in the last two decades (Table 4) does make clear, however, that analogues have been instrumental in the development of conceptual models, the provision of some specific parameter values, and for model validation.

Table 4: A summary of the application of natural analogue derived information in a number of published safety assessments

Safety Case	Conceptual model development	Data provision	Model validation
KBS-3 (Sweden, 1983)	➢ Radiolytic oxidation of spent fuel against observations from Oklo	➢ Maximum pitting corrosion factor for Cu ➢ Bentonite stability at T < 100 ^{o}C	
Projekt Gewähr	➢ Stability of borosilicate glasses	➢ Long-term steel corrosion rates	

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
Kristallin-I (Switzerland, 1993)	➢ Back-up in scenario development	➢ Bounding conditions on redox front development using information from Poços de Caldas ➢ Depths of matrix diffusion penetration	➢ Radionuclide solubility model testing and comparison with observed solubilities at Poços de Caldas, Oman and Maqarin ➢ Testing models for redox front development
PNC 1st Progress Report (Japan, 1993)		➢ Bounding values for metal corrosion (archaeological analogues) and bentonite longevity	
AECL EIS (Canada, 1994)	➢ Support development of conceptual models for fuel dissolution, Cu corrosion, clay buffer behaviour and	➢ Geochemical processes and parameter values for redox control on UO_2 stability (e.g.	➢ Testing of models and databases for radionuclide solubility, colloid formation and organic complexation,

Safety Case	Conceptual model development	Data provision	Model validation
	radionuclide retardation, particularly the role of colloids and organics	radiolysis bounding values), Cu corrosion, bentonite-to-illite conversion, and radionuclide retardation (e.g. matrix diffusion bounding values)	and Cu corrosion, using observations from Cigar Lake, the Canadian Shield and Kronan cannon
NRC IPA (USA, 1995)	➢ Disruptive scenario development (volcanism) ➢ Back-up source term conceptual model from Peña Blanca ➢ Relative importance of meso-microfracture and matrix transport at Peña Blanca ➢ Back-up for vapour phase transport from Valles Caldera ➢ Back-up conceptual model for transport in fractures	➢ Identification of secondary phases for long-term release at Peña Blanca	➢ Model testing for elemental transport in unsaturated media at Akrotiri
TILA-99 (Finland, 1999)		➢ Support for conservatism in assumptions regarding spent fuel dissolution rate using observations from Cigar Lake; occurrence of matrix diffusion; and canister life time with reference to the Hyrkkölä native copper occurrence	
SR-97 (Sweden, 1999)	➢ Use of permafrost data in development of Ice-age scenarios ➢ Use of post-glacial tectonic data in development of Ice-age scenarios	➢ Bentonite stability related to temperature effects; availability of potassium. ➢ Clay as a barrier to microbial activity (i.e. Dunarobba) ➢ Gas transport in shales ➢ Insignificant colloid concentrations at repository depths ➢ Bounding calculations supporting reducing conditions at	➢ Justification of model for radiolytic oxidation of UO_2 ➢ Reference to matrix diffusion data for model testing (Palmottu and Cigar Lake) ➢ Testing models of redox front propagation using observations from Poços de Caldas ➢ Development and

Safety Case	Conceptual model development	Data provision	Model validation
		repository depths ➢ Incursion of oxidising meteoric waters ➢ Lack of mineralogical evidence for Fe(II) oxidation	testing of groundwater mixing model (Palmottu and Oklo)
SFR (Sweden, 1999)	➢ Support for long-term durability of concrete barrier system using observations from Scawt Hill, N. Ireland, Maqarin and ancient/aging concrete structures ➢ Hyperalkaline plume scenario using observations from Maqarin	➢ Hydrogeochemical processes and parameter values for released hydroxides due to leaching; CSH and CASH phases; zeolite phases; pH reduction due to reaction with silicate minerals; and colloids/microbes/organics	➢ 'Blind predictive' testing of thermodynamic databases at Oman and Maqarin

4.2 Conceptual model development

Developing a conceptual model to represent the anticipated evolution of a repository is at the heart of safety assessment.

Analogues are fundamental to this task because they provide the only means to observe how the natural environment operates over long time periods. In very broad terms, the entire knowledge base of the earth and material sciences could be said to be used to inform the development of conceptual models in an analogous way. Thus it is not only information that has been derived from studies labelled as 'analogues' that can and have been used in this way.

In practical terms, analogue information should be used in conceptual model development to determine such things as:

- which processes need to be explicitly simulated in the model (i.e. what process occur in analogous systems, which of these processes are dominant and which are of secondary importance);
- what are the relevant spatial and temporal scales over which the model should apply;
- what are the main process interactions that need to be accounted for (e.g. between thermal, chemical and mechanical effects); and
- what is the range of applicability of a model (e.g. for what range of Eh and pH conditions does the model hold true).

It is beyond doubt that the development of safety assessment conceptual models has always been informed by an understanding of geological, physical and chemical processes but rarely has this fundamental analogue based approach been adequately documented or acknowledged.

Within the NAnet project, relatively few examples were identified where credit has been given to analogue studies in the broadest sense for support to the development of conceptual models. One of the better examples comes from the Maqarin study in which observations of unusual assemblages of secondary minerals that resulted from interactions between the hyperalkaline groundwaters and the rock [Savage, 1998] were used to develop and constrain a conceptual model to explain the possible interactions which might occur between a hyperalkaline plume migrating away from a repository through the host rock (Figure 7). When this conceptual model is applied in a safety assessment, confidence in the model is enhanced because the realism in the model can be demonstrated.

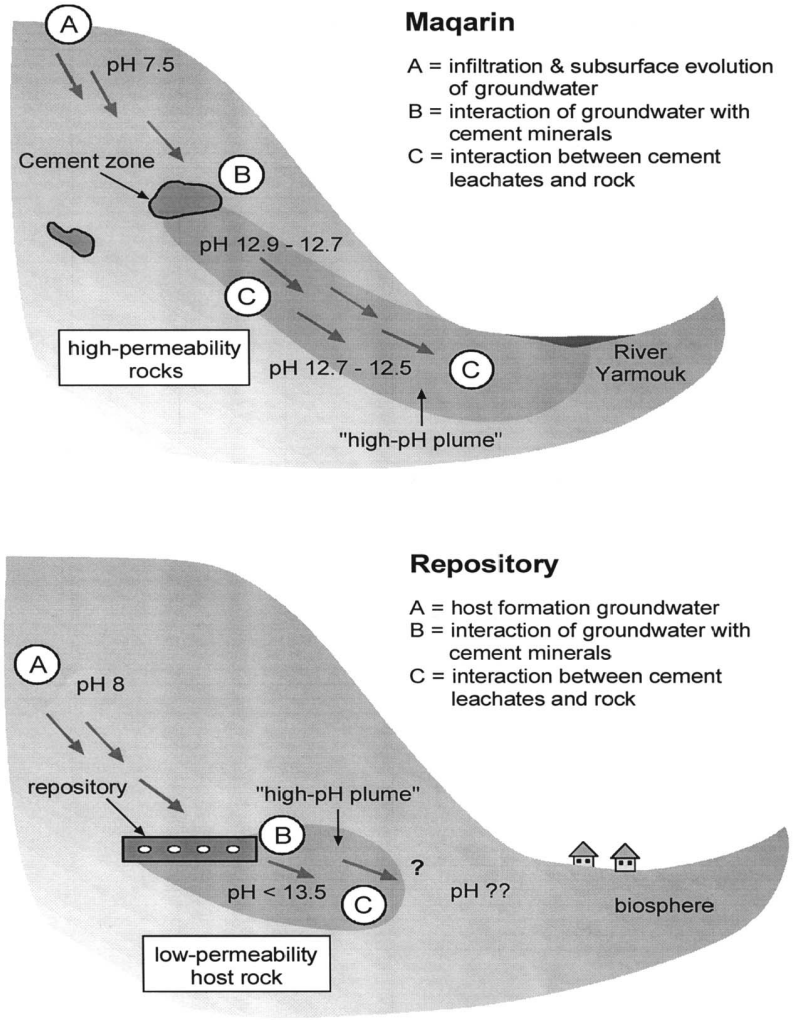


Figure 7: The basis of the analogy between the Maqarin analogue site and a cementitious repository. From Savage [1998]

This example indicates that it is largely the qualitative information from analogue studies that is most useful in the development of conceptual models.

We recommend that conceptual models used to describe the evolution of a repository system should be presented clearly in assessment documentation. This could involve a visual 'storyboard' supported by illustrations from relevant analogues showing how the expected evolution has been derived and to justify the inclusion (and omission) of specific processes in the models through the mechanism of abstraction and simplification.

As well as helping in the development of conceptual models of repository processes, analogues have a similar role in safety assessment to help identify appropriate scenarios to be assessed: a scenario is essentially a very high-level conceptual model that describes the driving force for repository evolution.

In scenario-based assessments, likely and less likely evolution scenarios are constructed in a bottom-up manner from combinations of FEPs which are thought might occur in the repository system during its lifetime. Natural analogues are proving themselves to be of primary importance in identifying and screening FEPs, and therefore, in defining appropriate scenarios to be assessed. As most recent assessments are scenario-based, there is a growing role for analogues in this regard.

As with conceptual model development, however, the role of analogues in FEP screening and scenario construction is usually implicit and not widely acknowledged in the assessment documentation.

4.3 Data provision

With regard to parameter values, analogues can be used to help the safety assessor to decide what are appropriate values to input to the mathematical models, either as best estimates or as conservative values or ranges. It is now generally accepted that analogue studies rarely provide quantitative values that can be input directly into safety assessment models. Only a few cases were identified in the NAnet project where safety assessments have used quantitative analogue data directly, e.g.:

- matrix diffusion depths in fractured crystalline rock from the Grimsel Test Site were used in the Swiss Kristallin-I assessment [Nagra, 1994]; and

- native copper corrosion from Hyrkkölä were used in the Finnish TILA-99 assessment [Vieno and Nordman, 1999].

This situation arises because the complexity of natural systems means that it is very difficult to be sure where a measurement from an analogue study would fall in the pessimistic to optimistic value range when applied to a repository system. As a result, the primary source of parameter values for mathematical models comes from laboratory studies and from site characterisation. Nonetheless, analogues have a fundamental role in providing support in the form of bounding limits to values derived from laboratory experiments. This is because the inherent complexity of long-term analogue systems counterbalances the implicit simplicity of short-term laboratory experiments.

4.4 Model, code and data testing and validation

Natural analogues provide a potential means for testing safety assessment models and codes, and databases. The basic concept is to test an assessment model to see whether it can simulate the conditions observed in a natural system that is considered to be analogous to the repository system.

Although simple in concept, there are some practical problems in this approach. The main difficulty arises because of the ‘direction’ of the model simulation. In a safety assessment, models are used to simulate a future end-state from a known set of initial boundary conditions, whereas for an analogue system, the end-state is known but the original boundary conditions may not be well defined.

To use analogue systems for model testing, therefore, it is critical that the system is well defined and understood, so that any discrepancies between the model simulation and observed conditions can be explained.

Whilst this concept has been discussed for many years, relatively few examples of its application were identified during the NAnet project. Of those that were, almost all cases were related to the testing of thermodynamic (geochemical) solubility and speciation codes and databases. These geochemical codes have been rigorously tested in a number of analogue studies, including those at El Berrocal, Maqarin, Osamu Utsumi, Cigar Lake and Palmottu.

In each case, a 'blind predictive modelling' approach was used to test the suitability of assessment codes and databases for predicting the solubility of radionuclides in particular geochemical conditions that are analogous to repository near or far-field conditions. In this approach, the modellers are provided with the basic properties of the rocks and waters in the analogue system (the type of information a safety assessor would be provided with from a repository site characterisation study) and are asked to use these data to predict how specific trace elements will behave. In the analogue case, these trace elements are naturally present in the waters, and their actual speciation and concentrations can be measured separately and compared with the modeller's predictions.

It is not clear why this approach has not been used more widely to test other assessment codes but presumably it is partly to do with the inability to identify natural systems that are sufficiently simple and well characterised to allow the initial boundary conditions to be established with confidence. A number of assessment codes could possibly be tested in this way, assuming suitable sites, such as those used to model solute diffusion and advection, colloid transport, metal corrosion, wasteform degradation etc.

We recommend that more effort is put into the identification of analogue systems for the purpose of model testing. The most likely candidate would be far-field codes that simulate solute advection in fractured rock systems, since these are amenable to description using standard site characterisation methods. There is a clear overlap between this application of analogues and palaeohydrogeology. Thus, of all the possible applications of analogues in the safety assessment model building process, model testing is seen as being the area where there remains considerable potential for further development.

4.5 Sub-system understanding

A repository will evolve over time as a single, complex system and radionuclides migrating from the waste may move through the engineered barriers and the host rock, to reach the surface, along a continuous path variously affected by a number of physical and chemical processes.

A safety assessment aims to replicate the entire repository system adequately and conservatively but it is usual, for the sake of convenience, to consider the system as separate near-field, far-field and biosphere (surface environment) sub-systems. Usually a safety assessment employs separate models for each sub-system. These are then linked together, with the output from one model fed, as input, to the next. As well as the models used in the main safety assessment calculations, other research codes may be used during the assessment to perform scoping calculations to ascertain the significance of some processes. These research models are a fundamental part of

safety assessment. If they indicate that a particular process is significant for safety, then that process may be explicitly included within the safety assessment calculations.

