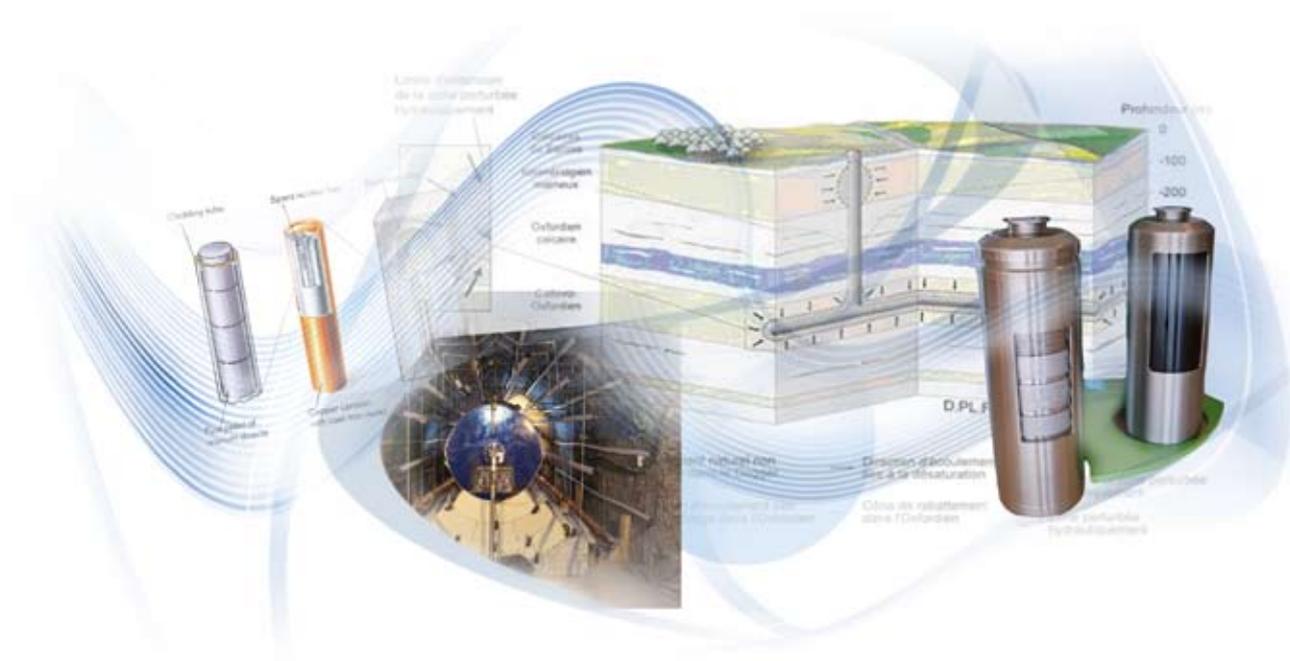


Geological Disposal of Radioactive Waste: Moving Towards Implementation

W.E. Falck and K.-F. Nilsson

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EXECUTIVE SUMMARY

This report analyses the state-of-the-art of science, technology and procedures needed to implement the desired end-point in (high-level) radioactive waste management: deep geological disposal. A range of topical areas of relevance has been identified:

- technical concepts
- regulatory issues
- confidence building
- knowledge management
- site selection
- safety cases
- alternative concepts
- governance

However, this report does not address the engineering, construction or operation of a repository, such as excavation, stabilisation, ventilation and drainage, waste transportation and waste emplacement equipment, or the pre-closure operational safety.

Overall it has been observed that a certain level of maturity has been reached in many scientific and technical areas important to geological disposal. There is a world-wide scientific consensus that safe geological disposal is technically feasible. This observation is supported by the fact that several countries, including Sweden and Finland, have defined road-maps for implementation with specific dates. Other countries, such as Germany or the UK, may be technically as advanced, but have not made much progress towards concrete implementation steps or programmes have (temporarily) foundered, mainly for reasons of public acceptance. In other countries, particularly those that have more recently joined the EU, there are still important deficits in knowledge acquisition and in funding all activities related to the development of waste management programmes with geological disposal as end-point.

Research activities can be divided into site specific and generic R&D activities. Generic research addresses fundamental physical and chemical processes as well materials properties and behaviour. It may also concern (knowledge) management and governance processes as well as regulatory processes of relevance to geological disposal. Site specific research concerns the generation and collation of data and information on sites that may be considered for hosting a repository. Usually there is no clear-cut distinction between these two types of research. Generic research in a variety of areas has

reached a state of maturity that will allow to proceed with confidence towards a step-wise implementation. This does not mean that research will stop at this point. Generic research will have to continue in response to general scientific developments and to results from site specific investigations. Generic research by its very nature has considerable scope for international collaboration and harmonisation of concepts and approaches and this will increase confidence in the ensuing results. In fact, collaboration and harmonisation has been practice since the early days of the EU Framework Programmes. Site specific investigations have to be repeated for each national programme, but harmonisation of concepts and approaches will aid in confidence building among stakeholders.

This study did not identify major conceptual and research gaps for the host rocks and repository systems currently envisaged, namely those in (indurated) clays, fractured hard rocks and salt. It is expected that the final reports on the EC programmes FUNMIG and NF-PRO will provide a comprehensive picture of our knowledge of far-field and near-field processes respectively. It is already sure that certain processes still require better quantification and for various coupled (thermal-hydraulic-mechanical-chemical) processes models still require further development. However, the forthcoming results are not likely to change the principal conclusions on the feasibility of geological disposal.

The report examines in broad terms the various elements of a deep geological repository system for high-level waste and/or spent fuel, if the latter is declared a waste. These elements include the waste forms, the containers, buffers and backfills, as well as host rocks. The respective safety functions, such as retention and buffering, are examined with respect to their conceptual development and quantitative knowledge.

The safety case is the major instrument to guide and assess the development of a geological repository. The conceptual approaches and remaining unresolved issues are examined. Overall it can be concluded that this instrument has already attained a high degree of maturity and further work mainly addresses confidence building issues. However, not all EU Member States have yet attained the same level of procedural understanding and level of application for various socio-economic and political reasons.

Site selection remains a contentious issue and has to balance technical requirements with constraints imposed by the availability of suitable host rock formation on a national basis as well as socio-political constraints. Repositories shared by two or more Member States may overcome some of the above constraints, but face various legal as well as public acceptance challenges. In any case these issues can only be resolved at the political level.

Demonstration tests are an important instrument in confidence building, both within the scientific community and with respect to outside stakeholders. Such tests are mainly carried out in the various Underground Research Facilities (URFs), which in fact are the focal points for intensive collaboration.

While the scientific and technical community might be quite confident that implementation can begin, the situation with the regulator and the public in general may be different. Confidence building among all stakeholders with a view to 'close' issues remains an important conceptual and practical challenge. Two important instruments for confidence building are (natural) analogues and monitoring activities.

It is important to note that continuing R&D activities are not a sign of immaturity or lack of confidence. General scientific developments may require to revisit even 'closed' issues from time to time in order to demonstrate that the scientific basis for decisions is still valid or with a view to further increase margins of safety.

Knowledge management issues have found considerable attention in the past few years. While strategies for corporate knowledge preservation and for preserving general scientific knowledge are being successfully developed in various other industries, strategies for the preservation of knowledge about a repository site over time-scales exceeding a few centuries are less clear. The most promising approach appears to be to develop an 'active' relationship between the host community and the site, so that knowledge is continuously renewed.

A number of terms, such as 'Best Available Technology' (BAT) or 'optimisation' have been brought into the discussions on radioactive waste management from other technical or regulatory areas. It may be argued that these are implicitly covered by the development of safety cases.

Retrievability, reversibility and long-term storage as management options have entered the discussion and respective socio-political or economic requirements will have their bearing on the repository design and the timing of disposal programmes. The implications for the safety case are not yet clear, but it is well understood that these must not compromise safety.

Governance issues, i.e. the way a society arrives at accepted waste management decisions, are strongly related to confidence building. In the wake of various failed national programmes a paradigm shift to more participatory decision making processes has occurred and it is also advocated in international guidance documents. Such governance issues have been studied in a number of projects supported within both the Euratom and EC Framework Programmes over the years. It may be noted, however, that there appears to be only limited direct interaction between these sociology oriented projects and the technical R&D projects.

The critical step in implementing waste management solutions is regulatory approval. This requires an adequate set of regulations, criteria for evaluation and that regulators are adequately enabled. A paradigm shift away from a focus on human protection only towards environmental protection is being observed. Harmonisation of the regulatory framework in Member States meets with some difficulties owing to varying historical and cultural traditions. However, the NEA LTSC-project, for instance, concluded that such harmonisation would not be necessary, if consensus can be achieved over regulatory objectives. It may be noted that national regulations are typically based on ICRP and IAEA recommendations, which are also reflected in EC guidance. A possible benefit

from harmonisation of regulatory criteria would be that it may help to prevent risk displacement from one country to another through the development of shared disposal solutions in countries with less stringent regulations.

As to the concern that EC, NEA and IAEA have overlapping constituencies and possibly overlapping areas of work and interest, one may note that the *de facto* roles of the EC can be seen as providing the policy framework and R&D funding, of the IAEA as providing regulatory guidance, and of the NEA as providing the conceptual framework.