As a consequence of this modelling approach, it is valid to consider the relevance of natural analogues separately to the near-field, far-field and surface environment, and this was the focus of Work Packages 1-3 respectively. It should be noted, however, that many analogue studies have relevance to more than one repository sub-system. For example, study of the Cigar Lake uranium orebody in Canada revealed useful analogue information on the degradation of spent fuel (near-field) and radionuclide transport through fractured sandstone rock (far-field).

For this reason, it is important that natural analogues should not be pigeon-holed specifically as 'near-field', 'far-field' or 'surface environment' analogues. As assessment models improve, and whole-system assessment codes are developed, the relevance of particular analogue studies may change, and analogue researchers and assessment modellers should keep an open mind to the relevance of particular analogue studies for specific repository concepts and processes.

The following sections provide a summary of the main conclusions from Work Packages 1-3 on the relevance of analogues to current safety assessment modelling approaches for the near-field, far-field and surface environment sub-systems.

4.5.1 Near-field issues

The designs of most repositories adopt the 'multi-barrier' principle, with the isolation capacity provided by a series of engineered barriers in the near-field and the host rock in the far-field (geosphere). The near-field itself generally comprises:

- the wasteform,
- the waste packaging, and
- various buffers, backfills and seals.

Some people also consider the excavation damaged zone (EDZ) and the chemically disturbed zone (CDZ) in the host rock that surrounds the repository excavations to be part of the near-field rather than the far-field.

In safety assessment models, the performance of the near-field can be evaluated by calculating the radionuclide release rate from the near-field to the geosphere. The release rate is a measure of progressive barrier failure over time, due to a combination of physical and chemical processes (and, in some cases, microbial processes) that act to:

- corrode and perforate the waste package or canister;
- dissolve or leach radionuclides from the wasteform; and
- transport (by advection or diffusion) radionuclides through the near-field barriers.

Other processes and their couplings can, however, affect near-field performance in complex ways, for example cement leachates can buffer the chemical conditions in the near-field thus reducing the solubility of many radionuclides. Nonetheless, the

performance of the near-field barriers can be approximated most simply by quantifying the corrosion and degradation rates of appropriate materials.

Since their conception, natural analogues have been recognised as a useful means of 'predicting' barrier performance. Many tens of individual analogue studies have been performed in the last few decades on materials that can be found in natural or archaeological systems (such as glasses, iron, copper and clay) with the aim of 'measuring' corrosion and degradation rates. Some of these studies have provided quantitative information but the majority have provided only qualitative information that has, nonetheless, proved useful for conceptual model development.

The materials that are likely to be found in the near-field of a repository (either in the wasteform, packaging or buffer and backfill) include the following:

- silicate glass (vitrified waste),
- spent nuclear fuel,
- mineral and ceramic wasteforms,
- metals such as steel, copper and titanium,
- bentonite clay,
- cement and concrete, and
- organic materials (e.g. bitumen matrices and paper wastes).

A number of these materials exist in nature or have similar natural counterparts (e.g. copper and bitumen) but others are man-made technological developments (e.g. steel) which do not have natural equivalents but possibly may be found in the archaeological record.

Table 5 below provides a summary of the most important analogue information relevant to near-field barrier containment. More complete details are provided in the Work Package 1 report.

Table 5: A summary of the main analogue observations with regard to the performance of near-field barrier materials

Repository material	**Analogue material**	**Analogue observations**
Silicate glass	Natural basaltic glass	Natural basaltic glasses have similar SiO_2 concentrations to waste glass but do not have high boron or actinide contents. Usually they are from near-surface or submarine oxidising environments, rather than reducing environments. Basaltic glasses are thus only approximate analogues to borosilicate glasses. Natural and borosilicate glasses corrode by the same mechanisms. Devitrification is very slow in nature, so is not considered a problem for the repository. In nature, glass dissolution and hydration result in a layer of secondary alteration products which slows further alteration and which may also incorporate radionuclides. Quantitative analogue derived corrosion rates exist that

Repository material	Analogue material	Analogue observations
		may be used to provide bounding limits to corrosion rates (for example, obsidian hydration is an established technique for dating archaeological artefacts). Overall, analogues suggest glass is a stable wasteform.
	Archaeological glass	Some archaeological glasses are coloured with metal oxides, including U compounds and up to 5 % U can occur in some glasses. These may provide useful information on radionuclide leaching and incorporation in secondary alteration products. A few analogue studies have examined the corrosion of uranium glasses but the results do not provide quantitative information. Overall, these studies confirm glass is a stable wasteform.
Spent fuel	Natural uraninite	Natural uraninite has a similar UO_2 composition and mineralogical structure to spent fuel but natural uraninites have not experienced criticality and do not contain transuranic nuclides and daughters (except those from Oklo). Abundant very old uraninites (10^9 years) indicate UO_2 is very stable in reducing environments. Slight oxidative conversion due to radiolysis of groundwaters is seen at Cigar Lake and at Oklo but very limited in extent. No reliable quantitative analogue corrosion rates under reducing conditions are available to input into safety assessment models. Analogues can provide only upper bounding limits to corrosion rates. Analogue observations show more rapid oxidation occurs in near-surface environments. Data from Peña Blanca on radionuclide release rates have been used as input to Yucca Mountain safety assessment to test for conservatism in models. Overall, analogues suggest spent fuel is a stable wasteform.
Mineral and ceramic wasteforms	Natural zirconolites and pyrochlores	Zirconolites and pyrochlores have compositions and mineralogical structures that are similar to the Synroc wasteform but have much lower actinide contents. Natural zirconolites and pyrochlores show very limited alteration, suggesting high stability. They are rare minerals and usually found as detrital grains, so it is not possible to relate this lack of alteration to in situ physico-chemical conditions. No reliable quantitative analogue corrosion rates are available to input to safety assessment models but qualitative analogue information suggests mineral and ceramic wasteforms are stable.
Metals	Native metals	Native Fe is rare in nature except where it is isolated from groundwater. This indicates the instability of Fe in geological environment and suggests the corrosion of steel canisters in a repository on geological timescales. Native Cu is relatively abundant and found in a number of environments, indicating the higher stability of Cu and suggesting long-term durability of Cu canisters in the repository.

Repository material	Analogue material	Analogue observations
		No reliable quantitative information from analogues exists on corrosion rates from native metals to input to safety assessment models. Natural analogues can provide qualitative information only.
	Archaeological metals	Abundant Fe artefacts occur in the archaeological record (e.g. Inchtuthil nails) but many more artefacts presumably corroded away. Fe artefacts from reducing conditions are preserved longer than those in oxidising conditions. Semi-quantitative information suggests Fe canisters may last for 10^3 years, at least, in reducing environments. Common Cu or bronze artefacts occur in the archaeological record and these generally show low corrosion rates in most environments. Semi-quantitative information suggests Cu canisters may last for 10^5 years.
Bentonite clay	Natural bentonite	Bentonite is a relatively common natural material which qualitatively points to its stability in many geological environments. The clay undergoes ion-exchange with dissolved K to form illite but the mechanism is usually limited by the supply of exchangeable ions. Analogue information suggests this is unlikely to be a problem in a repository due to the low groundwater flows and chemistry. Contact metamorphism causes cementation and fracturing of bentonite but this is not really analogous to near-field conditions since temperatures much higher. Thermal impacts on bentonite not yet fully resolved in analogue studies: further appropriate studies are warranted. Compacted clay layers show a long-term ability to restrict movement of water and air to preserve organic materials (e.g. Dunarobba). This provides qualitative evidence for the long-term hydraulic barrier function for buffer. Overall, analogues suggest bentonite is a stable material.
Concrete and cement	Natural cement minerals	Natural cement minerals are rare and occur in unusual geological environments. When isolated from free-flowing waters, these cement minerals can remain stable for 10^7 years. When in contact with water, they dissolve slowly to buffer high pH groundwater conditions. No reliable quantitative information exists on the cement mineral dissolution rates to input to safety assessment models but there is quantitative evidence (e.g. from Maqarin) to indicate that chemical conditions will exceed pH 12 and be maintained for 10^3 years or longer, buffered by the dissolution of portlandite. Analogue information suggests that pH conditions in a repository will remain hyperalkaline for thousands of years.
	Archaeological cements	Numerous archaeological cement compositions have been found. Those similar to Portland cement

Repository material	Analogue material	Analogue observations
		(containing calcium silicate hydrates) show long-term durability and resistance to dissolution. Many Roman cements (e.g. Hadrian's Wall) remain perfectly stable after 2000 years. Overall, archaeological analogues suggest cement and concrete are stable materials.
Organic materials	Natural bitumens	Natural bitumens are found in a number of locations indicating they are stable in many near-surface conditions, including water saturated environments. Bituminous materials found at Oklo indicate that radionuclide retention can be enhanced by a bitumen matrix. No reliable quantitative information exists on corrosion rates to input to safety assessment models. In particular, no natural bitumens have been examined from hyperalkaline conditions so it is not possible to extrapolate these analogue observations directly to the near-field of a cementitious ILW repository.
	Natural cellulose	Natural cellulose (plant material) has been found in a variety of environments exhibiting only limited degradation, even after thousands of years of burial, when in chemically reducing conditions. Dunarobba extends this to 1 million years. This study provides qualitative evidence for the possible slow degradation of cellulose in the repository. No reliable quantitative information exists on corrosion rates to input to safety assessment models. In particular, no natural cellulose has been examined from hyperalkaline conditions so it is not possible to extrapolate these analogue observations directly to the near-field of a cementitious ILW repository.

In addition to providing information on the rates of degradation of near-field materials, natural analogues also provide information on the stability of the repository system itself, in particular the near-field excavations. Several repository concepts now anticipate leaving the repository open for an extended period of time after the waste is emplace to allow future generations to make decisions about whether or not to close the repository or to retrieve the waste. Such phased repository concepts are dependent on the repository excavations remaining stable and open for hundreds of years, rather than the decades that a standard repository would need to remain open for during emplacement operations.

Examination of natural and man-made caves and caverns, and statistical data on their depths and structural integrity, has demonstrated that there is plentiful evidence for the survival of underground caverns of repository size scales over prolonged periods of time at repository relevant depths. The information is particularly relevant to the stability of the EDZ in phased repository concepts. As discussed in Section 3, it is evident that the explicit use of analogue information in safety assessments has been quite limited. One reason why this may be the case is that the potential users of analogue information are unaware of what information there is that could be relevant to their work. It was recognised in Work Package 4 that the potential users of analogue information, particularly the safety assessors and the communications specialists, need easy access to analogue information that is relevant to the issues at hand.

Table 6 presents this information in the form of a matrix with the range of near-field materials on one axis and the range of processes that operate in the near-field on the other. Intersections of the axes identify unique material-process combinations and relevant analogue studies are listed at the appropriate intersections. It should be noted also that on an analogue matrix, not all material-process interactions are possible in a repository. For example, radionuclide diffusion within the metal of a canister is not a relevant combination. In this matrix, these 'invalid' combinations are shaded. Table 6 also indicates, unsurprisingly, that there has been a preponderance of studies on materials that are widely found in nature, such as uraninite and bentonite, and processes that occur readily in different geological conditions, such as chemical corrosion and alteration. For these process-material combinations, there is a wealth of analogue information that provides substantial support for the development and testing of conceptual models, and some quantitative data to help constrain the rates of processes.

The matrix also indicates there are a number of gaps, where only a few or no analogue studies have examined particular process-material combinations. For example, analogue studies have only examined diffusion through bentonite clays but not through other near-field materials such as cement and concrete. Similarly, there is little available analogue information on some other transport processes through cement and concrete, including colloid transport and two-phase flow. Thus the matrix provides a useful means of identifying gaps where further analogue studies may be required.

The matrix in Table 6 is generic and does not represent any particular repository design. It is recommended that repository specific matrices should be developed by analogue researchers and performance assessors to reflect their own particular repository designs and site characteristics. These matrices could then be populated to indicate how individual analogue studies have been or could be used to inform the development of their own safety assessment models for the near-field. As an example, Figure 8 illustrates a number of analogue studies that provide information on the performance of the near-field barriers that are found in the Swedish concept for a spent-fuel repository, and these are specified in Table 7.