Overall it can thus be observed that

- *our scientific understanding of the processes relevant for geological disposal is developed well enough to proceed with step-wise implementation;*
- *scientific and regulatory co-operation, e.g. through the Framework Programmes, ensures a Europe-wide harmonised level of scientific understanding and regulatory oversight;*
- *mechanisms to demonstrate equivalency between Member States' regulations might be a more efficient way forward than harmonised or unified regulations;*
- *the awareness of the need to involve all stakeholders in the decision making processes towards implementation of geological is now high throughout Europe;*
- *there are still unresolved issues on how to involve stakeholders in practice;*
- *supporting more advanced countries in their effort to move to implementation is likely to have synergetic effects in other countries by increasing stakeholders confidence;*
- *the de facto roles of the EC can be seen as providing the policy framework and R&D funding, of the IAEA as providing regulatory guidance, while the NEA compiles and analyses the national experience with the strategic principles and technical and social aspects of implementation.*

1. Introduction

Objectives

Research and Development into the various aspects of geological disposal of radioactive waste can look back to a history of some four decades. The question may be asked with justification which areas are sufficiently well understood so that the issue can be ‘closed’ and where further work is needed. In other words: how close are we to proceed to implementation. Of course, the different Member States of the European Union that have accumulated radioactive wastes are at rather different stages of development as geological disposal is concerned. On the other hand, international organisations such as the IAEA and the OECD-NEA provide a forum for exchange and thus making accessible the know-how to all.

Implementation is understood here to begin when concrete steps to establish a final repository are taken, for instance by filing an application to construct a repository, either as an individual national effort or in the context of shared facilities. On the other hand, many national programmes are gradually homing in on particular host rock formations, with the generic research focussing on it and thus making a gradual transition into site specific research. From when on a programme can be called ‘implementing’ would also depend on the Member State’s regulatory philosophy and framework: in some programmes intensive interaction between operator and regulator takes place. At some stage during this iterative process a formal license application is submitted. In other countries the operator develops the safety case without or only with very limited interaction with the regulator and at the end submits a license application that is then either granted or rejected by the regulator.

Considering this backdrop, the present report was compiled to

- provide an overview over the recent past, current and planned programmes of the IAEA, OECD-NEA and the EU in the area of radioactive waste disposal and to assess them with respect to the completeness of coverage;
- identify those areas that can be covered by generic research and thus can be supported by international collaborative research vis-à-vis those areas that require site specific investigations and thus need to be carried out by national organisations;
- identify areas where harmonisation will help to reduce resources use and increase stakeholder acceptance, and to
- help to decide when enough research is ‘enough’ vis-à-vis regulatory acceptance and implementation of a repository.

The structure of the report is based on a deductive concept that begins with a descriptions of the objectives of geological disposal, the natural and engineered system properties by which these objectives are to be achieved, the means by which this is tested and demonstrated, namely in so-called safety cases, and finally how these criteria are to be used in selecting a suitable site. Added are observations on various overarching issues, such as on confidence building within the scientific/technical community and among the various stakeholders, on governance issues and the implications for the regulators. Given the fact that research on geological disposal has been going on for more than 40 years and will continue for perhaps another 50 to 100 years, knowledge management can become a critical issue that is also discussed in this report.

Note on the use of this report: the key findings in each section are highlighted by printing them in ‘bold’ typeface. In addition to the references cited in the various sections, the reference list contains additional material for further reading.

Paradigm

It is widely agreed in the scientific and technical community that geological disposal is the desirable management end-point for highly radioactive materials that arise from nuclear energy systems and are considered waste. Deep geological disposal appears to be the most reliable post-closure ‘passively’ safe option as stipulated by Requirement 5 of the draft Safety Requirements for geological disposal (IAEA, in prep. f). Research into the technical feasibility, the scientific implications and the safety requirements has been going on for more than three decades. While one major obstacle against implementation of such management solutions appears to be their public acceptance, one may also ask at this point, whether generic RTD world-wide up until now has adequately covered all relevant aspects, which open questions are still being addressed or need to be addressed, and what further work is needed to demonstrate safety. It is

understood that in practical terms there will be no clear distinction between generic research and detailed site characterisation work.

It is also important to note that ‘safety’ is a necessary pre-condition, though in practice the decision of what is an acceptable safety is not necessarily made only by the regulator, but public acceptance may have a bearing on it. At the same time, the regulator has to ensure that other stakeholders’ wishes do not compromise safety. In essence, a broad societal consensus is needed to enter into the implementation phase.

A stocktaking exercise and gap analysis will also be valuable in the preparation of the next Framework Programme.

Current status of work supporting the safety case

As will be discussed in detail in Chapter 3, a ‘safety case’ may be broadly defined as a structured presentation of the evidence, analyses, and lines of reasoning related to the long-term radiological safety of a proposed or actual radioactive waste repository. Research and development in supporting safety cases has been going on for the past 30+ years and has reached a certain maturity in various topical areas. The work has been funded largely by the national programmes (operators and regulators) in more advanced Member States, but a considerable amount of resources has also been invested by the European Commission.

Progress has been thus that scientists and engineers in general are confident that repositories that will perform as expected over the projected time horizon of 10^5 or even 10^6 years can be built. Nevertheless the long periods of time for which safety has to be demonstrated remains a key challenge in the development of safety cases for geological repositories (OECD-NEA, 2006i).

While disposal research has reached a certain level of maturity in a number of topical areas, continuing work is driven by six main factors:

- previously identified knowledge gaps,
- changes in the overall radioactive waste management concepts, including the introduction of the requirements for reversibility/retriev-

ability, long-term storage, as well as security issues, resulting e.g. in different potential radionuclide source terms or the reaction of repository components to long exposure to the atmosphere,

- innovations in nuclear energy conversion systems, such as a move to higher burn-ups or new reactor types with different wastes,
- to confirm that previous work is still valid given new insights coming from other areas of research,
- the desire to further increase the already identified safety margins, and finally,
- scientific curiosity.

The first five are drivers coming immediately from within the community of those concerned with the safe disposal of radioactive waste, namely the operators and regulators. The last driver refers to academic research that may not be directed to the immediate needs of the safety case or performance assessment.

It is important to stress that continuing research does not indicate a lack of confidence in the principle of geological disposal as such.

The aim of international organisations, such as the OECD-NEA and IAEA, is to provide a sounding board for national programmes and to organise collaborative work on generic topics so that efforts can be distributed and resources applied efficiently. In addition particularly the IAEA is working towards a harmonisation of standards with a view to increase (public) acceptance of waste management solutions. The membership in these organisations is different, the OECD-NEA membership being nearly the same as that in EU25 plus Japan, Canada and the USA, while the IAEA addresses explicitly the needs of the less developed countries of their 145 strong membership.

Implementation of any geological disposal project will depend on the preparation of an adequate safety case and on the licensing authorities determining what is adequate and accepting the safety case. It is therefore useful to review the status from both perspectives.

Topical areas of concern

The tasks towards implementation of disposal solutions can be subdivided into

- ensuring that an adequate regulatory framework is in place
- development of a conceptual model,

- providing for the scientific-technical basis to support the chosen concepts, and
- undertakings to ensure confidence among stakeholders.

This will be supported by a number of cross-cutting or overarching areas of research an implementation work, including resolving governance issues and ensuring efficient knowledge management.

2. The Technical Concept of Geological Disposal

Overview

The fundamental objective of geological disposal is to retain radionuclides in either the engineered repository or in the host rock so that they do not enter the biosphere over a pre-defined time span. Geological disposal relies on a sequence of complementary and/or redundant barriers (a 'defence-in-depth' concept), namely the waste form, the container, the buffer/backfill, and the host rock (cf. IAEA, 2003j). Each natural or engineered component of the disposal system is assumed to fulfil certain functions, either alone or in combination. The relative degree of complementarity and redundancy required depends on the national legislation and the chosen host rock (see also OECD-NEA 2007g for a discussion on this subject). It may be noted here that this teleological, engineering-type concept has come under scrutiny and a more holistic view of how the natural systems will react to the disturbance introduced by the repository is gradually being developed among geoscientists. This view is guided inter alia by insights into how for instance natural mineralisations are preserved over very long time-scales.

Three principal types of host rock are currently under investigation in Europe: hardrocks such as granite, sedimentary rocks such as plastic or indurated clays, and rock salt. In the USA also volcanic tuffs are considered (Yucca Mountain). Depending on the host rock, different emphasis has to be placed on different elements of the disposal system.

In granites discrete migration pathways will exist, but their frequency and length is difficult to assess quantitatively. For this reason more emphasis has

to be placed on the integrity of the waste packages, the buffer/backfill and other engineered elements of the repository itself. Granitic systems are under investigation in Sweden, Finland and Switzerland (as a second option), and are also considered by the Czech Republic as well as Spain.

Clay formations are chosen such that discrete pathways in form of fractures etc. will be minimal. Thus the retention capacity of the host rock can play an important role in retaining any radionuclides and less emphasis can be placed in relative terms on the other system components. Belgium, France and Switzerland are investigating this option in various types of plastic or indurated clays.

In rock salt the main vector for radionuclide migration, the pore waters, is virtually absent. Thus the various barrier elements can have a more equal weighting, although their failure would be due to any residual water present. Germany is the only European country that in earnest considers a disposal option in salt.

Waste inventory

The radioactive wastes due for disposal in a deep repository have been in some instances accumulated over a period of more than six decades. Due to poor record keeping and a lack of awareness of the importance to be able to describe source terms adequately, the nuclide composition of many wastes is not known or not known very precisely. In addition to radionuclides, certain wastes destined for deep disposal also contain chemo-toxic elements or compounds.

Analysis of the elemental composition of legacy wastes is often not possible for safety or commercial reasons. Therefore, estimation techniques based on the knowledge of previous processes and practices are being developed. The NEA currently has a project on the isotopic composition of spent fuel under way (see <http://www.nea.fr/html/science/wpncs/ADSNF/index.html>).

Waste forms

Two main types of high-level waste, respectively waste forms, are under consideration for deep geological disposal in Europe: vitrified high-level waste and spent nuclear fuel, should it be declared a waste. In other countries (Australia, USA) ceramic- (e.g. VANCE, 2007) or phosphate-bonded (OELKERS & MONTEL, 2008) high-level waste forms are also under investigation. In addition certain other wastes containing long-lived radionuclides are also destined for geological disposal in some countries, e.g. Switzerland.