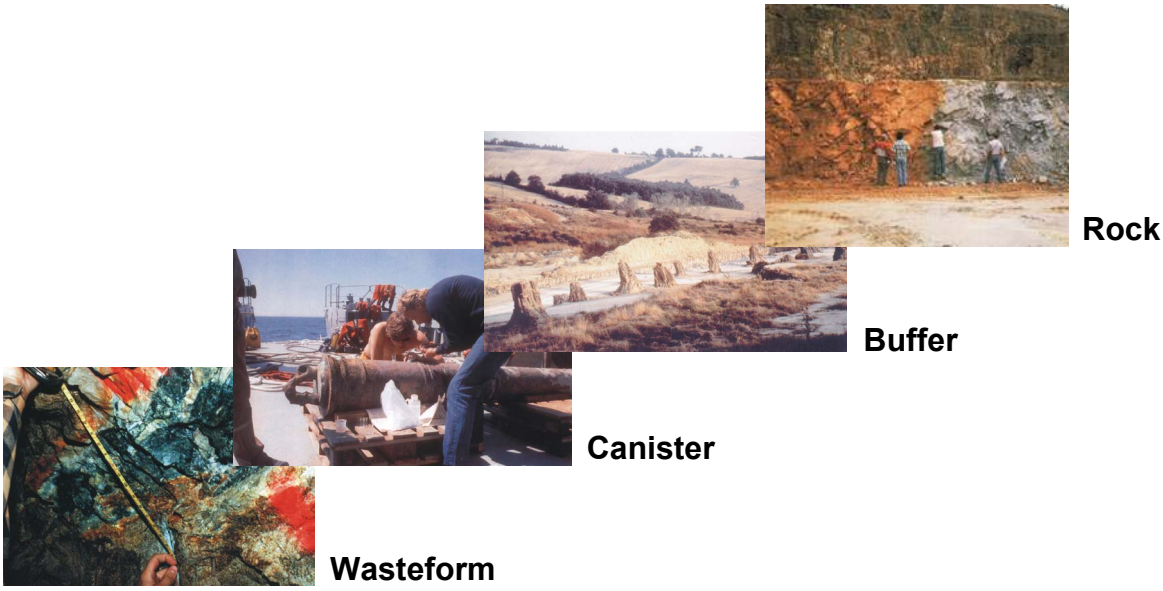


Figure 8: Analogue representation of the near-field materials planned to be used in the Swedish concept for a deep spent-fuel repository

Table 6: The generic analogue matrix for the near-field. The shaded squares represent 'invalid' process-material combinations that would not occur in a repository. The empty squares represent process-material combinations that can occur in a repository but no analogue study has investigated

		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	

Waste package				Buffer		Near-field rock
Copper	**Steel**	**Titanium**	**Concrete**	**Bentonite**	**Concrete**	
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
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
			Beziers Maqarin Khushaym Matruk Hadrian's Wall	Dunarobba	Beziers Maqarin Khushaym Matruk Hadrian's Wall	Björklund BORIS Caves El Berrocal Geothermal systems Morro do Ferro Osamu Utsumi
				Loch Lomond Bangombe Boom Clay Cigar Lake Dunarobba Kinnekulle		Akrotiri Bangombe BORIS
				Bangombe Cigar Lake		Alligator Rivers Bangombe BORIS El Berrocal Menzenschwand Morro do Ferro
				Gas studies		Gas studies Geothermal systems
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

Table 7: Analogues of relevance to the near-field materials planned to be used in the Swedish concept for a deep spent-fuel repository

Near-field component	Fabrication material	Analogue
Wasteform	Spent fuel	Cigar Lake uranium orebody
Canister	Copper	Bronze Kronan cannon
Buffer	Compressed bentonite	Dunarobba fossil forest
Near-field rock	Granite	Osamu Utsumi mine

4.5.2 Far-field processes

The key requirement of the host rock that makes up the far-field is that it should be relatively stable so as to protect the engineered barriers in the near-field and its behaviour should be adequately predictable. In this regard, geological stability relates not only to the physical features of a site but also to the geochemical and hydrochemical aspects. The rocks usually considered as potential host rocks include:

- crystalline basement rocks;
- extrusive volcanic rocks (e.g. lavas and pyroclastics);
- low-permeability sedimentary sequences; and
- thick or diapiric evaporite (salt) deposits.

In safety assessment models, the performance of the far-field can, in broad detail, be evaluated by calculating the rate of migration through the geosphere of those radionuclides that are released from the near-field and, ultimately, the concentration of those radionuclides that reach the biosphere (surface environment). As part of a repository safety assessment, consideration also needs to be given to those processes that could affect the stability of the far-field and, therefore, the rate at which radionuclides may migrate through it.

These migration processes operate today, and have done in the past, in many natural systems without a repository being present. The main difference is that only naturally-occurring chemical species (such as natural uranium) are affected by them. It is the migration of naturally occurring radioelements in geological environments similar to those anticipated to host a repository that first attracted natural analogue researchers as a means of 'predicting' far-field performance. Many tens of individual analogue studies have been performed in the last few decades on natural radionuclide migration systems, usually in the vicinity of uranium orebodies, with the aim of 'measuring' transport and retardation processes. Some of these studies have provided quantitative information (e.g. on matrix diffusion depths) but the majority have provided only qualitative information that has, nonetheless, proved useful for conceptual model development and testing. The main process that operate in the far-field that control radionuclide transport and retardation are:

- radionuclide transport, including diffusion and fracture and porous media controlled advection;
- radionuclide retardation, including chemical (sorption, precipitation/co-precipitation, immobilisation) and physical (filtration and ion-exclusion) processes etc.;

– geostability and tectonic processes, including uplift and subsidence, volcanism and seismic activity; and

– palaeohydrogeology and palaeohydrogeochemistry.

Table 8 provides a summary of the most important analogue information relevant to these far-field processes. More complete details are provided in the Work Package 2 report.

Table 8: A summary of the main analogue observations with regard to processes in the far-field that control radionuclide transport and retardation

Repository process	Analogue system	Analogue observations
Radionuclide solubility	Geochemistry of natural groundwaters	Most repository safety assessments focus on release of radionuclides into flowing groundwater. Simple geochemical observations of groundwaters around uranium ore bodies and in rare high pH systems indicate that many relevant elements are present in low concentrations which are controlled by the solubility of specific minerals. In most cases, these minerals are solid-solutions (mixed minerals) and not pure compounds. It is not possible to examine geochemical behaviour of transuranic elements because they do not exist in nature. Geochemical models used in safety assessment are tested in some analogue studies. These demonstrate that the models are generally adequate for predicting concentrations of most trace elements but a few cases of under prediction if wrong mineral is assumed. Additional analogue studies are required in specific systems with measurable concentrations of potentially problematic elements (e.g. Se, Sn, Ni).
Sorption		Most radionuclides dissolved from the waste will interact with the rock as they move with the groundwater. Such rock/radionuclide reactions retard radionuclide transport with respect to the groundwater and, hence, are beneficial from a repository safety standpoint. Analogue observations provide qualitative evidence that trace elements become fixed to many minerals. It is, however, very difficult to distinguish between fixation by true sorption or by precipitation. Several quantitative measurements of sorption made in analogue studies in fractured crystalline rock/groundwater systems. These data cannot be applied directly to safety assessment because of uncertainty over the extent of precipitated phases. Further natural analogue studies and method developments are required to provide accurate, precise *in situ* sorption values to input to safety assessment or to lend support to laboratory values.
Matrix diffusion		Matrix diffusion is the process by which dissolved radionuclides carried in flowing groundwater in a fractured rock penetrate the bulk of the rock mass by diffusion. Analogue observations of the rock mass adjacent to fractures provide qualitative evidence for the operation of matrix diffusion. The depth of matrix

Repository process	Analogue system	Analogue observations
		diffusion is usually limited, so the entire rock mass is not available for diffusion around a repository. Several quantitative measurements of interconnected porosity depths made in analogue studies in fractured crystalline rock/groundwater systems suggest 10 mm is a conservative value to use in safety assessment.
Matrix diffusion		Fewer studies have been undertaken in sedimentary rocks but there is clear evidence from analogue studies that matrix diffusion occurs in sediments. Reduction spots suggest very slow diffusion in low permeable sedimentary formations.
Colloid transport	Natural colloids	Colloids are very small, suspended particles which may be carried along by advecting groundwaters at the groundwater flow rate. Due to their size, they have a very large surface area and a substantial capacity to sorb (attach) radionuclides. As a consequence, colloids can potentially increase the mobility of otherwise poorly soluble and/or strongly sorbed species and, potentially, can transport them at the groundwater flow rate. Abundant analogue evidence exists for the presence of colloids in most natural waters. In groundwaters close to uranium ore bodies, there is clear evidence of radionuclide fixation to such colloids. No reliable quantitative analogue information on colloid populations because they are site specific. There is no appropriate natural analogue evidence of colloid transport over long distances, although there are some indications of transport through permeable materials on tens of metres scale. Observations of clay layers at Cigar Lake and at Oklo suggest that they filtered colloids from the water, and indicates that the bentonite buffer will do the same in a repository. Further analogue studies are required in appropriate systems to address issue of colloid transport in geosphere.
	Atomic bomb test sites	Radionuclide-containing colloids have been found hundreds of metres to kilometres from explosion sites. However, it is uncertain if transport was on colloids over the entire distance. The fact that the rock mass is heavily perturbed by explosive damage and that inappropriate sampling techniques have been employed means that the observations are probably irrelevant for repository safety assessment.
Gas transport	Hydrocarbon industry observations	Gas may be produced in repositories after closure by anaerobic corrosion of steel, microbially induced degradation of organic materials and radiolysis of water. The formation of a gas phase in the repository can potentially have a number of impacts on repository behaviour and safety, including the enhancement of radionuclide transport. This could result from the direct incorporation of radionuclides in a gas molecule (e.g. as ^{3}H in hydrogen gas or ^{14}C in CH_4), attachment of radionuclide bearing colloids or molecules to bubble

Repository process	Analogue system	Analogue observations
		surfaces, or gas pressures forcing groundwater movement. Qualitative observations from the hydrocarbon industry indicate that gas transport in the geosphere is rapid via permeable features. Migration may be parallel to bedding as well as vertical. This information may be useful to develop or validate conceptual models for gas migration in the far-field but there are no known analogue studies undertaken in the radwaste industry to date. However, several studies have been carried out to support the idea of CO_2 sequestration by pumping CO_2 gas/liquid into deep aquifers.

It was recognised in Work Package 4 that the potential users of analogue information, particularly the safety assessors and the communications specialists, need easy access to analogue information that is relevant to the issues at hand. Table 9 presents this information in the form of a matrix with the range of potential host rocks on one axis and the range of processes that operate in the far-field on the other. Intersections of the axes identify unique rock-process combinations and relevant analogue studies are listed at the appropriate intersections.

4.5.3 Near-surface and surface environment processes

Traditionally, natural analogue studies have not paid attention to near-surface and surface environments, dealing instead only with the near and far-field systems. There are a number of reasons for this but the main one stems from the fact that, in most assessments previously undertaken, the biosphere was considered primarily for the purpose of providing a discharge-to-dose conversion factor for each radionuclide and relatively little attention was paid to the role of the terrestrial biosphere within the disposal system in limiting potential exposures to radionuclides. Put simply, analogue studies have largely been viewed as a means of understanding barrier performance and the biosphere has not been traditionally been considered as a barrier.

There are other possible reasons why analogue studies have not previously examined near-surface and surface environments, and these relate to the fact that the biosphere is highly complex, dynamic and both spatially and temporally variable. Therefore characterising, evaluating and modelling the biosphere (for the purposes of safety assessment) is even more challenging than it is for the near and far-field systems.

Lastly, there has for some time been a division between workers in biosphere studies and those in natural analogues and geosphere studies. This may be due to the fact that they are working to understand different natural process but this division is somewhat arbitrary and is more likely due to the mundane fact that safety assessments employ different models and codes to simulate the biosphere than the geosphere.

Nonetheless, when stepping back and taking a wider view of natural systems, it is rather short-sighted not to pay the same attention and to take a similar approach to learning about biosphere process as is applied to geosphere processes. As such, the NAnet project took the view that the definition of analogues should be widened to include near-surface and surface environment as well as deep geological processes. To make the task manageable, however, the scope of Work Package 3 specifically excluded biologically influenced surface processes, i.e. those related to radionuclide uptake, transfer and exposure to flora and fauna.

Table 9: The generic analogue matrix for the far-field

Features, Events and Processes (FEPs)	Mudrocks e.g. Clays, Shales, Slates	Crystalline e.g. Granites, Metamorphics
Disruption to Geosphere		
Mechanical/Chemical		
Tectonics	Tono	Tono
Neotectonics		Lansjärv; Pärve; Scotland
Seismicity		Tono; China mines
Volcanism		
Diapirism	Gorleben; Morsleben	
Hydro-/Geothermal	Oklo; Bangombé	Marysvale; Osamu Utsumi; Palmottu; Mina Fe; El Berrocal
Cold Climate Events	Gorleben; Morsleben; Mt. Terri; Boom Clay; Opalinus Clay	Lupin Mine; Palmottu; Äspö, Sellafield; Stripa URL , Whiteshell
Gas overpressure	Gas reservoirs; North Sea sediment analogies	Gas reservoirs
RN Migration at Low Temperature (< 100 °C)		
Hydrogeological		
Advection (Saturated)	Cigar Lake; Bangombé; Morro do Ferro; Oklo; Ruprechtov; Osamu Utsumi; Needle's Eye; South Terras; Bangombé; Broubster; Heselbach,	Äspö; Palmottu; Whiteshell; Grimsel; Steenkampskraal; Oklo; Grimsel; Eye-Dashwa Pluton; El Berrocal; Osamu Utsumi; Stripa; Needle's Eye; Coles Bay; Klipperås; Mina Fe; Kråkemåla; Menzenschwand
Advection (Unsaturated)	Morro do Ferro; Heselbach; Bangombé	El Berrocal; Osamu Utsumi
Diffusion	Cigar Lake; Mt. Terri; Morro do Ferro; Oklo; Loch Lomond; Tono; Boom Clay; Bangombé; Opalinus Clay	Äspö; Palmottu; Whiteshell; El Berrocal; Tono; Grimsel; Kråkemåla; Mina Fe; Osamu Utsumi
Colloids	Cigar Lake; Boom Clay Morro do Ferro; Tono; Oklo; Bangombé; Broubster; Ruprechtov	Äspö; Palmottu; El Berrocal; Grimsel; Osamu Utsumi; Grimsel; Oklo; Alligator Rivers; Steenkampskraal; Whiteshell; Menzenschwand;
Microbes	Osamu Utsumi; Boom Clay; Cigar Lake; Ruprechtov; Bangombé; Tono?	Åspö; Palmottu; URL Whiteshell; Mina Fe; Tono?
Organics	Osamu Utsumi; Oklo; Boom Clay; Cigar Lake; Ruprechtov; Broubster; Morro do Ferro; Tono?; Needle's Eye; Bangombé; Heselbach?	Åspö; Palmottu; URL Whiteshell; Oklo; Stripa; Osamu Utsumi; Mina Fe; Tono?
Two-phase Flow		

Salts	Sandstones	Limestones (including marls)	Tuffs (including ashes)
	Tono		
		Maqarin	
			Peña Blanca
Gorleben; Morsleben	Gorleben; Morsleben	Gorleben; Morsleben	
	Cigar Lake; Oklo		
Gorleben; Morsleben	Gorleben; Morsleben; Cigar Lake	Gorleben; Morsleben	
Wolfcamp	Cigar Lake; Tono; Broubster; Oklo; Boris; Heselbach; Morsleben	Maqarin	Nevada Test Site
			Peña Blanca; Akrotiri
	Cigar Lake; Oklo; Boris; Tono	Maqarin	
	Cigar Lake; Oklo; Boris; Tono	Maqarin	Nevada Test Site; Mortandad Canyon
	Cigar Lake; Tono?	Maqarin	
		Maqarin	

Table 9: The generic analogue matrix for the far-field (continued)

Features, Events and Processes (FEPs)	Mudrocks e.g. Clays, Shales, Slates	Crystalline e.g. Granites, Metamorphics
RN Migration at High Temperature (> 100 °C)		
Hydro-/Geothermal		
Advection	Oklo	Palmottu; Marysvale; Osamu Utsumi
Diffusion	Oklo	Palmottu; Marysvale
Vapour Transport		
RN Retardation at Low Temperature (< 100 °C)		
Physical		
Pore Space		
- *colloid filtration* - *microbe filtration*	Morro do Ferro; Cigar Lake; Dunarobba	El Berrocal
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; Äspö; Grimsel; Bangombé; Palmottu; Tono; Eye-Dashwa Pluton; Osamu Utsumi; Stripa; Mina Fe; Klipperås; Coles Bay; Kråkemåla; URL Whiteshell
Matrix Diffusion	Tono; Cigar Lake; Ruprechtov; Heselbach; Opalinus Clay; Bangombé; Boom Clay	El Berrocal; Äspö; Grimsel; Palmottu; Eye-Dashwa Pluton; Tono; Coles Bay; Kråkemåla; Stripa; Osamu Utsumi; Opalinus Clay; URL Whiteshell
RN Retardation at High Temperature (> 100 °C)		
Physical		
Pore Space		
Chemical		
Sorption	Oklo; Bangombé	Marysvale; Osamu Utsumi; Palmottu; Mina Fe; El Berrocal
Precipitation/Co-precipitation	Oklo; Bangombé	Marysvale; Osamu Utsumi; Palmottu; Mina Fe; El Berrocal
Immobilisation	Oklo; Bangombé	Marysvale; Osamu Utsumi; Palmottu; Mina Fe; El Berrocal
Matrix Diffusion	Oklo; Bangombé	Marysvale; Palmottu; Mina Fe; El Berrocal
High pH Plume		Semail Ophiolite (Oman)?

Salts	Sandstones	Limestones (including marls)	Tuffs (including ashes)
Wolfcamp	Cigar Lake; Oklo		Peña Blanca; Long Valley Caldera; Alamosa River Long Valley Caldera Alamosa River
Wolfcamp	Oklo; Cigar Lake; Boris; Morsleben; Tono	Maqarin; Khushaym Matruk?	Akrotiri; Peña Blanca
Wolfcamp	Oklo; Cigar Lake; Tono	Maqarin; Khushaym Matruk?	Peña Blanca?
	Oklo; Cigar Lake Oklo; Cigar Lake Oklo; Cigar Lake Oklo; Cigar Lake		
		Maqarin; Khushaym Matruk	

The analogues considered therefore relate to studies dealing with non-biologically influenced (or at least very poorly influenced) analogues of interactions between contaminated groundwaters and near-surface features, such as soil horizons and rivers, lakes and streams, occurring at the geosphere-biosphere interface zone (GBIZ).

There is a very large body of literature concerned with radionuclide migration in the GBIZ. Much of this is derived from studies of anthropogenic contamination such as spillages and leaks, and from major accidents such as Chernobyl. As a result, much of the literature concerns systems in which surface deposition of contaminants has occurred and migration is through the unsaturated soil zone downwards to the water table. Whilst this is the reverse of what is to be expected from any repository releases that may occur, some of the detailed transport processes occurring in the sub-systems are fundamentally the same and, therefore, these studies may be considered as analogues.

It is the case that much of the specific research on radionuclide migration in the near-surface has focussed on relatively few radionuclides (e.g. Sr-90). These radionuclides are only of marginal relevance to deep geological disposal as other nuclides tend to dominate the long-term impacts that may arise from releases from deep radioactive waste repositories (e.g. C-14, Ni-59, Se-79). A thorough literature search was conducted for sources of information potentially relevant to near-surface environment analogues in which key elements were involved in migration across the GBIZ. Not unexpectedly, such studies are few in number. The search was therefore broadened out to include studies of elements that might be considered analogous in their behaviour to the key elements of interest. The search resulted in a literature review of over three hundred publications. More complete details are provided in the Work Package 3 report.

Whilst there is no such thing as a perfect analogue, none of the papers reviewed for this report described a situation that was considered to be a direct analogue for key radionuclides being discharged from a deep repository and migrating across the GBIZ. As a general observation, much of the literature dealing with both natural and anthropogenic sources of pollution or contamination that is of potential value in the context of GBIZ analogues seems to be more relevant to near-surface disposal than to deep disposal. It is also apparent that the modes of contamination (e.g. solid residues from processing plants) and the concentration levels, cocktail of chemicals, and minerals/species involved are usually inconsistent with the perceived specification of potential analogues for near-surface situations in the context of deep disposal.

Despite the above findings, a number of the papers reviewed suggested the potential for using field studies of biosphere systems and processes that could be used in support of safety assessments. The most promising areas for biosphere analogues would seem to be consideration of specific examples of different classes of interaction between surface waters and groundwaters under different climate, landscape, geological, soil and ecosystem conditions. The range of situations that could arise simply due to the various combinations of these factors is, however, enormous. Consequently, it must be the responsibility of the experts involved to decide on what analogues are appropriate in the context of the research and safety assessment needs.

As a result of the dynamic nature of the surface environment, the observable biosphere conditions at the time of repository closure are unlikely to reflect the conditions that are relevant to the long-term release of radionuclides. For this reason, analogues for the surface environment (and processes) need to be selected according

to the principle of space-time substitution after careful consideration of likely patterns of climate, landscape and biosphere evolution. However, it is stressed that when considering the deep geological environment (and processes) current conditions may provide an excellent analogue for the future conditions at the site.

One of the most promising ways in which biosphere studies may be employed is, therefore, in identifying and describing present-day landscape and climate settings and, within them, geosphere-biosphere interfaces that can be used to help communicate biosphere concepts relating to potential future situations of interest in safety assessment. From this suggestion, and from a brief review of the literature, it is proposed that three categories of near-surface analogue information can be specified for use in model conceptualisation, model building, model verification and for confidence building:

- ***System Context Studies:*** these are those factors concerned with regional or super-regional spatial scales, such as analogue climate and landscape states.

- ***Whole System Studies:*** studies of discrete hydrogeological settings that depend on particular combinations of lithologies, soils and vegetation. They will generally correspond to groundwater or surface water catchments in which contaminant migration through the near-surface lithologies to soil or to rivers, lakes etc. have been studied and in which the effects of numerous transport-related processes have often been aggregated.

- ***Sub-System Studies:*** involves analogues of detailed contaminant transport-related processes, such as those involving physical and geochemical features and mechanisms.

With regard to whole system studies, one of the most promising uses of biosphere analogues in safety assessment is in providing examples of demonstrably self-consistent biosphere process systems as a basis for model conceptualisation and confidence building. For the most part the key radionuclides will not be present (except in cases such as Chernobyl) but the approach should be to identify the main factors that would determine radionuclide behaviour, such as exchange mechanisms controlling the advection and/or diffusion of groundwaters across the GBIZ and will include factors that influence dispersion.

The number of potential GBIZ systems and associated surface environmental conditions is extremely large and it will be necessary to select distinct examples that will best illustrate to stakeholders the range of potential futures that might arise at a specific repository site. Whole system near-surface analogues may have considerable value in communicating radionuclide transport concepts to stakeholders because they may visit and observe the situations envisaged and thereby appreciate the context for the assessment model in a way that it may be difficult to convey by words and numbers alone.

Present day analogues based on alternative climate states and landscape contexts may also be identified in alternative climatic zones. This is especially useful if the physical characteristics of the analogue are known as well as the key meteorological variables derived from local weather stations. The relevance of catchments in other areas needs to be assessed based on reconstructions of past sequences of landscape change and plausible future changes. This approach is particularly pertinent to those parts of Europe that have been influenced by glaciation and deglaciation as formerly glaciated landscapes may take thousands of years to ‘relax’ to non-glacial conditions.

With regard to sub-system studies, another promising application of near-surface analogues is in demonstrating that a model (and its database) can adequately represent a given real world process in detail. In this type of application analogues are sought that describe the detailed distribution of contaminants in the near-surface system resulting from a protracted release via shallow groundwaters and relate these to specific transport or retardation processes. Ideally, the real world analogue will involve one or more radionuclides that are of interest in the context of deep geological disposal. However, the study of other contaminants (e.g. stable selenium) may also serve a useful purpose in refining models.

Consideration of surface and near-surface processes is new in terms of analogue studies. When identifying suitable analogues for surface and near-surface processes and systems, it is necessary to consider first how they may be used in support of safety assessments. This might be for developing conceptual models (at various levels of detail) or for providing quantitative information to parameterise, calibrate or validate numerical models of radionuclide migration in the near-surface.

A thorough description of the near-surface at the present day is required as a starting point for considering future changes. It would also be necessary to have a good understanding of the Quaternary evolution of the near-surface system from palaeo-studies as a basis for extrapolating system change into the future, driven by climate and environmental change. These drivers provide the regional context and will be necessary for defining appropriate landscape/climate analogue states. The analogue data for precipitation and temperature should be chosen from climate stations that provide a broadly similar geographic setting to the repository site of interest, e.g. maritime or inland and similar altitude. Landscape analogues need only be broadly similar in order to narrow the range of whole system analogue sites that would be suitable for study.

After defining the analogue attributes that set the regional context, consistent whole system analogues would need to be identified by considering the range of GBIZ systems relevant for the landscape settings that are known to have occurred in the past or that might occur in the future. The GBIZ descriptions need to be provided in terms of lithological, soil and structural controls. These primarily affect hydraulic conductivity (saturated and unsaturated) and porosity (storage). The vegetation and ecosystems likely to be present need to be part of the scenario descriptions as they affect potential evapotranspiration and capillary rise. Groundwater-surface water interactions are also dependant on human interactions, e.g. through dewatering by groundwater abstractions or diversion of water courses. Once each of these factors has been described for each climate and landscape state, suitable analogues of the whole system can be sought.

Finally, the detailed processes that are considered to be potentially pertinent to the hydrogeological system operating under each landscape setting need to be decided, based on the level of detail required for the assessment context and based on the understanding of the operation of the transport process for the associated soils, sediments and biota (and possible agroecological systems) chosen. Once the transport processes and the physical conditions are decided at a local scale, appropriate sub-system analogues can be sought.

5 SPECIFIC APPLICATIONS OF ANALOGUES TO COMMUNICATION

Communication and dialogue between stakeholders is essential to the successful implementation of a repository development programme. Natural analogues can play a useful role in communication, along with information from other sources, and this role for analogues has grown in importance in the last few years. This section summarises some of the main uses and suggests some approaches to using analogues for communication purposes. More complete details are provided in the Work Package 4 report.

5.1 Benefits and difficulties in using analogues for communication

Broadly speaking, there are a number of characteristics of natural analogues that make them valuable for communication purposes. Analogues are directly observable in the environment and offer tangible links to many people's own experiences, a factor that is not shared by experimentation in laboratory conditions. Added to that is the inherent attractiveness of nature to most individuals. Most people have some interest in the natural environment and can offer experiential comment about nature. The tangibility of analogues means that they are often seen as vehicles for communication with the 'general public' as opposed to other important stakeholder groups.

As mentioned previously, analogues are inherently qualitative. This has often been seen as a weakness because it can make them difficult to use for modelling and quantitative prediction. For communication purposes, however, this can be a strength because, for most people, life is qualitative and intuitive. The fact that 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.

Ironically, the qualitative nature of natural analogues and the fact that they represent the consequences of integrated environmental processes also causes the greatest potential difficulties in their use in communication. It can mean that analogues are open to a wide range of different interpretations which can lead to different groups using them to support markedly different agendas.

As a consequence, there is often hesitancy in using analogues for communication but this says more about the culture of the group seeking to use them than about the intended audience. For example, it can be very difficult for an experimental scientist to consider using an analogue because the conditions under which it has developed have not been controlled as they would have been in an experiment. A modeller may be hesitant because the analogue will only rarely provide quantitative information of direct relevance to a particular model. A communications specialist may be concerned about using natural analogues because it is not so easy to assert the scientific validity of an analogue and a physical scientist may be reluctant because the analogue may be from outside their sphere of scientific expertise. These concerns are reflected, to some degree, in the way analogues have been used in past communications material.