A considerable amount of research has been undertaken to understand the dissolution behaviour of glass in the presence of different types of groundwater and other repository components. As the choices of repository systems were narrowed down, glass compositions were developed to suit the anticipated geochemical conditions. All repository systems assume that the vitrified waste will be emplaced in steel cylinders. Most of the current near-field designs assume that some argillaceous material, either bentonite, bentonite/sand, bentonite/crushed rock or crushed clay host rock will be in immediate contact with the steel, while in the salt case this will be a mixture of crushed salt and bentonite. The chemical interaction of these three systems components has been extensively studied. The FP6 project NF-PRO in particular aimed to sum up the current knowledge of glass and fuel dissolution and to identify and address any remaining gaps. While there are indications that this research area has reached a certain level of maturity, a variety of detail questions remain open and the unexpected behaviour of steel corrosion products (see below) may require further investigation with respect to waste form dissolution. However, experts seem to agree that these questions mainly concern the optimisation of the near-field of a disposal system, but would not compromise its fundamental functioning (HODGKINSON, 2007).

Given the limited number of principal disposal concepts and the limited number of glass formulations, harmonised approaches to process description would be warranted. **Research into glass corrosion in different types of environments and due to the interaction with the various components of a repository systems appears have reached a certain maturity.**

Spent fuel consists mainly of UO_2 -pellets with the fission products contained within. These pellets are contained in the fuel cladding. Such fuel bundles are placed in containers made of steel or a combination of copper and steel. Thus the interaction of the fuel with the other components of the near-field need to be investigated. Similar to glass, an extensive body of research has been accumulated on this subject. This work indicates rapid dissolution of the fuel in natural environments and in the absence of geochemical buffers, such as the alkaline environment provided by concrete in the repository. **Much of the basic research into spent fuel dissolution is of generic nature and equally applicable to several countries' disposal systems.** However, processes and respective models need to be verified using site specific materials during the development of the safety case.

Disposal concepts to date assume waste forms and spent fuel associated with past and current types of reactors. New reactor types and changes in the fuel design will necessitate research into the behaviour of the respective spent fuels under repository conditions, should they be declared waste and destined for direct disposal. Given the rising prices of uranium and general notions of resources conservation together with the expectation that more new reactors will be built, it is not unlikely that the Member States concerned will review their policies on direct disposal. However, waste management organisation have to be prepared for all eventualities and, hence, such research is needed.

Waste containers

The main function of the containers or canisters, once emplaced in the repository, is to provide the first physical and geochemical barrier against dissolution of the vitrified waste or spent fuel. Surface temperatures of the waste packages will have been let to drop below the boiling point of water in most Member States, but the interactions between the glass matrix and the argillaceous backfill materials

are difficult to assess under such conditions. In order to provide this function over the specified life time, the canisters must also be able to resist the geomechanical forces that will be exerted on them after the closure of the repository. This is particularly an issue with the casks for spent fuel. While all-steel casks are designed to provide the strength in themselves, copper canisters require steel inserts to provide more strength against deformation. In certain disposal systems, such as that envisaged by Belgium, the primary carbon steel canister is surrounded by an overpack consisting of a layer of portland cement cast into a stainless steel canister. This 'supercontainer' thus provides alkaline buffering in addition to mechanical strength and low hydraulic conductivity. In general, the introduction of foreign materials, such as alkaline cements, is being reconsidered as the benefit of lowering radionuclide solubilities and corrosion passivation is off-set by difficult to predict detrimental effects on argillaceous materials in the repository system. In other systems chemical buffering is provided by the backfill.

The number of types of canisters needed is determined by the various reactor types and their associated fuel assemblies that must be accommodated in the canisters. As with most aspects of the disposal system, one can group the research work into generic type of research and work that has to be undertaken on country-specific problems. There will be, however, groups of countries that require the same type of canister for a similar type of disposal environment. The project CATT (<http://catt.jrc.ec.europa.eu/>) *inter alia* investigates how transferable waste packaging designs might be. Materials properties' and structural strength analysis and modelling have reached a certain maturity. Current research addresses specific design issues and failure modes and probabilities.

There have been extensive research programmes over the past decades into the behaviour of various types of steel and of copper in the different engineered repository types. The long-term behaviour of these materials has also been assessed using man-made analogues, such as archaeological copper artefacts. Research into corrosion of steel and copper in aqueous solutions appears to have also reached a certain maturity, judging by the smaller number of projects on the subject in recent years. ***While corrosion as such appears to be reasonably well understood, rate determining processes, and the behaviour at interfaces, such as***

the behaviour of corrosion products at the interface between steel canisters and backfill require further investigation (HODGKINSON, 2007).

Corrosion gases generated and their migration is being addressed in various national and EC projects, e.g. DECOVALEX (<http://www.decovalex.com/>) or PAMINA (<http://www.ip-pamina.eu/>). For the NEA-IGSC (<http://www.nea.fr/html/rwm/igsc.html>) gas generation and migration was identified as an important study subject.

More recent developments in the nuclear world, such as a move to higher burn-up and the introduction of mixed oxide (MOX) fuels, have necessitated the revision of container designs, giving rise for a need for new research in this field. New and revised designs have to accommodate higher thermal loads and are exposed to higher risks of radiation-induced embrittlement of structural parts. The changed criticality risks – lower risks of criticality, during the life-cycle of the canister can also be taken into account.

Additional references: IAEA (1987,1997,2003).

Buffer and backfill materials

In virtually all repository designs the residual space around wastes as well as the drifts and shafts excavated for operational purposes must be backfilled. This backfill is needed to prevent uncontrolled settling of the host rock onto the waste. In addition the backfill may have various additional safety functions attributed to it. Thus argillaceous backfill materials will provide a hydraulic and sorption barrier against radionuclide migration. It also serves to 'key in' the repository into the excavation damaged zone (EDZ), preventing rapid transport pathways. These safety functions are challenged by the inevitable drying out after the emplacement of the hot waste canisters.

In clay and granite systems bentonite or bentonite/crushed host rock-mixtures are the buffer and backfill material of choice in most national programmes, while in salt systems mixtures of crushed rock salt and bentonite are likely to be used. As there is only one country left that considers disposal into salt formations, namely Germany, there is not much scope for collaborative research and harmonisation in this particular area. This applies to both, the geochemical and the geomechanical aspects.

Since the principal clay buffer and backfill systems are largely site independent, they have provided ample scope for collaborative research, which is reflected particularly in the programmes of the NEA and the EC and in joint undertakings of these two organisations.

Mineralogical, geochemical, hydraulic and geomechanical aspects are closely related in clays and often several macroscopic phenomena are controlled by the same microscopic process. The NEA in particular has focused for many years the research in this field through the 'Clay-Club' and their work on the engineered barrier zone (EBZ, OECD-NEA, 2007a and earlier reports). A comprehensive and scholarly review of clay as barrier was commissioned by NEA and may have become the ultimate word, if it had not been cut short by the unexpected death of its main author. The NEA will have the report completed, but also taking into account the more practical aspects.

Elevated temperatures will change the mineralogical, geomechanical and hydraulic properties of clays and it is intended to keep the surface temperatures of waste packages at the time of emplacement below 100°C. Indeed, storage period and repository layout is selected to keep the surface temperature of canisters below this value that has been found to be critical. The buffer and backfill materials will be put in place with a water content that is at the optimum from a geomechanical point of view, allowing e.g. maximum compaction. The heat emitted from the waste will dry out the materials and alter their suction potential. A complex sequence of dehydration and rehydration of the materials will result. Elevated temperatures and the presence of corrosion products from waste and containers will also alter the mineralogical assemblage in the clays, possibly changing the hydraulic properties due to precipitation or dissolution of minerals. Such processes have been studied in small scale laboratory experiments as well as in demonstration mock-ups in laboratories and in underground research laboratories, including the FEBEX in the Grimsel Laboratory (http://www.grimsel.com/pdfs/flg_febex_de.pdf). Many of these studies are not only relevant for buffer and backfill material, but clay as a host rock in general. The new work programme of the NEA-IGSC acknowledges this in setting up relevant cross-cutting activities.

Corrosion processes at the interface between canisters and structural steel on side and clays on the

other, and to a lesser degree radiolysis, can produce significant amounts of hydrogen in a repository. This goes in hand with the thermal loading of buffer and backfill material. This complex scenario of corrosion under changing degrees of saturation and the fate of the corrosion products is not yet fully understood and subject of ongoing research e.g. in the DECOVALEX project and new projects to be initiated during FP7.

While much of the basic phenomena in clays are understood, their quantification for given cases remains difficult. The complexity of the clay mineralogy makes it often difficult to arrive at unique explanations and quantitative predictions. Sources for suitable bentonites are not too frequent around the World and many have been extensively studied by now, but the situation is different with clay as host rock (see below). While the response of bentonite to changing conditions, such as water saturation at its boundaries, temperature, salinity/pH of engrossing water etc. are reasonably well understood the combined effect and possible interactions between different mechanisms are still difficult to predict quantitatively. It can be expected that the project NF-PRO will provide a good picture of the current status of knowledge and further research needs.

It appears that no major phenomena have been overlooked and further research will aid in quantifying the functioning of buffers and backfills, rather than putting the system as such into question.

Additional references: IAEA (1990,1992), OECD-NEA (2003c,2003d,2004c,2005c, 2007a).

Host rocks

Rock types

In Europe salt as an envisaged host rock is unique to Germany and therefore does not offer much scope of collaborative research, though the Netherlands may be looking into this option also. Rock salt in massive formations, e.g. diapirs, offers some special properties, such as convergence, which is effecting the sealing of a repository. Particularly the geomechanical properties without and with thermal loading have been studied extensively in Germany, both in the laboratory and underground facilities (the Asse former salt mine).

The following is mainly concerned with crystalline rocks and clays. There are three aspects of the host rock that need to be investigated, its geomechanical properties, its hydraulic properties, and its mineralogy and geochemistry. As has been noted before in the case of clay, these properties are closely related to each other. This is less the case for granite.