5.2 Previous applications of analogues in communication

The typical mode of presentation of analogues in communication materials has been in the form of brochures and leaflets. There have been a few examples of other modes of presentation including a number of newspaper information advertisements (Figure 9). In some cases (e.g. Nirex), analogue studies have been sufficiently high profile for

them to be included in Company Annual Reports. The most sophisticated example of analogue communication to date is a video called 'Traces of the Future' [Güntensperger, 1993] that was co-funded by a number of national and international bodies involved with radioactive waste disposal.

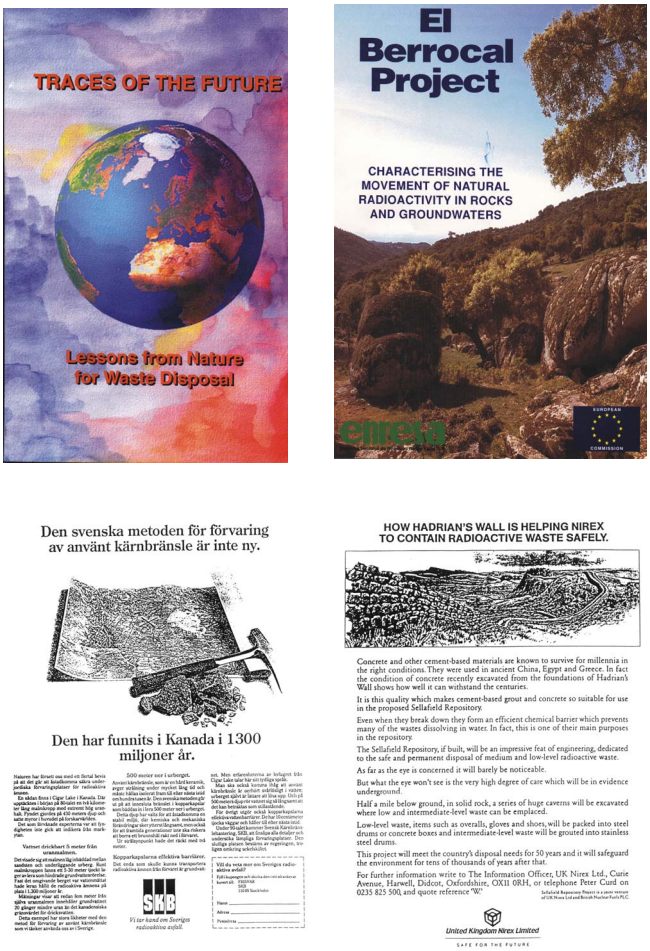


Figure 9: Examples of communication material

A number of observations can be drawn from these forms of communication material that are common to most examples:

- they are almost always focussed on the 'general public' rather than specific stakeholder groups;
- they generally assume little or no technical knowledge on the part of the reader, contain limited text and technical information, and are often illustrated;
- they present information that their author thinks the public should be interested in, rather than present information about issues the public actually asks about (i.e. they form part of a one-way communication not a two-way dialogue);
- they are often generic in style, rather than presenting information on a specific analogue study, and rarely provide bibliographic references to allow an interested reader to obtain more detailed information or gain access to primary technical reports; and

– they appear disconnected from other publications, such as the safety assessment and research reports, and rarely explain how the organisation itself uses analogue information, giving the impression that analogue studies are not fully integrated into research and development programmes.

Another key observation is that only a small number of analogue studies have actually been used for this purpose, despite the large number of studies that have been undertaken. The most commonly cited are:

– Oklo, because of its uniqueness;

– Cigar Lake, as the closest example of a 'global' repository system analogue;

– Hadrian's Wall, as an example of the durability of cement; and

– Inchtuthil Roman nails, as an example of the durability of iron and steel.

Despite the numerous examples of communication material citing analogues, there is no direct or empirical evidence from which to judge their efficacy in terms of gaining wide spread public understanding or acceptance of waste management proposals. In fact anecdotal evidence from discussions with key staff in a number of disposal agencies suggests that these communications have brought very little benefit.

It is difficult to determine why this may be the case, and a full evaluation is outside of the scope of this project, but initial impressions are that, although the analogue examples used may be interesting to many people, they may not be effective in static forms of communication (e.g. in the printed literature). Another reason may be that the messages contained in the communications material are, at best, not relevant to the concerns of the reader or, at worst, confusing.

More seriously, it is likely that one reason for their limited impact is that most communication materials have inherently been designed to send a message, to educate or to *convince* the intended audience. This is a rather patronising idea and is likely to cause many people to be turned off.

Despite these negative observations from past applications, the option of not using analogues in communication does not seem to be viable. What are required are better approaches for their use that help to engage a wider range of stakeholders in a productive dialogue. This means targetting communication materials so that they address the concerns and interests of the stakeholders, and the key to this is ensuring the material answers the questions that people ask.

5.3 Recommendations for the future uses of analogues in stakeholder dialogue

The first question to be addressed is *'With whom are we trying to communicate?'* There are a number of stakeholder groups who can be identified as potential audiences for analogues and analogue derived information. For each of these groups, however, the relevance of analogues will vary. Understanding something of the needs of these different audiences will help to identify a strategy for moving forwards in using analogues for communication.

– *Safety assessors:* The application of analogues to safety assessment is discussed in Section 3. It is important to realise that the analogue researchers must attempt to communicate with the safety assessors just as clearly as with the

wider public, if analogues are to have a more explicit role in future safety assessments.

- *The public:* The public is not a homogenous group. The information needs of such a group cannot easily be anticipated by a specialist group such as the natural analogue community. Additionally, the information needs will be dependent on national and local context and culture, and will change over time. Communication with the public is strongly influenced by the relationship between those receiving the information and the information provider. It is therefore difficult to conceive that natural analogues can be presented in a single package that will suit all situations and all individuals.

- *Communications specialists:* Most radioactive waste management programmes have communication specialists working at the interface between their own organisations and the public. Identifying the needs of these communicators is one way of beginning to make analogues more available to the public. If the communication specialists are not aware of the possibilities of natural analogues in dialogue, then they will not be reflected to the public. This means that one of the primary audiences for the analogue researchers should be the communications specialists in their own organisations.

- *Decision makers:* These are people who, for example, are trying to determine waste management policy and are generally looking for weight of opinion. Their decision will be very context-specific and very dependent on individual relationships or the results of consultation. The *direct* communication of natural analogues is, therefore, not likely to be seen of particular relevance to the decision-maker. The views of those individuals or groups whose opinion the decision-maker is seeking will, however, have an impact and there should be some scope for analogues to be used in communication with these groups.

- *Other scientists:* A problem with identifying the needs of other scientists is that it involves crossing a cultural divide that exists between different types of expertise. The potential for dialogue as a result of this is great, however, partly because people are pushed outside their comfort zones and partly because there is much to debate scientifically about analogues because of their non-uniqueness and the fact that they develop under uncontrolled conditions.

Considering that the potential audiences for natural analogues varies so widely, the objectives of using analogues in communication will also vary widely. Clearly, natural analogues will be of more interest to some audiences than to others.

We recommend that the emphasis for *analogue researchers* should be on communicating with the safety assessors, communication specialists and other scientists to raise their awareness of analogues and their usefulness. If this can be achieved, analogue researchers may then seek to work with the communication specialists on communication packages for the wider stakeholder groups.

A fresh approach could be adopted that takes as its starting point the ability of analogues to provide information relevant to the questions about radioactive waste management that different stakeholders may ask. This would represent a dynamic use of natural analogues to promote a two-way *dialogue* that would be markedly different from previous static public relations uses that adopted one-way communication methods. The focus of future work when developing analogues for communication should thus be on meeting the needs of specific audiences.

Determining the needs of stakeholder groups, particularly the public, is a matter for public consultation, market research and societal analysis. The analogue research community can contribute to such processes but should not expect to determine these needs in isolation. A more realistic ambition could be to work with more easily accessible audiences such as safety assessors and communications specialists to use analogues to open up dialogue between different stakeholder groups by engaging interest and encouraging thought. To achieve this, it is vitally important that the use of analogues has to be seen to be relevant by the audience.

A first step in opening up any form of dialogue is to raise awareness. The natural analogue community has a deeply held belief that analogues contain information that is relevant to the issues of radioactive waste management. Whilst this remains undoubtedly true, it must be recognised that analogues contain only a sub-set of the full range of information required for full debate and discussion amongst stakeholders, and that different audiences will require information at different technical levels. Analogues must, therefore, be used in dialogue in a complementary manner with other sources of information to address the questions that different audiences may ask.

Figure 10 represents the notion of an *information pyramid* that illustrates the hierarchy of questions and information needs of different audiences, and the relationship between data, concepts and questions. Whilst this figure makes some sweeping generalisations, it does help to suggest how information from natural analogues can be used in dialogue.

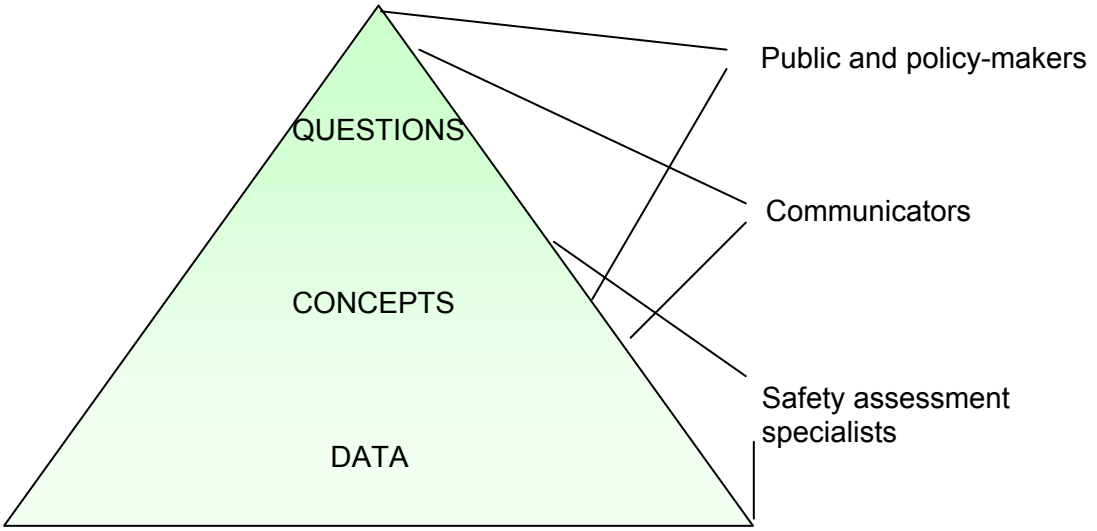


Figure 10: The information pyramid and the information needs of different audiences

As part of the NAnet project, analogue studies were reviewed with regard to their ability to provide information about concepts (conceptual models) and, to a certain extent, data. These uses of analogues were discussed in Section 4.

On the basis of Figure 10, the nature of the relationship between analogue studies and the concepts and data zones of the information pyramid and, thus, the relationship between analogue researchers and safety assessors is quite clear. The figure implies that safety assessors should be involved in the planning of any future analogue studies to help ensure they provide information about data and concepts that can be used to

help develop credible models for safety assessments (i.e. to identify the questions to be answered and any other information needs).

The relationship between analogue studies and the questions that sit at the top of the information pyramid is not, however, quite so obvious. The role of analogues in dialogue with communications specialists and, consequently, with decision makers and the wider public needs therefore to be thought through carefully.

Dialogue is a responsive process. The extent to which analogues can be applied successfully in dialogue with communications specialists depends on how well analogue studies can provide information of relevance to the questions being asked. There is now quite a lot of experience coming from public dialogues about the sorts of questions people ask in the context of radioactive waste management. The following list includes a few example questions that arose from a dialogue in the UK concerning Nirex's phased geological disposal concept included:

- Why does Nirex use stainless steel for its containers? Isn't lead a more effective means to contain radioactivity? Isn't titanium more resilient and longer lasting?

- Aren't the walls of the 500 litre drum too thin? Wouldn't they be easily damaged or pierced? Hasn't Nirex thought about making the walls thicker?

- Is cement effective as waste packaging and backfill? Is Nirex proposing to use normal cement from the local hardware store?

- Would a lorry carrying radioactive waste be given a police escort? Would the vehicle be marked or unmarked?

- Has an underground repository already been built? If yes, then why isn't it already being used? Is there a technical reason for needing to keep the waste packages on the surface for a few more decades?

- Where will the repository be built?

- How will you dig a hole big enough for a repository? Won't the earth on top of the repository be looser than before (because you've dug it up)? And won't that affect the ability of the geology to contain the waste?

- Has anyone ever built anything this far down? On this scale?

- What is the capacity of the repository?

- How many vaults are there going to be?

Due to the very nature of analogues, they can only ever provide information about the behaviour of natural systems and the impact of natural processes on a repository. It is obvious, therefore, that analogue studies alone cannot answer all of the questions that people will ask. In very broad terms, analogues can be used to provide information about the behaviour of natural systems relating to four key themes:

- ***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 that been?

This broad classification can potentially be used to index past analogue studies and the information they have provided, so that relevant examples can be readily identified to help address the questions that stakeholders may ask in an open dialogue.

It is recommended that repository specific indexing systems should be developed to reflect a programme's own repository design and site characteristics, and dialogue process. This can become a 'living' document, hosted on a website, so that as each new question or issues arises from the stakeholder group (e.g. compiling a list of frequently asked questions (FAQs)), any relevant analogue information that helps to illuminate the issue can be mapped to it. The structure of the indexing system would need to be adapted to the dialogue process but it is important that it is simple to understand and that the mapping is done honestly so that the relevance of each analogue is not over-stretched.

6 CONCLUSIONS

The NAnet project set out to review the past and present use and understanding of natural analogues and to make recommendations for their use in future safety assessments and for stakeholder dialogue.

The project met this objective and completed peer-reviews of over 70 individual analogue studies that covered the traditional analogue territory of near and far-field systems but also included investigations of natural processes in surface and near-surface systems that have not generally been considered within the scope of analogue studies. Nonetheless, these studies use analogue style thinking and are very closely associated with similar approaches to safety assessment model development and testing.

In undertaking these reviews a number of important conclusions have been reached and a number of high-level recommendations can be put forward. These are summarised below and are described in further detail through the main sections of this report.

1. Natural analogues remain as one of the most useful tools we have to increase our understanding of the processes that will control the evolution and safety of a repository over time. They should be considered as complementary to field, laboratory and modelling studies, rather than as stand-alone investigations, and implementing organisations should aim to integrate them fully into their research and development programmes. Their primary role is one of helping to understand processes and to develop and challenge conceptual models. Expectations should not be unrealistically high for the acquisition of quantitative data from future analogue studies for input to safety assessment models.

2. Analogue researchers should be clear about the intended audiences for their studies and the information they generate. We recommend that the emphasis for analogue researchers should be on communicating with the safety assessors, communication specialists and other scientists *in their own organisations* to raise their awareness of analogues and their usefulness. If this can be achieved, analogue researchers may then seek to work with these specialists on communication packages for the wider stakeholder groups. This is particularly important at a time when stakeholder dialogue is increasingly becoming an integral part of repository development and siting programmes.

3. Future analogue studies should be undertaken with the specific aim of answering the questions and addressing the issues that stakeholders (including safety assessors, decision makers and members of the public) raise. This means that a two-way dialogue is required between the supplier of information (e.g. the analogue researchers) and the user of the information (e.g. the stakeholder) to determine what is necessary to be done. This is one of the key recommendations from this project and, if adopted, should help to avoid the expense of undertaking studies that are largely ignored by safety assessors and communication specialists alike, which has often been the case in the past.

4. We recommend the information pyramid (Figure 10) as a useful concept for structuring the information derived from analogue studies (and focussing any new studies) so that they can be related to the high-level ‘questions’ that members of the public and decision makers may ask, as well as the more

detailed concepts and data that safety assessors may wish to address. We also recommend that the information pyramid is used together with a simple indexing system that links analogue studies to high level questions. This may take the form of a 'living FAQ' on a website, so that as each new question arises, the relevant analogue information that helps to illuminate it can be recorded and sign-posted.

5. It is essential that the detailed information from analogue studies is structured and indexed in a simple way so that the potential users of analogue information can find relevant information quickly and easily. Particularly to help the safety assessors find information to help develop and challenge conceptual models and databases, we recommend the concept of an analogue matrix (e.g. Table 6). We suggest that repository specific matrices should be developed jointly by analogue researchers and performance assessors to reflect their own particular repository designs and site characteristics. These matrices can then be populated to indicate how individual analogue studies have been or could be used to inform the development of their own safety assessment models.

As several repository development programmes are moving forward and siting decisions are being made, it is clear that the potential role for natural analogues to support stakeholder dialogue and inform safety assessments is greater than ever.

Most of the issues facing radioactive waste management programmes are not, however, unique. The technical aspects and stakeholder concerns described in this report are often shared with other developments, particularly in the energy and waste sectors. It is recommended, therefore, that the analogue approach should be applied more widely to the resolution of environmental and technical problems. This has begun to happen (for example analogues have been used to help understand the migration of carbon dioxide sequestered in sub-surface reservoirs) and this new direction is to be encouraged.

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 evolved over time in subsequent projects, to support radioactive waste and other programmes. This work could be funded by the EC, possibly within the remit of the Natural Analogue Working Group (NAWG). This is important because, without keeping these reviews up to date, the suggested relevance of these analogues to evolving safety assessments will change and the recommendations provided here will become outdated.

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APPENDIX: INTERNATIONAL WORKSHOP

Workshop Summary

Natural Analogues: Their Application to Repository Safety Assessment and Stakeholder Communication

NAnet International Workshop

12-13 May 2004, Château de Cadarache, France

1 Background

The NAnet project is a Thematic Network within the 5th Euratom FP which brings together a partnership of 10 European organisations who are either users or providers of natural analogue information. The project runs from January 2003 to December 2004 and its overall aim is to promote more considered applications of analogue information in safety assessments of radioactive waste repositories and for communication purposes. To fulfil this aim, NAnet is undertaking a critical review of published natural analogue studies and their previous applications to safety assessments and public communication.

One of the planned objectives of NAnet was to host an international workshop at the project half-way stage to provide a mechanism for soliciting additional relevant analogue information from researchers, safety assessors and representatives from waste management organisations not directly involved in the project, and to allow the aims and preliminary findings from the project to be disseminated to the international community. This workshop was held over two days in May 2004 at the Château de Cadarache, France and was attended by 45 participants, representing 30 separate organisations from 11 different countries. A full list of participants is included in Annex I.

2 Proceedings

The Agenda for the meeting is given in Annex II. On the first day of the workshop, a number of presentations were given by invited speakers. These included overviews of natural analogue projects associated with national radioactive waste disposal programmes: the CSN/ENRESA analogue project in Spain (Maria Jose Gimeno, Univ Zaragoza), analogue projects in Germany (Matthias Beushausen, BfS), analogue studies for the H12 safety assessment in Japan (Dora Yoshida, Univ Nagoya), the US DoE analogue project in support of the Yucca Mountain repository programme in the USA (Pat Dobson, LBL) and US NRC's considerations of analogue applications to safety assessment (David Pickett, SWRI). In addition to these, there were a number of other interesting presentations on more general considerations of analogues as applied to radioactive waste disposal and their use in other industry sectors: analogues in support of stakeholder dialogue (John Stuckless, USGS), analogue precedents in repository engineering (Les Knight, Nirex) and geological analogues for CO_2 sequestration (Jonathon Pearce, BGS).

These presentations helped to set the scene, and to raise a number of questions and issues that were then used to set the context for small syndicate group debates that were held on the second day. The participants were split into 5 groups [Blue, Yellow, Green, Orange and Red] of around 8 or 9 people, and deliberately mixed so that each group had a number of non-european participants, and roughly equal numbers of participants from disposal agencies, regulatory bodies and research organisations. Each syndicate group was first asked to debate a common set of general questions, and second to debate one or two more specific topics drawn from a longer list. Each syndicate group was co-chaired by member of the NAnet project and another participant from outside of the project. The debates in each of the syndicate groups were recorded by the co-chairs, and these summary records are provided in Annex III.

3 Key observations

Overall, the workshop was considered to be successful in meeting its stated objectives, i.e. to provide an opportunity for NAnet members to gain additional relevant analogue information from researchers not directly involved in the project, and to allow the aims and preliminary findings from the project to be disseminated to the international community. Of particular note is the large number of analogue related activities being undertaken in the US that the NAnet project members were not previously aware of.

The syndicate group debates proved to be extremely lively and all participants welcomed the opportunity to debate these issues with a wide ranging group of individuals. Each of the syndicate groups summarised their debates with a series of comments, suggestions and recommendations. Essentially these fell into two broad groups (1) specific recommendations concerning the NAnet project, its scope and deliverables, and (2) general comments concerning the application of natural analogues to safety assessment and stakeholder dialogue.

Most participants considered the objectives and planned deliverables from NAnet to be useful and important. It was recognised that NAnet cannot be fully comprehensive of all analogue studies but that the list of studies being reviewed is sufficiently representative. Some participants noted that new studies are being undertaken and old studies are often reinterpreted, so that there is a need for NAnet or some follow-on project to remain updated to be of most value. The analogue matrices were also generally recognised as being a useful method for organising the various analogue studies and their applications to different repository designs and concepts. It was considered, however, that they should be seen as being 'templates' that could be modified as necessary to fit particular safety assessment applications. Most participants would welcome a database of analogue information but felt that it should be done well or not at all. Generally it was agreed that the development of the database should be undertaken in a follow-on project, rather than in NAnet.

A few specific observations were made about the workshop:

– There is some duplication of effort between NAnet and various ongoing or recent projects, such as those in Spain and Germany. Although the scope and objectives of these projects are geared towards particular national programme requirements, there is an opportunity for synergy between them.

– Much of the effort is focussed in reinterpretation of old studies, and few new analogue studies are being undertaken or planned. Most of the more recent studies have been initiated in the US to support the Yucca Mountain Project. This is despite the international view that analogues remain important both to safety assessment and for stakeholder communication. There is an opportunity within NAnet to undertake some simple gap analysis to identify where new analogue studies may be worthwhile.

– Most effort in the workshop was focussed on technical issues, rather than on stakeholder communication, although it is recognised that there is a specific work package within NAnet to address this topic. This is partly a reflection of the fact that it is hard to get technical and communications specialists together to agree a common strategy for communication of analogues and other topics to all interested stakeholders within a national programme.

– The extension of the analogue concept to the surface environment was recognised as an important development for NAnet, and one that was largely welcomed. Further developments of this approach were suggested but would not be possible to implement within the time constraints on NAnet. Close cooperation with ongoing and planned biosphere projects would be necessary to ensure best value for the work in this area.

– There was a general agreement that it would be useful if the various projects with similar objectives of reviewing analogues could be better coordinated to avoid replication, and used as the framework for a new international project that could involve european and non-european organisations. Almost all participants considered that some form of follow-on project would be valuable and could be run under the auspices of a larger international consortium, possibly within the responsibility of the EC, NEA, IAEA or other body.

4 Way forward

The NAnet members have taken time to give consideration to the comments and recommendations from the workshop, and the specific records of the syndicate group discussions. The majority of these

were considered to be valid and it was subsequently agreed by the project participants that the NAnet needs to take these into account, so far as is possible given the resource constraints to the end of the project.

A number of comments have already been taken into consideration in the structuring of the final NAnet report and its deliverables, and the observations concerning analogue applications will be used to inform the set of recommendations that NAnet will draw-up at the end of the project. It is anticipated that the final NAnet project report will be made available in early 2005.

The NAnet members recognise the general consensus for some form of follow-on international project, and it is hoped that the NAnet report and deliverables, plus the momentum from this workshop, will help promote the development of such an initiative.

Annex I Participants

Name	Organisation	Country
Paul Degnan	Nirex	UK
Les Knight	Nirex	UK
John Dalton	Nirex	UK
John Smellie	Conterra	Sweden
Ulrich Nosek	GRS	Germany
Martin Navarro	GRS	Germany
Matthias Beushausen	BfS	Germany
Lasse Ahonen	GSF	Finland
Runar Blomqvist	GSF	Finland
Kari Rasilainen	VTT	Finland
Karl-Heinz Hellmuth	STUK	Finland
Juhani Suksi	STUK	Finland
Ales Laciok	NRI	Czech Republic
Karel Kunc	RAWRA	Czech Republic
Laurent Trotignon	CEA	France
Laurent Wouters	ONDRAF	Belgium
Valentine Vanhove	ONDRAF	Belgium
Jan Marivoet	SCK-CEN	Belgium
Pedro Hernán	ENRESA	Spain
Antonio Vela	CSN	Spain
Maria Jose Gimeno	Univ Zaragoza	Spain
Michel Raynal	EC	Belgium
Bill Miller	Enviros	UK
Phil Richardson	Enviros	UK
Dora Yoshida	Univ Nagoya	Japan
Mostafa Fayek	Oak Ridge	US
Lee Riciputi	Oak Ridge	US
David Diodato	NWTRB	US
Richard Parizek	NWTRB	US
John Stuckless	USGS	US
David Pickett	SWRI	US
Pat Dobson	LBL	US
Jean Claude Parneix	ERM	France
Charles McCombie	Arius	Switzerland
Francois Gauthier-Lafaye	Univ Strasbourg	France
Meritxell Martell	Enviros	Spain
Jonathon Pearce	BGS	UK
Scott Altmann	ANDRA	France
Isabelle Techer	Univ Montpellier	France

Annex II Agenda

DAY ONE, Wednesday 12 May 2004

0900 Welcome (Michel Raynal)

0910 Objectives and structure of the workshop (Bill Miller)

0930 Background to and progress of the NAnet Project (Bill Miller)

1000 The CSN/ENRESA analogue project (Maria Jose Gimeno)

1100 Coffee

1130 Analogue studies in Germany (Matthias Beushausen)

1200 Analogue studies in Japan (Dora Yoshida)

1230 Lunch

1400 The US DoE analogue programme in support of the Yucca Mountain Repository (Pat Dobson)

1430 Natural analogues and the Yucca Mountain Review Plan: the NRC perspective (David Pickett)

1500 Analogue reasoning applied to underground CO2 disposal: the NASCENT project (Jonathan Pearce)

1530 Coffee

1600 Natural analogues to help build public confidence in geological disposal (John Stuckless)

1630 An alternative view of natural analogues (Les Knight)

1700 Notice on syndicate groups, locations, chairpeople etc. (Bill Miller)

1715 Syndicate group discussions – part one (All participants)

1800 Close

Conference dinner

DAY TWO, Thursday 13 May 2004

0900 Syndicate group discussions – part two (All participants)

1200 Lunch

1430 Syndicate group wrap-up (All participants)

1500 Plenary session and reports on syndicate group discussions (All participants)

1600 Coffee

1630 Open discussion and workshop conclusions (All participants)

1730 Close of Workshop

Annex III Summary records from the syndicate group discussions

Summary records were provided by the syndicate group co-chairs and these are reproduced here without editing to reflect directly the views of the participants involved.