Geomechanical properties

Waste packages, buffer, backfill and surrounding host rock form a complex system. Excavation of a repository causes changes in the stress patterns in the rock, which in turn causes deformation. Some of the deformation will be passed onto other components of the repository after closure.

Mining and tunnelling techniques can look back to a centuries long tradition and the practical aspects are well established. Each host rock type and the specific geological setting requires the appropriate tunnelling technique. Tunnelling techniques have to balance speed and economy with the specific requirements of a repository. Even more so than in conventional tunnel projects, it is important during excavation to keep the disturbance of the surrounding rock to a minimum. The properties of the resulting excavation damaged zone (EDZ) have been and continue to be investigated in detail, as they will influence the overall permeability of the backfilled and sealed repository. As several waste management programmes move towards actual implementation, such construction and constructability issues find more attention in the respective R&D programmes.

Excavation will result in stress release and increased permeability due to the opening fractures etc. These can be sealed to some extent using geo-engineering techniques, but the seals may be subject to erosion over long time scales. Some clays exhibit self-healing properties e.g. due to convergence and this advantageous property has been investigated in detail from both, the scientific and geo-engineering point of view. The self-sealing and self-healing properties of rock salt due to creep and convergence also have an important safety function in repositories in this type of host rock.

The DECOVALEX project investigates the heat transfer, fluid flow and stress/deformation/failure in rocks and buffer, and their interactions

(coupled THM) over a few hundreds of years from excavation to post-closure. While the development of numerical modelling tools can be undertaken on international level, much of the actual process investigations have to be site specific, taking into account the specificities of the geology selected.

Tunnels and other excavations in hard rock are usually stable over prolonged periods of time and do not require any lining for geomechanical reasons. In clays and salt the convergence, which is a desired property during and after closure, requires built structures to keep the excavations open. This will introduce considerable amounts of steel and concrete into the repository environment. While the concrete has desirable effects on the geochemical environment by lowering the solubility of many radionuclides, its effect on the various clays can be detrimental and their properties have to be carefully chosen. Overall there seems to be a growing consensus that at least in repositories that are constructed in clays as host rocks only a minimum of additional foreign material should be introduced.

By the same token, alteration processes that occur during the operational phase, such as oxidation of sulfidic minerals, will have some influence on both, the geomechanical properties and the geochemical properties of the near-field. Such processes are the subject of the IP NF-PRO.

Considerations of constructability have several implications for the repository design. When locating a repository, or parts of it, at the chosen location one will generally aim for areas that are as homogeneous and undisturbed as possible. This has both advantages for the isolation of the waste and the safety of construction. Fault zones would provide pathways for migration and may also provide additional challenges during the construction of drifts and other excavations. Geotechnical measures to make safe certain parts of the excavations, for instance by rock anchors, will introduce additional foreign material into the repository and may have to be considered in the safety case. As the actual construction of the repository proceeds generally an optimisation process will have to be put into place that weighs the various technical constraints and safety objectives.

The introduction of new operational concepts, such as retrievability and long-term (→ 100 year) underground storage, results in increased requirements for the geomechanical stability of the open spaces

in a repository. Processes such as convergence and the ‘weathering’ of exposed rock surfaces will have to be approached in a slightly different way under those circumstances. ***The implications of delayed closure have been recognised, but not yet fully investigated.***

Additional references: IAEA (2001,2003), OECD-NEA (2004d,2005b).

Hydraulic properties

Concerning their permeability, geological materials are usually classified either as conducting in their porous matrix or along discreet features, such as fractures. This distinction, which was originally developed in the context of water resources investigations, is not so clear-cut in the low-permeability rocks chosen as host rocks for a geological repository. Even granites that are typically considered to conduct on fractures only, can have a considerable water-filled ‘porosity’, though no or only negligible water movement may take place in this porosity domain. Conversely, there are also indurated clays in which there can be considerable water movement along fractures.

The average permeability of rocks is scale dependent or in other words a reflection of the heterogeneities in the rock. Single, high-permeability features may dominate the permeability at any scale. While the properties of such features can be assessed in the laboratory and the field, their frequency, spatial persistence and distribution is more difficult to elucidate.

For fractured rocks various *in situ* experiments such as those at the Grimsel and Äspö sites are aimed to develop methods for describing quantitatively the distribution of fractures and their hydraulic functioning using modern borehole geophysical techniques in combination with tomographic imaging. Tomographic imaging techniques in combination with modern analytical techniques such as positron emission tomography (PET, e.g. GRÜNDIG *et al.*, 2007), or the permeation of rock samples with acrylic resins doped with radiotracers followed by autoradiography (LESKINEN *et al.*, 2007), help to better understand flow-path distribution on the cm-scale.

This distribution, their interconnectivity and permeability at a regional scale cannot be known with certainty, but has to be approximated using

statistical techniques. Even more difficult to capture are time- and scenario-dependent changes in permeability due to, for instance, blocking of flow-paths by the precipitation of secondary minerals or, conversely, corrosive dissolution. The net effect of the respective variability in parameter value distribution can be investigated by developing ‘what if’-type scenarios and sampling the system response. A variety of models for this purpose has been developed over the past decades both, within the radwaste community and in other geoscientific areas. This kind of uncertainty is also the subject of collaborative project PAMINA (<http://www.ip-pamina.eu/>). ***While there is considerable added value in international collaboration in the development of the respective techniques, actual assessments will have to be repeated at each planned repository site in the context of detailed site investigation.***

Depending on the geographical location, hydraulic conditions and other properties are expected to vary over longer time-scales. For instance, a glaciation is likely to reduce horizontal permeability as some fracture systems will close due to an overburden of several kilometres of ice. In any case, the ice cover will change the regional flow patterns by providing additional head and by modifying the recharge areas and recharge rates. Akin to all climatological models, predicting the extent and distribution of an ice cover over Scandinavia or the Alps is fraught with many uncertainties. For constructing the safety case for repositories located in areas that may be subject to glacial conditions at some time, it may be more effective to understand whether and how the flow patterns at repository depth would be significantly changed. Various national and projects under the IP FUNMIG have targeted this question utilising for instance various isotope techniques.

The movement of water in clays is more controlled by physico-chemical effects rather than by classical fluid mechanics. Unless fractures provide a fast pathway, water movement in clays is very slow. This is confirmed on a long time scale and over considerable distances by salinity and isotopic studies. The bulk permeability of clays can be significantly changed by ingressing fluid whose constituents may interact with the clay minerals. Saline or high pH solutions, such as those resulting from contact with concrete, can increase permeabilities by disaggregation and reduced swelling pressure. Rearrangement of the mineral assemblage due to corrosion and newly formed minerals can lead to permanent changes. Some of

these changes may be considered detrimental to the retention capacities of the clays for radionuclides. These processes have been extensively studied and continue to be studied under the IPs NF-PRO and FUNMIG. Not all of the mineralogical processes are yet quantitatively understood. Once a repository site has been selected and site investigation work has begun, some of the interaction studies will have to be repeated with the actual materials present in the area where the repository will be excavated.

Additional references: IAEA (1999a), OECD-NEA (1997b,1999b,2001a,2001b),

Processes affecting radionuclide behaviour

Overview

Permeability and the mechanisms controlling the migration of (dissolved) constituents in the porewaters are closely related. There is a wide spectrum of physical and chemical processes that lead to the distribution and effects the retention of constituents. The scale of the responsible features and associated processes may range from the kilometre-scale to the molecular level. Thus the migration behaviour of radionuclides is determined by the hydraulic properties of the respective host rocks, the chemical properties of the element in question and by the mineralogical and geochemical properties of the material, buffer/backfill material or host rock, in which migration occurs.

The way how the water itself moves in the various types of materials on a laboratory scale (cm to dm) is becoming reasonably well understood. With considerable success tracer migration has also been investigated in small domains, such as single fracture, utilising rock laboratories such as those in Grimsel or Mol. One RTD component of the IP FUNMIG (<http://www.funmig.com/>) is directed to investigate the respective processes and their upscaling. Processes at the molecular level find increasing attention.

Clays, as buffers and backfill materials as well as host rocks, have been studied extensively with respect to their mineralogy and how it may change when in contact with different repository materials. Various national programmes and namely the Clay Club (<http://www.nea.fr/html/rwm/clayclub.html>) participants studied how radionuclides are retained and how this retention is changed in contact with different repository materials (OECD-NEA, 2005b).

While geochemical processes in clays have been studied extensively for the past three decades, these processes have found less attention in granites. The general notion has been that the major retention capacity is provided by fracture infills, that may be similar to clays or by a largely physical process that was dubbed 'matrix diffusion'. Owing to the generally lower geochemical retention capacity in granites, compared to clays, safety cases for repositories in such rocks place more emphasis on the engineered barriers.

Advection, hydrodynamic dispersion and diffusion are the physical processes that shape the concentration distributions of radionuclides released from a repository. In soft clays diffusion will be the dominating process, while in indurated clays there may be also advective transport along fractures. Advective transport dominates in fractured rock, provided there are no significant fracture infills. On the macroscopic level the presence of an assemblage of flowpath of differing length as well as the velocity distribution within open fractures leads to the phenomenon that is dubbed as hydrodynamic dispersion. These dispersion phenomena lead to a lower peak of absolute concentrations, but not to retention *sensu strictu*, meaning that the total mass of migrating radionuclides is not lowered.

The physical process that leads to retention and on which safety cases for repositories in host rocks such as granites have increasingly come to rely on is the one called 'matrix diffusion'. Here one or more classes of water-filled 'pores' are observed, in which no advective movement takes place. Radionuclides diffuse into these pores driven by concentration gradients. When concentrations in the adjacent fractures drop below those in the matrix, the radionuclides are released again. As in the case of dispersion, this phenomenon lowers the peaks of absolute concentrations, but does not reduce the total mass of migrating radionuclides, unless these are fixed by e.g. precipitation.

While in the past diffusion processes were studied using short rock columns that were treated largely as 'black boxes', progress in analytical and modelling methods is leading to a better understanding of processes at the microscopic level. IP FUNMIG has a dedicated RTD component on this area that has fostered significant progress. These investigations focus less on the purely physical processes, rather than on their combination with sorption and (co-)precipitation processes.

There appears to be a wide consensus in the scientific world that argillaceous materials and rock salt as host rocks are capable of sufficiently retaining the relevant radionuclides. Ongoing research is mainly directed towards further increasing the safety margins and to demonstrate the overall resilience of the disposal systems to abnormal developments in the near field.

The retention capacities of fractured rocks are lower and more difficult to predict quantitatively over the long term.

Additional references: GRENTHE & PUIGDOMENECH (1997), IAEA (1989,1999f, 2005a, 2005c, in press), OECD-NEA (1997b,1998,1999b,2000a,2001a-c,2002a,2005b,2005g).

Thermochemical properties

At the beginning of the research into geological disposal many fundamental thermo-chemical properties of the majority of radionuclides were not known or not known quantitatively. Thus the occurrence of certain oxidation states of plutonium, neptunium and americium was debated. A wide field of research has been the chemical forms, or speciation, of uranium and transuranic elements in such complex media, as are porewaters in geological materials. Most of the fundamental research into the chemistry of these elements has been carried out under conditions far from those occurring in nature with respect to element concentrations, ionic strengths, and ligands present.

Various projects had been initiated over the past two decades at EU and NEA level to address this problem of missing and inconsistent thermodynamic data, e.g. the CHEMVAL-project (FALCK *et al.*, 1996). The NEA Thermodynamic Database Project (<http://www.nea.fr/html/dbtdb/>) in particular has helped to improve this situation by critically reviewing the available data, by identifying gaps and by providing the rationale for targeted research. In addition significant progress has been made in the development of a variety of spectroscopic techniques that allow the observation of speciation under conditions that are close to those found in nature.

It was found that there were knowledge gaps not only in the chemistry of uranium and transuranic elements, but also in the chemical properties of various common major elements. The workplan for the NEA TDB project for 2008 and beyond addresses

some of these gaps explicitly now. This work is also driven by the needs and findings of performance assessment calculations. Thus in recent years certain fission products, such as selenium, have come into focus. The underlying causes for this change in focus are a better definition of the repository radionuclide inventory and an improved design of the repository barriers that are expected to retain efficiently uranium and transuranic elements. Work towards better understanding the (geo-)chemistry of those 'new' radionuclides is ongoing.

A major gap throughout the thermochemical databases continues to be temperature correction data for equilibrium constants. The majority of speciation experiments have been and are carried out under standard laboratory conditions, i.e. at 25°C and ambient pressure. A limited set of high-temperature data are available for some major ions that are found to be of interest for hydrothermal systems. While these would be relevant for the immediate area of the engineered repository, there is still a gap for the temperature range between 25 and 150°C that would be expected in the backfill and the host rock.

Another well-known gap are data to support advanced models for activity correction at higher ionic strengths, such as that proposed by PITZER (1991). Currently only data for some major ions are available. These corrections will be needed when the drying out of the buffer/backfill is to be modelled and for far-field migration calculations with salt as host rock.

The IP FUNMIG comprises work packages to fill gaps in the thermodynamic data, with particular emphasis on compounds relevant to geological disposal. Further work on actinides will be carried out under FP7.

Heterogeneous reactions

Precipitation of pure phases, co-precipitation and sorption as processes can be reasonably well defined under equilibrium and laboratory conditions. In many natural systems, however, the respective reactions will be neither instantaneous nor reversible; it becomes difficult to distinguish between the three processes.

Sorption on near- and far-field materials has been studied for decades by now. In the early years predominantly batch experiments were carried out,

but it was soon realised that the conditions investigated were far from any realities in the field. The usual method of evaluating these experiments, resulting in a single value for the distribution co-efficient (K_d -value) was recognised as not reflecting *in situ* conditions and not to have any prediction capabilities. Nevertheless, K_d -values are still widely produced and then used in performance assessment (PA) calculations. The underlying reason is that (probabilistic) PA calculations require simple models in order to keep CPU-times at a reasonable level. More mechanistic descriptions of sorption with a larger number of adjustable parameters would result in a calculational complexity that would be difficult to manage. A wide range of models to describe sorption and its various controlling factors, including competing individual ions, major ion concentration, pH-value, has been developed over the years. Obviously, the more variables a model has, the better it can be adjusted to a given reality, but in practice it is impossible to parameterise all of these variables over the whole domain to be investigated. The NEA Sorption Project intends to find a compromise between the sophistication of thermodynamic sorption models and the practical requirements of performance assessment. Hybrid models that bound possible changes and provide a parameterisation within these boundaries are being developed.

Simple pure phases involving radionuclides other than uranium are not likely to occur in the far-field. Along the potential migration pathways of radionuclides a wide variety of precipitation and dissolution reactions between major system constituents can and will occur as the system develops and time progresses. Studies on natural systems have proven very valuable in helping to understand the fate of e.g. uranium. However, many other radionuclides do not occur in nature or have suitable analogues. The structure of many of various naturally occurring solid phases will be such that radionuclides can be accommodated in their lattice. In other words solid solutions and co-precipitation can occur. A comprehensive review of solid solutions as a process and a state-of-the-art proposals for its description have recently been completed on behalf of the NEA (BRUNO *et al.*, 2007).

Reactions within the aqueous phase are fast on the time-scale of interest for a repository. For heterogeneous reactions this is not necessarily so and reaction kinetics can become a controlling factor. The Damköhler-number would indicate, whether

reaction kinetics need to be considered in a given system, ***but very few heterogeneous reaction kinetic data are available to this date for natural systems.***

Redox-processes

The majority of the radionuclides of interest in the context of nuclear waste disposal occur in several valence states that may have distinctively different geochemical mobilities. In general, the reduced state is less mobile than the oxidised state, for instance U(IV) vs. U(VI). It has been the objective of all near-field engineering designs to provide a high-pH environment, as under high pH values the solubilities of most metals are relatively low. Conversely, there have been not been such decided attempts to control the redox environment. It is tacitly assumed that the corrosion of structural steel and ferrous metal packages would result in a reducing near-field environment.

Experimental investigations, whether on the near-field or on the far-field, are frequently hampered by the fact that it is difficult to achieve anaerobic conditions in the laboratory or even in tests in underground research laboratories.

In any case, the construction and operation of a deep repository will result in a redox anomaly underground that is likely to take considerable time to dissipate. This process requires a sufficient redox buffering capacity of the surrounding host rock and of the far-field as a whole. While this may be not so much of concern in the context of clay host rocks, as these frequently contain significant amounts of reducing minerals such as pyrites, the situation is different for fractured hard rock. The question here is also whether the radionuclides experience sufficiently long residence to become reduced.

These and related processes and properties remain to be studied in depth in FP7 under the project ReCosy.

Colloids and organic complexation

While complexation by simple inorganic and small organic ligands is being treated within the various TDB projects, complexation by organic macromolecules has been treated as a separate issue owing to the wide variety of possible interactions and of molecule species involved. These fulvic or humic acid molecules may range in size from small dissolved molecules to large ones

that would classify as colloidal particles. Colloidal particles, which range in size between 1 nm and 1 μm , can also have inorganic sources, such as eroded clay minerals or precipitates of major ions or radionuclides from porewaters. A variety of models to describe the binding behaviour including interaction with discrete binding sites and unspecific interaction due to their polyelectrolytic properties (surface complexation) have been proposed. At the same time it has been attempted to devise sampling and analytical techniques to investigate colloids and macromolecules as such as well as their complexing behaviour without disturbing the natural state. These activities had been harnessed together under EU and NEA auspices in what became known as the CoCo-Club, the Colloids and Complexes Club.

Owing to the difficulties in working with (redox-sensitive) transuranic elements and fission products, much of the work on complexation by fulvic and humic substances to date was carried out with uranium. ***In consequence, there are still considerable knowledge gaps as far as the other elements are concerned.***

Another field that still is not very well understood is the trilateral interaction between micro-organisms, organic (macro)molecules and radionuclides. The body of research on this subject is limited.

Many of the knowledge gaps with respect to organic macromolecules are attributable to the very complex and changeable nature of these molecules. Unlike other constituents, such as inorganic molecules or simple organic molecules, they do not re-appear necessarily as the same identifiable compound. Important parameters, such as conformation or molecular mass, can also easily be changed by sampling and measuring procedures.

Thus, while the problems and their origin have been established, a solution is not straightforward. There is still much more experimental work required to quantitatively understand the behaviour of transuranic elements and fission products (and indeed most metals) in waters containing fulvic and humic substances. However, a sensitivity analysis within the performance assessment will show to what extent these uncertainties will influence the final outcome of the PA. Projects such as PAMINA (<http://www.ip-pamina.eu/>) will offer some guidance for determining when enough research in the context of a particular site has been done.

Inorganic colloid formation was recognised as another vector for enhanced radionuclide migration. Since colloids are not an entity, but rather a state of matter in the aqueous phase, their state is easily disturbed by sampling procedures. A range of sophisticated analytical techniques have been developed to investigate the interaction of radionuclides with colloidal particles.

A major source of colloids in a repository system is the bentonite buffer and backfill. Many experiments aimed to understand the migration of such colloids into the surrounding hard host rock have been carried out and continue to be carried out. Colloid generation is a function of the very specific geochemical conditions at a site and in the material under investigation. For this reason it is likely that such investigations have to be repeated for each chosen repository design and assemblage of materials. Colloid transport is also a function of the geochemical and flow conditions.