IIIa Group responses to the general questions

1. *Could you define what is or is not a natural analogue?*

   [Blue] Suggested amendment to the definition of a natural analogue: 'An analogue is a natural, archaeological, anthropogenic, industrial system with some definable similarity with one or more components of a radioactive waste repository, its surrounding environment and processes that control its evaluation'.

   [Yellow] The group suggested the replacement of the phrase 'a natural, anthropogenic or industrial system' by 'any system'.

   [Green] The chairman is uneasy with the broad definition given by NAnet for natural analogues: 'A natural analogue can be defined as an occurrence of materials and/or processes which resemble those expected in a proposed geological waste repository'. If the definition stays as it is, about everything in geology (cf. presentation of L. Knight) can be described as a natural analogue. Most of the ongoing studies concerning site or host rock characterization will fall under the natural analogue definition: the Opalinus Clay in the Benken Borehole in Switzerland can than be considered as one huge natural analogue ! The other members of the discussion group agree more or less with the proposed definition but advise replacing the term "natural" by "environmental" in order to include the archaeological, historical and industrial analogues. There must be distinct time and space dimensions of the material and/or process compared to laboratory conditions .

   [Orange] The definition given by NAnet was agreed to be OK. However, the main objective of natural analogue studies, i.e. to increase understanding, should be included in the definition.

   [Red] Members of the group noted that the term "analogue" had no strict definition in the context of radioactive waste management studies. Also, simply by calling something an analogue, it restricts the degree of dialogue possible with outside stakeholders (either other scientists or public) as the term is often meaningless to those not involved in radioactive waste disposal or the geosciences. A general lack of jargon required. It was suggested that an analogy required to support PA is between the processes involved and not necessarily the whole system. Although the emphasis on the use of analogues should (could) be on process orientated factors, in reality this should also cover features and events. In recommending analogues for use in PA or for communication (or for other reasons), we have to be clear about the boundaries of the study, its purpose and limitations. In addition to analogues based on scientific study it was noted that "kitchen sink analogues" and anti-analogues could be used much more widely, especially for stakeholder communication. Natural analogues could also be used more by the scientific community to guide the need and design of experiments. In considering the definition in detail, some members noted that (i) the use of the word "similar" is a subjective assignment, and (ii) "historical" as well as archaeological and anthropogenic should be used in the definition. After discussion it was agreed within the group that the following definition was suitable: "An analogue is a natural, historical or anthropogenic system that permits that study of repository-related processes, including its surrounding environment and processes that control its evolution."

2. *Would it be useful to consider natural analogues as part of a wider group of 'natural system studies' that includes similar observational and field investigations?*

   [Blue] It was felt that natural analogues should adhere to the definition (or other variants) and be divorced from site characterisation investigations and other field studies. The use of the term 'Natural system studies' was considered acceptable. There is no problem integrating other relevant disciplines as long as the integrity of natural analogues is maintained. In fact, disciplines such as palaeohydrogeology, biosphere studies and climatic studies are already an integral part of any field study, including the characterisation of large-scale natural analogue sites. With respect to site characterisation studies, natural analogues can provide valuable and tested field experience in addition to recognising the value of integrating supporting laboratory and in-situ

experiments. Other useful cross pollination experience includes the testing and development of models at the site description scale leading ultimately to further development of safety cases.

[Yellow] There was a consensus that natural analogues should be considered as part of a wider group of natural systems studies.

[Green] The green group is in favour of including natural analogues in the wider group of "natural system studies". The observation and measurement of processes in their natural environment, the latter being considered in its widest possible sense, will support our understanding of many processes that are included explicitly as well as implicitly in safety assessment models.

[Orange] It was agreed by all group participants that natural analogue studies should be regarded as part of a wider group of natural system studies. Furthermore it was pointed out that e.g. climate studies are already an important task regarded within the Yucca Mountain project.

[Red] It was noted that safety indicators are certainly broader than just analogies and the most appropriate natural system evidence to be used in a safety case will be defined by what its use is (e.g. analogues, palaeohydrogeology, natural safety indicators etc to support concepts or model parameterisation). Anthropogenic analogues could usefully be included in the wider natural system studies as a sub-set on the basis that they are essentially unplanned experiments, and they do have a use in this respect to support natural system arguments.

3. *What makes a good or a bad analogue study?*

[Blue] Some responses:

- An analogue can be qualitatively good but quantitatively bad (e.g. in deriving physico-chemical parameters of importance).
- A bad analogue does not parallel the repository process/component in question.
- Intrinsic vs. external? It is important that the process in question is not studied in isolation, for example it may be necessary to study the analogue in a more regional context regarding groundwater flow rates/infiltration rates etc.
- Ideally, analogue studies should initially follow a broad approach, leading subsequently to more focussed studies.
- Difficult to specify degrees of measurement to assess similarities between analogue studies mostly due to: a) natural analogues are process-specific, and b) several focussed analogues on similar issues are better then one.
- Since many of the large-scale analogue studies have been associated with uranium occurrences of economic value, mining activities have sometimes curtailed the scope of analogue studies (e.g. through flooding, alteration of groundwater flow direction etc.), thus reducing their potential value.
- Longevity of the system was considered the primary reason to use natural analogues.

[Yellow] A number of features were suggested as making a good analogue. In practice there is often very little choice in the analogues that are available.

- Similarity with the system being considered.
- Context of the analogue.
- Can data be taken from the analogue?
- Familiarity with the analogue.
- Quality and appropriateness of the investigation methods and their stated QA.

[Green] The use of the adjectives "bad" or "good" for analogues should be avoided and replaced by "relevant" or "less relevant". It is also not useful to attempt to rate natural analogues using generic criteria. The relevancy of an analogue should be judged on a case by case basis, and will be determined more specifically when a reference site is chosen according to the needs of the safety assessment process.

[Orange] The view of the group was that the quality of an analogue study can not be judged generally to be good or bad. The quality of an analogue study depends on its application. As an example the acceptable uncertainty of a natural analogue result was discussed (see also question 5): A relatively high uncertainty of a result could be enough to exclude a process in a safety analysis (together with other lines of reasoning), but might be to high to use it for a model parameter.

[Red] In assessing the value of analogues, it was stated that good analogues were very clear in the understanding they provide, that the data acquisition and interpretation methods were transparent and the use that was made of them was appropriate.

4. *Is the list of analogue studies being considered in NAnet comprehensive?*

   [Blue] The natural analogue studies listed by NAnet were considered comprehensive, but there were still gaps to be filled.

   [Yellow] It was felt that there was an unlimited number of analogues that could be utilised.

   [Green] The list of analogues is judged to be representative, but is obviously not comprehensive. An example of a missing analogue type is analogues for solubility limits in natural systems in order to support the thermodynamic database.

   [Orange] The list of analogue studies considered in NAnet is not comprehensive; this becomes clear by the fact, that a large number of analogue studies performed for Yucca Mountain are not included. However, the list represents an appropriate working basis. Within the NAnet project a gap analysis should be performed, comparing the work carried out in Spain, Germany and the US. This should be done to not forget one of the very important analogue studies. A detailed comparison and inclusion of a lot more natural analogue studies (especially from the US) is a task for a follow-on project.

   [Red] No specific response.

5. *Is the analogue review template appropriate?*

   [Blue] The review template was considered appropriate but there were requests, for example:

   – Additional relevant illustrations/diagrams/plots to further visualise the studies.
   – Ensure that the repository components(s) in question are emphasised.
   – Mention should be made of the participant groups involved and the duration of the study.

   [Yellow] Experience from the CSN/ENRESA reviews is that such a template does work. However, the design of the template does depend on the ultimate users. It was felt that it was a starting point but may have to be made more specific to individual audiences. It was not felt to be directed at members of the public.

   [Green] The discussion group members didn't have the opportunity to have a close look at the review template, the reviews and the matrices. Therefore no valuable discussion could take place concerning these items. About the template, the question was raised about who are the users? Safety assessment model developers, communicator The chairman has the feeling that the reviews are, on the one hand, not detailed enough for safety assessment support, and, on the other hand, too technical for communication uses. One participant stated "that they give a nice overview". The question is raised if the reviews should be just "nice" or should they be "useful" ? Was the target public for, or the purpose of the reviews, defined well enough? In any case, all agreed that more emphasis should be put on the bibliography, to allow people to have access on the data they need.

   [Orange] The template for the reviews is appropriate. One topic is recommended to be added: the spatial scale of the analogue. The issue "Uncertainties" was identified as one of the most important for users of the reviews and also the most difficult to be evaluated. Therefore some guidance should be given to the reviewer. If a quantitative result, for example a parameter value, is derived from the study, the uncertainty has to be quantified, too. This wasn't done e.g. in the Kronan cannon review.

   [Red] No specific response.

6. *Is the matrix approach to ordering analogue studies useful?*

   [Blue] The matrix approach was considered useful in the absence of the CSN/ENRESA work. For non-technical audiences the matrix should be revamped; how this could be carried out successfully was not discussed.

   [Yellow] The matrix approach is useful in that it provides an index and front end to the database. It highlights gaps. It is not appropriate for discussion with members of the public.

[Green] At first sight the matrices seem to be too complex. A proposal could be to separate the different waste types (near-field) or to separate the different host rocks (far-field). The key entry points should be the processes, maybe grouped somewhat differently than that presented.

[Orange] The matrix approach is basically OK, but should either be extendable or flexible to be applied to distinct safety assessment studies. Yucca Mountain was given as an example, where an important near-field barrier is made up by the empty space in the drifts, which is not included in the actual matrix. The matrix approach is not appropriate for the public, since it is too technically focussed. For communication with the public FAQs or fact sheets are more suitable.

[Red] No specific response.

7. *Is the near-field matrix correct?*

   [Blue] Generally yes, but the time available was inadequate to provide a critical review. There was a suggestion to include a 'Thermo-chemical Disturbed Zone' for completeness.

   [Yellow] Did not consider this question.

   [Green] Answer as for Q6.

   [Orange] The time was too short to check, whether the near-field or far-field matrices are correct. The matrix structures with processes and materials, or rocks have been regarded as suitable. It was recommended to send the drafts to external reviewers, such as agencies or other individuals, which not belong to NAnet to request additional entries.

   [Red] No specific response.

8. *Is the far-field matrix correct?*

   [Blue] Generally yes, but the time available was inadequate to provide a critical review.

   [Yellow] Did not consider this question.

   [Green] Answer as for Q6.

   [Orange] Answer as for Q7.

   [Red] No specific response.

9. *Is there an appropriate matrix that could be developed for the surface environment?*

   [Blue] Complex issue and uncertain as to whether it is possible — no bright ideas emerged. Suggestion to deal with two main categories to try and simplify the situation: a) surface processes affecting dose, and b) surface processes affecting the repository itself (e.g. erosion; infiltration; glacial etc.).

   [Yellow] Did not consider this question.

   [Green] Answer as for Q6.

   [Orange] It would have gone too far to discuss a potential matrix structure for the surface environment. In contrast to the NAnet approach it was discussed, that all biosphere processes should be regarded (also uptake by plants etc.), because they are an important part of safety assessment and also often included in questions from the public. It became clear that this scope would have been too large for NAnet, but there was a strong opinion to include it in a follow-on project. But in order to not expand too much, the surface environment topic needs to be limited to safety assessment relevant radionuclides and homologues. It is also necessary to check an overlap with existing biosphere projects.

   [Red] No specific response.

10. *Do you consider there is a real need for the electronic database planned to be developed in NAnet?*

    [Blue] Yes, this was considered essential.

    [Yellow] An electronic database was considered to be very useful but there was a feeling that it should be done well or not at all. This related the need to continually update the database which was considered to be outside the resources currently allocated to NAnet.

[Green] The discussion group considers the development of a relational database as essential. The implementation of such a database is not a task for NAnet, but should be outsourced to an international consortium, e.g. under the responsibility of the NEA.

[Orange] Did not consider this question.

[Red] No specific response.

11. *Are there other sources of information that could be used in NAnet or future similar projects?*

[Blue] The present focus of NAnet should be to conclude the project by successfully fulfilling the initial objectives. The level of ambition will depend on available resources. Certain issues should be stressed including glaciation effects and the influence of the biosphere. The finished document could provide a suitable platform from which: a) an international natural analogue group can be formed with the responsibility of coordinating natural analogue studies and providing a forum for discussion and future planning (somewhat similar to the previous NAWG), and b) a comprehensive electronic database can be developed and updated continuously based on input from point (a).

[Yellow] The sources that could be used are only limited only by imagination. Specific additional sources included:

- Palaeoclimate data.
- Palaeohydrogeological data.
- Database of geochemistry of sediments, shallow and deep groundwaters which are being compiled across Europe.
- URLs.

[Green] If the definition of natural analogues is enlarged, than other sources of information could be implied (cf. comments regarding comprehensiveness of analogue list).

[Orange] Did not consider this question.

[Red] No specific response.