Colloid mediated transport of radionuclides is of particular concern as experimental evidence points to effects such as size exclusion, which may considerably speed up the migration of colloids. The actual distribution of radionuclides in the three-phase system water-colloid-rock is still difficult to predict and subject of continuing studies. ***While there is clear evidence for colloid-mediated transport of some radionuclides from laboratory experiments, the real importance of this mechanisms over long distances and long times scales needs to be assessed quantitatively in the context of a sensitivity analysis, e.g. by making assumptions about enhanced solubility or size exclusion effects.***

Biological activity

The potential importance of microbial activity for the evolution of the repository-relevant geochemical systems has long been underrated. This is not so much due to the neglect by those specifically involved in research on geological disposal, but rather a phenomenon common to all work on geochemical systems. It has often been reasoned that microbial activity cannot alter thermodynamics and thus the end points of chemical reactions are independent of microbial activity, which only would effect reaction rates. However, there may be several possible reaction pathways, each with a different end-point. As the actual pathways being followed may depend on the reaction progress per time unit, microbes

might well be a determinant factor in outcome of a reactive chemical system.

In comparison to other geochemical research, biogeochemical research has found comparatively little attention in the context of deep geological disposal. This in spite of the fact that over the past twenty years viable microbial communities have been found even at great depth in geothermal systems on land and off-shore.

Biogeochemical processes are one work package of the IP FUNMIG. The existence of micro-organisms in rocks at sites considered for deep repositories has been demonstrated nearly ten years ago (e.g. PEDERSEN, 1999). Only a few laboratories are undertaking research on the interaction of micro-organisms with radionuclides of interest (e.g. MOLL *et al.*, 2007).

Overall the quantitative role of micro-organisms in repository development and far-field migration is not fully understood yet.

Gas generation and multi-phase flow processes

There are several situations in or around a repository, where the flow of more than one phase has to be considered. Corrosion of ferrous components will change not only the geochemical redox environment, but will be also, together with radiolysis, a possible source of gases within a repository for high-level radioactive waste and/or spent fuel. Significant amounts of hydrogen can be produced in a repository.

As these corrosion processes go in hand with dehydration resulting from the decay heat emitted from the waste, there has been a concern about a possible fast dissipation of the hydrogen and other, radioactive gases through cracked back-fill materials and the surrounding host rock. It is still not clear whether the production of corrosion gases would result in a three-phase system and whether the overpressure could result in fractures opening which then would provide fast migration pathways.

The amount produced and time distribution of the gases arising depends on various factors during repository evolution. Corrosion firstly depends on the availability of water, which in turn is a function

of the saturation process after closure, counteracted by the heat dissipation from the waste. The dissipation of any gases generated depends on the geomechanical and geochemical repository evolution as a whole, with many closely coupled processes and process feedback. Individual processes may be reasonably well understood, but not so the complexity of the system.

There is only a limited number of conceptual and numerical modelling tools available for such complex and transient processes. Hence, gas generation and transport has been earmarked for further investigation in FP7 as well by the NEA IGSC in their work programme for 2008 and beyond.

Interaction between repository components

The processes discussed above do not occur in isolation, but interact in a variety of ways. Particularly in the near field mechanical, hydraulic, thermal and chemical processes are interacting in order to dissipate the various man-made disturbances. These processes are mostly far from steady state and rather transient in nature. Several international projects currently address these problems from an experimental and modelling perspective, including the DECOVALEX project.

An engineered repository effectively constitutes a geomechanical, hydraulic and geochemical anomaly within the host rock body. A considerable thermal and chemical potential is stored within the waste and other components of the engineered repository. These potentials will lead to a wide variety of interaction of the components with each other and the surrounding rock. This has been recognised for a long time and a considerable amount of research in the national and international programmes has been directed towards understanding these interactions.

The different engineered repository components are either put in place to fulfil different 'safety function' or are necessary for constructional and operational reasons. Thus concrete may be used in waste packages to create an alkaline environment that exhibits low solubilities for the radionuclides in question. At the same time the alkaline plumes originating in the cementitious components of the repository are of concern as they may alter the (e.g. swelling) properties of argillaceous

backfill materials and host rocks in a detrimental way. Hence, the interaction between alkaline solutions and different types of clays has been extensively studied in past. The further interaction with corrosion products from steel waste packages and structural materials forms part of the work under

NF-PRO. ***While the geochemical and mineralogical aspects of the alkaline transformations of the clays are reasonably well understood, the interaction with steel corrosion products and other feedback and coupling mechanisms into the geomechanical properties deserve further investigation.***

3. Siting of Repositories

Regional geological setting

A geological repository will form together with the wider surrounding geology the system that is necessary to prevent radionuclides from reaching the biosphere. Therefore, system parameters and materials properties not only in the immediate vicinity of the repository are of relevance, but also those of the surrounding ‘catchment area’.

Given a planning horizon in the order of 1 million years, a first general site selection criterion would be geological setting that has been stable for several millions of years and is expected to remain stable for several more millions of years. Stable does not necessarily mean ‘no change’, but rather settings with slow, steady and predictable changes can be of advantage. Relevant changes can be of tectonic or climatic nature.

The climate provides important boundary conditions – past, present, and future one, for the hydrogeological system (IAEA, 1999a). Groundwater is expected to be the main vector for radionuclide migration. Slow rates of recharge and discharge and, hence, slow rates of turnover are of advantage. Over the past decades groundwater dating techniques using various stable isotopes and radionuclide decay chains have been developed. Such methods can not only be applied to groundwater samples, but also to fluid inclusions in newly-formed minerals for instance. Using such methods, it could be demonstrated at sites considered for the construction of deep geological repositories that ground- and porewaters have ages of several million years. This indicates that effectively no exchange or movement of water has taken place over this period of time, that the main vector for radionuclide migration is absent.

In addition, the actual site within a geological formation can be chosen so that flowpath lengths to the surface and mixing/dilution are maximised. For instance, in an earlier UK site selection programme one of the pre-stated conditions was that hydraulic gradients and regional groundwater movements would be pointing towards the sea. Low permeability formations in basin structures with recharge from the margins only would be of similar advantage, as discharge can only occur as ‘leakage’ across layers or fault zones. Current groundwater flow patterns can be evaluated using numerical regional hydrogeological models.

Significant changes in climate, such as glacial periods, will have a profound effect on regional and local groundwater circulation patterns. Groundwater ages in the order of millions of years in argillaceous formations for instance foreseen for geological repositories indicate, however, that these areas have not been affected by the last glaciations. The situation is different for repositories planned to be built at the margins of the Fenno-Scandian shield. Glaciation is expected to profoundly change circulation patterns in fractured hard rock. The scientific debate is going on about how deep oxidising melt waters would penetrate and how the transients of accumulating and retreating iceshields will affect actual circulation patterns.

A further subject of deliberation and debate are infrequent tectonic or volcanic events. These issues are usually addressed by expert opinion in conjunction with statistics. While a geologist or geophysicist may have a good ‘feeling’ for such issues, it is difficult to quantify such aggregate personal experience for use in safety assessments.

In Europe, after 150+ years of geological research we have accumulated a wealth of information that

allows us to draw quite a detailed picture of the geological formations in the top few hundred metres of the Earth's crust. Further relevant details have to be gathered during the site selection and site investigation process. In the first instance preference is given to non-invasive techniques, such as seismics. Seismic techniques have greatly profited from the extensive developments in computing hard and software, which are needed for the modelling and interpretation of the recorded signals. Much of the relevant technology has been developed in the context of hydrocarbon exploration. This and other fields of geological research are concerned with developing a three-dimensional picture of geological formations. Other such fields include facies analyses that use knowledge of the genesis of sedimentary formations to make predictions about the lateral extent and distribution of internal structures in sedimentary rock bodies. Such analyses are also supported by geostatistical techniques, including for instance kriging. Such geostatistical techniques are also used to make predictions about the spatial distribution of discontinuities such as faults and fractures.

It should be noted that invasive techniques, such as drilling, have to be used judiciously in order not to compromise barriers. Pre-existing boreholes from earlier explorations for raw materials, including water, can pose a significant problem as standards and requirements for backfilling were not adequate or have not been obeyed. Such boreholes can provide short-circuits between different geological formations that are difficult to evaluate quantitatively.

Overall the techniques and (numerical) models to investigate the regional and local geological and hydrogeological situation are sufficiently mature for the needs of geological disposal.

Strategies for using all available geological and hydrogeological information are being currently developed with a view of an integrated assessment in the context of the development of safety cases.

It may be noted that this emphasis on 'integration' reflects a paradigm shift in approaching the problem of deep disposal, away from an engineering approach towards an approach that tries to understand repository evolution as a response of the geological systems to the foreign body 'repository'.

Selection strategies

On a purely scientific and technical basis, two strategies for site selection are thinkable: one can pick a single site that is likely to be suitable and then attempt to demonstrate its suitability through safety cases. Scientific logic has it, however, that 'suitability' cannot be demonstrated, only unsuitability. It is largely a question of how 'suitability' is defined. In the simplest instance it could mean that a given set of repository related parameters do comply with a set of pre-defined objectives. This assumes, of course, that the pre-defined targets are relevant and adequate. It may not be possible to be sure of the latter.

Alternatively, one can subject a range of potential sites to a series of preliminary safety cases that are designed to eliminate those that are unsuitable or less suitable than others in the set. In practical cases the choices tend to be bounded by the types of host rocks available in the particular Member State. A possible outcome of such strategy is that no suitable site exists on the territory of the Member State in question. In practice, the site selection process is complemented by preliminary design studies. Site selection is a process that iterates between identifying desirable site properties and engineering features that complement the naturally available site properties (IAEA, 1990, 2004c). Based on the concept of multiple, complementary and redundant barriers host rock and engineered repository features together prevent that radionuclides reach the biosphere. Ideally, the engineered features would only increase the safety margin, but considering the availability of suitable host rocks, some countries will have to put relative more emphasis on the engineered features.