12. *Do you believe there would be value in arranging an international project that could build on the work of the NAnet project and other studies such as the CSN-ENRESA database?*

[Blue] The group suggested that any future efforts that may involve constructing a relational natural analogue database be integrated with that already accomplished by CSN/ENRESA, and that the group at the University of Zaragoza should be considered as the lead for such work.

[Yellow] Did not consider this question.

[Green] Did not consider this question.

[Orange] All participants of the group showed a great interest in a follow-on project to NAnet. The following issues were raised:

- There are a number of review studies running. The results of these studies should be considered in a follow-on project.
- The workshop showed that there is currently a strong focus of natural analogue reviews (Spain, Germany, US) with regard to safety assessment and only very rarely use for communication aspects, although there is great interest by many organizations like e.g. US DOE. Communication aspects should play a stronger role in a follow-on project, which needs the involvement of communication specialists. In this context, it was recognized, that the existing Natural Analogue film was not widely enough distributed (e.g. not shown in most major TV channels and even not recognized by participants from the US). It was proposed that a further distribution could be done by NAnet. One reason for not been shown is that the film might be “over educating”. A production of a new film with involvement of broadcasting specialists was raised as idea for the future.
- “Negative analogues” like caves, which have totally collapsed or pipes, which have corroded extremely fast, haven’t been considered so far. They should be included. Firstly, it is important information, why a steel corrosion was rather fast and what the boundary conditions have been. Such conditions then should be avoided in the repository system. Secondly it would be advantageous to be prepared, since a number of questions from the public regard those negative analogues.

– There are different ways to organize such a project, via EC, IAEA, NEA or an agency consortium. The advantage of the latter would be that it is easier to include participants from US or Japan. There are a number of projects, which correlate to such a follow-on project and where a coordination with is needed. Examples are AMIGO, Forum on Stakeholder confidence, FSC (NEA) or the Concerted Action COWAM (EC).

[Red] No specific response.

IIIb Group responses to the specific questions

1. *How can natural analogues be used to build confidence in our assessment methods and models (e.g. to help to construct, test, challenge and validate models)? How can natural analogues be used to build confidence amongst the many stakeholders? Is building confidence in our assessment methods and models using natural analogues the same as building confidence with stakeholders or are different approaches needed?*

   [Green] First of all a clear distinction has to be made between the end-users, more specifically the safety assessment model developers and the "explainers". In order for the NAnet exercise to be most useful for both, it should provide for each natural analogue presentations which are specifically adapted to each need. The message itself is intrinsically the same: to build confidence in the model developed (safety assessment) and to build confidence by providing information to the lay public (communication). Only the way that it is communicated is different.

   [Orange] It was pointed out, that the main part to build confidence is through increased understanding. The group proposed to distinguish between three different types of confidence:

   a. in repository safety
   b. in the underlying science
   c. in the involved scientists

   In which type of confidence analogues are used depends from the user, the target group and the state of the repository planning. This can be illustrated by the following examples. Public stakeholders are usually not concerned with models and data, therefore the application of natural analogues focus more to build confidence in the underlying science and the scientist involved. The regulator will not use analogues for confidence building in repository safety in an early stage of building the safety case (correlated to type a).

2. *Natural analogues are often unacknowledged in top-level performance assessment reports. Why do you think this is the case? Should natural analogues have a higher profile in these reports and, if so, how can natural analogues best be integrated with field, laboratory and modelling studies within a repository development programme to ensure this happens?*

   [Red] Firstly it was noted that performance assessment reports are written by modellers. In carrying out a PA they primarily want the model input numbers, for parameterisation, calibration and/or validation and they do not necessarily want the evidence to support the numbers. This is considered bad practice. Unfortunately, natural analogues can most often not be used directly to give model input numbers, but they can perhaps be used more extensively to restrict the range of reasonable numbers. In general there needs to be far more interaction between the PA modellers and the geoscientists that collect the data. Natural analogues are used in some organisations to support PA reports, in terms of support for conceptual models, boundary conditions, limits for data etc. but often these supporting reports are not published as part of the PA. They should be. The first conclusions of the group with regard to question 2 therefore are

   – Much closer integration is required between PA modellers and Natural Analogue researchers.

   – There is a need to reference everything that is used to support a PA.

   This second recommendation was followed-up by asking the question "What makes a good PA?" It was agreed that a prime factor was transparency of process. Such transparency could be demonstrated by referring to a hierarchy of reports (executive → high level → supporting) when publishing PAs. This would also make them far more accessible to non-specialist audiences. There should be a place in PA reports that demonstrates the supporting evidence as overlying layers of information, and this would include natural analogues. Although it was not initially expressed as such, the discussion effectively re-developed the 'multiple-lines of reasoning' argument for use in PA. It was agreed that the use of natural analogues should be undertaken

much more with a view to get data to support scenario development. Natural analogues can also help with developing methods for issues such as the up-scaling of laboratory data. They can also help in the evaluation of the adequacy of data and methods of testing, as well as in support of the development of models (noted above).

[Blue] Yes, natural analogues should have a greater profile. At present natural analogues are not recognised in the majority of safety assessment reports for several reasons:

– Safety assessments require hard numbers for calculation/modelling purposes; natural analogue studies only rarely can supply such data (e.g. metal corrosion rates; depth of matrix diffusion etc.).
– Much natural analogue information has been used to identify/confirm/support FEPs, but this has not been acknowledged. However, this demands the question as to why should natural analogues be acknowledged specifically above other sources?
– There is a lack of communication between safety assessment groups and the natural analogue fraternity.
– There has been a general failure of safety assessment to recognise natural analogues as an integral part of model development. Conversely, the natural analogue fraternity have been largely unsuccessful in convincing safety assessment groups.

This situation could be improved by:

– Greater integration of safety assessment groups and the natural analogue fraternity in the planning, execution and interpretation of natural analogue studies, i.e. a greater need for an interactive approach.
– Greater integration of parallel laboratory and in-situ experiments.

3. *What do you believe are the most important potential applications of qualitative information in a safety case that employs multiple lines of reasoning? Have you any recorded examples of the explicit application of qualitative analogue information used in a safety case? How can the application of natural analogues to safety cases best be improved in the future?*

   [Red] The group considered this question, but it was acknowledged that the discussion concerning question (2) had already 'drifted' into the area that question (3) was set to address. Nevertheless, the discussion restarted with the particular focus requested. An initial observation was that it was of great benefit that within the NAnet project that the existing analogue studies were being revisited in order to get extra information and benefit from the existing data. However, it was noted that after the NAnet project evaluations it might be beneficial to revisit certain well studied (or not so well studied) analogue sites to get additional information. A major benefit would be that the preliminary analogue studies would more suitably allow us to understand the analogue context. A point was reiterated that analogue information provides a useful source for data validation. More use should be made of this information and its context to integrate data with that derived from experiments. Indeed, analogue information could also be used usefully to direct experiments to obtain outstanding data in areas of high uncertainty. On the reverse side though, we need to acknowledge the limitations of analogue information and not try to force its use. Finally, it was recommended that radioactive waste management organisations need to firmly structure messages in different and appropriate ways and also make explicit the use made of natural analogues to the three key audiences: policy makers; scientists; the public.

4. *What do you believe are the most important potential applications of quantitative information in a performance assessment? Have you any examples of the provision and application of quantitative data derived from natural analogues in a performance assessment? How can the application of natural analogues to performance assessments best be improved in the future? Do you consider there is a fundamental difference in the application of qualitative rather than quantitative information in a performance assessment or safety case?*

   [Yellow] Quantitative analogue data is available to provide specific values or bounds to a number of relevant processes including:

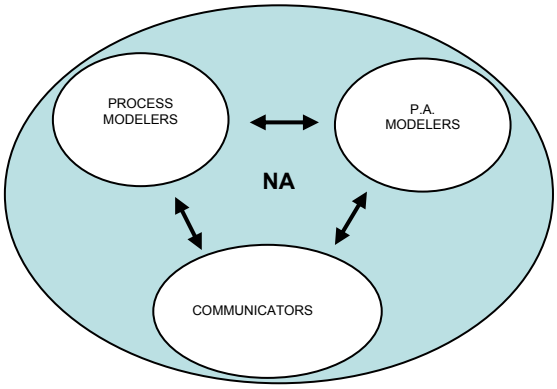
   – Canister and glass corrosion rates.
   – Spent fuel dissolution rates.
   – Radionuclide concentrations in solution.
   – Radionuclide flux.
   – Colloid concentrations.

– Matrix diffusion depths.
– Justification of thermodynamic and kinetic databases.
– Redox buffering capacity.
– Recognition of relevant solubility limiting phases.

Both quantitative and qualitative analogue data are relevant and have a valid role in the support for a performance assessment or safety case. In some cases the use of analogue data is prescribed by the regulatory requirements. It is clear that natural analogue data is capable of providing quantitative data in some instances, However, the relationship between quantitative and qualitative data is not necessarily fixed. Some users will consider the same data as quantitative while others will only consider that it provides qualitative information. Further, the status of such data may be affected by the ultimate use of the data. Quantitative analogue data can be used in a number of ways including support for decision making, communication between groups both within the radwaste industry and with groups outside the industry. In some cases this sort of data can be used to 'ground truth' models. There was a general feeling that the contribution of natural analogues to performance assessment and safety cases was typically understated in many of high-level the documents. This applied both to the use of analogues to derive relevant processes and data. However, care was needed when considering analogues both in recognising the relevance and limitation of individual analogues and the fact that data for many analogues was acquired some time ago when analytical techniques and quality assurance was not at the same level as today.

[Green] Concerning the near field, natural analogues can provide knowledge about the major characteristics of processes, limits (upper and lower), info on kinetics, and so on. Often, laboratory investigations just provide only one of the limits (upper or lower); in certain cases natural analogue data can provide the other limit. More specifically for the far field, the application of natural analogues can be the justification of homogenization or simplification of the safety assessment models vis-à-vis the "reality". It will give an added value (help build confidence) to the assumptions that are made while simplifying the model.

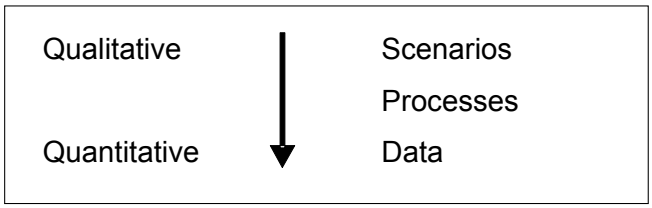
The discussion group is aware of the distinct need for a "team" approach where scientists and safety assessment modellers are working together, in order to improve the transfer of data, relevant information, needs, etc.



5. *Natural analogue studies frequently are subject to uncertainty, particularly with respect to the boundary conditions of the analogue system. How should these various types of uncertainty be assessed and managed in a safety case or performance assessment, and does this restrict the potential application of analogue information? Are there any other limitations of natural analogues and how should these be addressed?*

[Orange] First of all it should be made clear that uncertainties are normal and universal in science. Total, 100 % certainty is neither possible nor necessary. How much certainty is needed depends strongly on the application of the results from a natural analogue study. The certainty has to be higher, if derived parameters should be used in safety assessment, as in a case where the question is, whether a process is important or not (exclusion of a FEP). People form safety assessment, who are involved in building a safety case can help to clarify the need of the degree of uncertainty. It is important, that the uncertainties occurring in the results of a natural analogue study will be well documented. This gives the user additional information to decide whether the analogue is suitable for him or not.

Two kinds of expressions for uncertainties have been identified: qualitative and quantitative. As indicated in the following table the qualitative uncertainty is more used in the beginning of the safety case, i.e. when scenarios are constructed and the relevance of FEPs is discussed. In a later stage of the safety case more quantitative expressions of uncertainties are needed, as it is the case when processes are considered and in particular when data are derived from analogue studies.



Finally it was stated that the word uncertainties is rarely used in engineering, but play a main role in the radioactive waste disposal. There is a tendency of earth scientists to "downplay" their knowledge. It should be considered that in communication it will be better not to say we are uncertain to some degree but to say we are certain to a distinct degree.

6. *Do you consider that natural analogues are equally applicable to all future assessment time periods? If not, how should the treatment of analogues vary for different assessment time periods and how would this be balanced with other lines of reasoning? Are there any regulatory requirements that control the consideration of time in a licensing situation?*

   [Blue] No, natural analogues are not equally applicable to all future assessment time periods. The following timespans were considered relevant:

   – engineered barrier timespan
   – geosphere timespan
   – restraints to accommodate timespans relating to high release rates/high dose rates
   – similar timespans to expected repository timescales.

   Note: The longer the timespan the more qualitative the information and the greater the uncertainties involved. Yes, there are regulatory requirements that control the consideration of time in a licensing situation.

7. *Many different safety cases and performance assessments will be required during a repository development programme (e.g. at concept design, design optimisation, siting and licensing). Do you consider that natural analogues are equally applicable to the safety cases undertaken at these different stages? If not, how should the treatment of analogues vary with the different stages?*

   [Yellow] It was felt that natural analogues were applicable at all stages of repository development. The specific utilisation depends on the political, regulatory and technical context. The specific analogues called upon varied between those required in support of a high-level generic concept to those needed to support a specific concept in a site-specific setting. In simplistic terms this evolution from concept to site specific instigation was reflected in a move from qualitative to more quantitative types of analogues. The use of analogues at the Yucca Mountain site showed that once a combination of concept and site-specific instigation had been settled on a wide range of direct analogues could be found. Specific analogues may only become relevant in the later stages of repository investigation in support of such aspects as design optimisation, licensing, model validation and public communication.