It is possible to develop a catalogue of criteria by which suitable regions can be identified. This catalogue would be based on the catalogue of FEPs (Features, Events, Processes) by trying to identify sites that have a maximum of desirable FEPs while minimising those that are undesirable. Fundamental criteria include, for instance, long geological stability, low hydraulic gradients and permeabilities, low geochemical and other potentials, etc. In other words, a geological system is sought out that exhibits in its natural state a low potential for change and very slow rates of change. In most Member State there is a certain amount of knowledge about the geology already available that directs the search and eliminates particular regions at a very early stage.

The basic criteria for site selection are host rock independent and, therefore, can be developed on an international basis. A harmonisation of the basic criteria would also ensure equal treatment of regions within a country and the European Community as a whole. It would also facilitate trans-national solutions, whether these involve shared repositories (cf. project SAPIERR, <http://www.sapierr.net/>) or shared designs and other facilities (cf. project CATT, <http://catt.jrc.nl/>). ***Due consideration has to be given to the fact that repository programmes are quite far advanced in several countries already; establishing such harmonised criteria should not put these programmes in jeopardy.***

In practice, site selection is likely to be bounded also by non-scientific and non-technical criteria, such as the local acceptance, the availability of infrastructure, pre-existing nuclear activities, and a range of other socio-political and economic factors. In the past these considerations were often not made explicit. However, many national programmes now are introducing features to allow such considerations to be made explicit, in appropriate partnership with local and regional stakeholders (OECD-NEA 2007b). ***Because value systems, perceptions, legal***

systems, siting history, etc. vary among countries, sharing of best practice is considered more appropriate than would be a harmonising approach.

Given the fact that three major groups of promising host rocks have already been identified and basic repository designs developed, the iterative procedure of site selection can probably be shortened for Member States newly entering into this phase.

Human intrusion risk as a criterion

Site selection may also be the only viable strategy to minimise the risk of inadvertent human intrusion beyond a time-frame within which institutional control can be reasonably assured. Thus repository sites are chosen such that, based on today's knowledge and needs, they would have as little potential as possible for raw materials (minerals, ores, coal, oil, gas), (drinking) water or geothermal energy. This criterion would apply to all formations above and below the host formation and, of course, the host formation itself. Certain repository design features also aim to minimise the consequences of inadvertent intrusion.

4. Regulating Geological Disposal

Fundamental observations

A recent NEA report summarises the regulatory approaches to geological disposal and the underlying radiation protection criteria and societal processes ranging from the policy making to the implementation level (OECD-NEA, 2007d). This report provides a concise yet comprehensive overview over its Member States' regulatory systems and the underlying regulatory philosophies. Significant differences in the regulatory criteria between different countries were found. Thus dose constraints span a range from 0.1 to 0.3 mSv/year, while risk constraints are either set at 10^{-5} or 10^{-6} per year. The IAEA stipulates 0.3 mSv/year and 10^{-5} per year (IAEA, in prep. f). It was concluded that when comparing the approaches in different countries not only the different numerical criteria need to be considered, but also the philosophy and societal consensus that determine what acceptable consequences are and what not. However, it was also concluded that these variations do not

mean less adequate protection in some countries, but rather differing desired levels of confidence in the ensuing safety. In fact, the effect of a repository would not be detectable statistically even in the most exposed critical group for any of these constraints.

Radiation protection principles have seen a significant evolution over the past decades, with various general ethical notions, such as intergenerational equity and protection of the environment, being included. It is increasingly being realised that a prescriptive approach focusing on one specific numerical value for one exposure model does not necessarily provide optimal protection under all circumstances and may result in quite high societal costs without entailing adequate benefits. Radiation protection, as all other human activities, has to operate in a socio-economic context and certain trade-offs may provide overall benefits. However, for a number of reasons, not the least political ones, this is only slowly being acknowledged among regulators.

As has been noted in OECD-NEA (2007d) and elsewhere, the ethical dimension of radioactive waste management choices in general and of geological disposal in particular is gaining importance. Both, international guidance and national regulations increasingly adopt concepts and language, such as ‘intergenerational equity’ or ‘no undue burden to future generations’ that reflect certain ethical notions and programmes. The ‘Joint Convention’ (IAEA, 1997d) imposes in that way moral and legal obligation onto the signatory and ratifying states.

The traditions of the approach to implementing regulations in different Member States are quite different. Some countries prefer a prescriptive approach, whereby a given target value, e.g. a dose is set and the safety case must be constructed to meet this target. Other countries prefer a collaborative approach, whereby implementer and regulator (and perhaps other stakeholders) work together to arrive at a solution that is not only optimised with respect to a specific regulatory target value.

The increasing importance of stepwise decision making and of reversibility and retrievability are changing the nature of repository design to a process that itself may span several generations. This poses difficulties for the regulatory decision making process and for the ability to maintain transparency (OECD-NEA, 2007d).

Policy making and radiation protection

Waste management in general and geological disposal in particular operate within a policy framework determined at a level higher than that of the technical regulator. At this policy level fundamental decisions are made, such as those on the continued use of nuclear energy, reprocessing vs. direct disposal of spent fuel, on disposal vs. long-term storage and so forth. It is, however, not so straightforward to draw a border between national policy questions and regulatory matters.

The role and competencies of national technical regulators can vary considerably, reflecting the cultural differences and traditions and evolved with time (OECD-NEA, 2003f). This has resulted in varying radiation protection criteria and methods of demonstrating compliance with regulations (OECD-NEA, 2004k, 2005i). Indeed, the bases for approaching risk and for setting these criteria vary as well (VARI, 2004). A commonly accepted definition of what constitutes

‘safety’ and what constitutes ‘protection’ is still lacking to date (OECD-NEA, 2007d). The authors of this report concluded that it is not possible to draw a picture of an idealised, or even a typical, regulatory model for the different countries. It is also interesting to review OECD-NEA (2007f), which contains a discussion of the current thoughts on the state and future development of radiation protection that move away from the paradigms of dose as main measure and away from humans as the only species to be protected.

The development of safety cases iterates between implementers and regulators. The implementers act within a given regulatory framework, while on the other hand the regulators have to take realities and real-life constraints into consideration. Regulatory requirements must be practical. It must be possible to demonstrate that the requirements are met. At the same time, as science is progressing, radiation protection and environmental legislation is being further developed.

Regulating a geological repository involves judgements on events and developments far into the future. For this reason it does not only involve technical judgements, but also value judgements and ethical considerations, even though regulatory bodies might consider this outside their realm.

The NEA compiles a database on the respective regulatory framework in their Member States. The signatory states to the ‘Joint Convention’ (IAEA, 1997d) also have submitted information on the regulatory framework to the secretariat, the IAEA. In their Net-Enabled Waste Management Database (NEWMDB; <http://www-newmdb.iaea.org/>) the IAEA collects in addition to information about the waste itself information on how the waste is managed and regulated.

Differing needs of stakeholders

The three main groups of stakeholders in geological disposal, namely the implementer, the regulator and the general public (which is understood here as an all inclusive term), have differing needs and requirements for regulations.

The implementer needs clear and preferably quantitative guidelines by which the process and its end product can be designed. In principle the implementer would also prefer to have in place from the outset a clear set of regulations, requirements

and guidelines. However, as has been pointed out at several places, regulating geological disposal is in fact an ongoing process.

The regulator, in principle, would also prefer clear and quantifiable guidelines for which compliance can be demonstrated easily. However, due to the timescales involved compliance can only be demonstrated for the operational phase of the repository, while there is no guarantee that monitoring to demonstrate compliance will be carried beyond several generations. Regulators in general also seem to prefer solutions involving (active) institutional control and still seem to struggle somewhat with the concept that there cannot be active ongoing control to assure safety. For this reason, regulators tend to require a reasonable demonstration of confinement, rather than that no harm is done to humans and the environment.

The actual needs of the general public at any time of the process are difficult to assess and, hence, may be difficult to meet. Over the years a number of tools to identify stakeholder concerns have been developed and experience has been gained with various techniques for involving the public in decision-making processes and in addressing these concerns (e.g. OECD-NEA 2003e,2003k,2004e,2004f,2004m). Transparency of the decision making and licensing process is an overarching criterion. This transparency also needs to extend to the bases of the criteria for decision making (OECD-NEA 2003e,2004e,2004i).

Enabling regulators

Having regulations in place alone is not sufficient. It must be assured that the regulatory bodies are adequately equipped with competent and capable staff. The regulatory and supporting activities, such as independent research, must be adequately funded. The regulators must be given the necessary executive powers or the competence to invoke executive support from other government bodies, if needed. In order to instil confidence among all stakeholders, the regulator must be independent. These points are also stipulated in Requirement 1 of the draft IAEA Safety Requirements for geological disposal (IAEA, in prep. f) and in the 'Joint Convention' (IAEA, 1997d). Regulators must be continuously trained so that they are enabled to judge and challenge proposals put forward by the implementer.

Peer reviews of regulatory bodies and participation of regulators in international activities, such as those organised by the IAEA and the NEA will help to keep regulators at the forefront of developments and point to further enabling needs.

Regulatory gaps and inconsistencies

The regulatory process for geological disposal has been largely driven by radiation protection considerations, but various radionuclides are also relevant from a chemotoxicological point of view as has been pointed out earlier. No international or national legislation provides guidance on permissible environmental concentrations for radionuclides other than uranium (in some countries) and radon. Improved engineering design has resulted in the predicted retention of the most important nuclides, such as uranium and plutonium, with the effect that now long-lived, more 'exotic' nuclides, such as those of selenium, show up in performance assessment calculations.

Much of the existing radiation protection guidance and legislation was originally drafted for medical, laboratory and industrial exposures to discrete and directly controllable sources of radiation. Hence, the traditional basic measure in radiation protection is dose. However, calculating a 'dose' requires knowledge, or assumptions, about possible exposure scenarios. The radiation protection community has been very slow in accepting the fact that humans live rather different lives in different parts of the World and therefore would be subject to rather different exposure scenarios given the same environmental concentrations. Making predictions, or even assumptions, about life-styles beyond a few hundred years becomes rather speculative and on the scale of millennia even meaningless. Therefore, a consensus is developing (ICRP, 2000; IAEA, 2006a) that numerical criteria should only be used as a reference or an indicator, rather than absolute limits in a legal sense. It should also be noted that the objective of radiation protection is not the absolute prevention of harm, but rather the reduction of the potential of harm to acceptable levels.

Regulators and implementers alike continue to struggle with the phenomenon that the public may be less inclined to accept high-consequence/low-probability events than low-consequence/high-probability events, though both may entail the same risk. Regulators have been responding to this

by prescribing different risk or target constraints.

Exposures to disperse sources of low concentration and over potentially very long periods of time is a comparatively new challenge and guidance and legislation is still being adapted.

Further, as OECD-NEA (2007d) points out, the 'Joint Convention' leaves a number of important terms and concepts undefined, for instance what is exactly meant by 'future generation', which leads to differing interpretations in different Member States.

Not only do protection criteria and the methods of demonstrating compliance differ from country to country, but the bases for setting the criteria appear to vary as well. In fact, the difference may even reflect difference in fundamental protection objectives. Within the NEA RWMC Regulators' Forum 'Long Term Safety Criteria (LTSC) group the initial idea of arriving at a 'collective opinion' evolved to one of fostering a common understanding of the bases for regulation that countries have formulated or are adopting (OECD-NEA, 2007d). A number of important contributing factors were identified. Among them are

- the complexity and non-uniformity of the decision making processes across nations,
- a lack of consensus on how to characterise and measure protection in the distant future,
- the range of institutions involved in decision making,
- not fully worked-out fundamental ethical issues related to the nature of current society obligations to the future, and, reflecting all of this,
- international guidance that has been evolving with time and still is.

One of the goals of the IAEA has been to ensure that radiation protection and subsidiary regulations are in place in all of its Member States. This is certainly now true in principle for the EU Member States, where many of the newer members appear to have followed the IAEA guidelines and recommendations, while at the same time complying with both, the IAEA (FAO *et al.*, 1996) and the European (EURATOM, 1996) Basic Safety Standards. Some

Member States have subject themselves to international peer review procedures of their respective regulatory infrastructure.

Overall there do appear to be no significant regulatory gaps in Member States. However, there are differences in the regulatory approaches.

Towards a common understanding

Though the regulatory approach might be different in different Member States, it appears to be important that some basic criteria and underlying concepts are harmonised, for instance along the lines of thought developed by the RWMC (OECD-NEA, 1997c). Framing common ideas on our obligations to future generations may be an important conceptual and ethical issue to resolve here. Otherwise such differences might raise concern among stakeholders, who might consider themselves less protected in one Member State than in another. In the light of shared facilities or services varying protection criteria might also raise concerns over risk displacement, as operators might want to opt for solutions in countries with less stringent regulations. However, there will be limitations to harmonisation, as differing approaches also reflect national regulatory culture, values and technical differences in the Member States' programmes.

The need for an internationally harmonised approach to assessing safety cases has been recognised by the regulatory authorities. At European level the 'European Pilot Study' (BESNUS *et al.*, 2006; LACOSTE, 2007) and at wider international level, the IAEA GEOSAF project have been initiated. In addition, a Working Party on Nuclear Safety (WPNS) in the European Union is currently analysing to what extent common approaches to waste management are implemented by its Member States. A preliminary conclusion from these efforts is the observation that, while the regulatory framework may differ considerably, the regulatory practices do much less so. The latter is certainly owed to the intensive exchange between different regulatory authorities, implementers and international organisations as facilitators.

Efforts to harmonise safety criteria in the industrial aspects of the nuclear industry are somewhat more advanced, as is evidenced by WENRA's (<http://www.wenra.org/>) efforts (WENRA, 2006).

The majority of EU regulators are represented in international groups, such as the WPNS or the RW-MC-Regulators' Forum, which ensures, as it does for the scientific community, a comparable level of understanding in all Member States.

Due to the wide variability in the regulatory approaches, it appears to be more efficient to develop a common understanding of these approaches and the underlying safety objectives, but to abstain from recommending a unified approach.

Rather than trying to unify at EU level all regulations pertaining to geological disposal, it might be also more efficient to ensure through some international review process that these regulations are adequate and have a common set of safety objectives.

Additional references: IAEA (1999b, 2001, 2005b, in prep. b), OECD-NEA (2000, 2002f)

5. The Safety Case

Conceptual overview

Requirement 3 of the draft IAEA Safety Requirements for geological disposal stipulates that “The operator shall carry out safety assessments and develop a safety case, ...”. A ‘safety case’ may be broadly defined as a structured presentation of the evidence, analyses, and lines of reasoning related to the long-term radiological safety of a proposed or actual radioactive waste repository (OECD-NEA, 2004g). It aims to demonstrate that the repository will function according to prescribed requirements and to expectations over a range of conditions including ones that are deemed unlikely or extreme. The safety case will be the basis for licensing a repository. Thus the safety case has to demonstrate that all possible features, events and processes (FEPs) that might be of relevance over the prescribed time frame have been taken into account (OECD-NEA, 2000a; MAZUREK *et al.* 2003) and that adequate levels of protection are achieved (Requirement 13; IAEA, in prep. f). Moreover these FEPs have to be understood quantitatively with a certain level of confidence in order to be able to demonstrate in safety assessments that acceptance levels are met.

Establishing a safety case consists of three major activities, namely the development of a conceptual site model, collating site and process data to support the model, and making predictions about the future development of the site using these data and models. Considering and quantifying conceptual and data uncertainties is a vital element in this process. The quantifiable information will be complemented by scientific reasoning and expert opinion, thus providing multiple lines of evidence.

Many Member States face the difficulty that the regulatory framework from which the acceptance criteria are derived has to be developed concurrently with the safety case (see also Section 13). There is a good reason for this, as both are informed by the same type of fundamental research; as process and system understanding improve, the regulatory framework as well as the safety case are refined.

The NEA, together with the EC and the IAEA, organised in January 2007 an international symposium (OECD-NEA, 2008c) that was aimed to be a stock-taking exercise with respect to the development of safety cases. It was noted in particular that key evolutions over the past decade included:

- Improved and structured documentation to favour clarity and traceability of argumentation;
- argumentation that demonstrates the knowledge base accumulated by the project;
- the development of more sophisticated analytical tools and databases,
- the introduction of new conceptual tools, such as the concept of safety function, that embody key aspects of performance of the geological disposal system and from which internal requirements can be developed that relate the ability of the disposal system to fulfil these functions, thus making more transparent the role of various components (and their synergies) in the disposal concept;

- the utilisation of performance and safety indicators besides the traditional radiological dose and risk indicators;
- the open discussion – in the safety case itself – of extant issues of concern and the identification of a path forward to their resolution.

Natural systems are usually complex and often ‘chaotic’ and therefore difficult or even impossible to predict in quantitative terms over extended time scales. In order to capture possible outcomes, two conceptually somewhat different approaches to developing a safety case are possible and have been used around the World:

- a) the range of possible realities is captured by parameter variation in numerical models and statistical sampling of the results; this is the domain of probabilistic performance assessment modelling. Alternatively,
- b) no probabilistic performance modelling is used, but a system of logical reasoning and bounding of system performance parameters is developed.

The actual approach chosen by the respective waste management organisation depends on the regulatory requirements. In practice often elements of both approaches are combined into a stream of multiple evidence.

The development of the fundamental concepts for a safety case has been a truly international collaborative effort and is largely independent of the host rock to be chosen. The country specific differences arise from the differing regulatory requirements. In addition to the two fundamental approaches outlined above, the selected target measures may also differ. In some countries such measures may be doses to particular critical groups, while in other countries these may be fluxes or concentrations of radionuclides in particular environmental compartments.

The concept of using doses alone to assess performance and safety far into the future is being increasingly criticised, as it adds the additional uncertainty of having to make assumptions about exposure scenarios for times far into the future. The history of modern man (*homo sapiens*) goes back only about 200,000 years, therefore, it is not very likely that in a million years from now there will be a human species with feeding and other habits similar to present-day man. Therefore, doses should only be

used as performance indicators and for comparison of alternatives, but not as limits or targets. The last observation also implies that a dose calculated for a given repository system and evolution scenario will not be the only criterion for accepting or rejecting a particular site and repository system. Further, the decade-old paradigm that the environment will be protected, if man is being protected has been questioned and new guidelines for protecting the environment and non-human species are being developed currently (OECD-NEA, 2007f).

The term ‘safety case’ (or equivalent wording) is not used in all national regulatory frameworks. Nevertheless, the internationally developed concepts and criteria for safety cases are important benchmarking tools. Whether and how safety cases could be made comparable has been extensively discussed in international fora. Various NEA reports (e.g. OECD-NEA, 2007d) have given very strong cautions that the results of different safety cases cannot be compared directly due to the many ways in which they differ – the criteria, the sites, the range of scenarios considered, the statistical measures used to judge compliance, the various assumptions and stylisations, etc. However, it may be valuable in the European context for the purpose of comparison and confidence building to develop a translation scheme for the results from different types of safety cases. Putting a specific national safety cases into an international context would certainly help to increase local confidence and acceptance. Considering the already well-developed regulatory framework and repository programmes in several Member States, such procedure certainly would be preferable over harmonisation. International efforts, such as the ‘European Pilot Study’ (BESNUS *et al.*, 2006; LACOSTE, 2007) and at wider international level the GEOSAF project are aiming to prepare the ground for more harmonisation. The NEA INTESC initiative (http://www.nea.fr/html/rwm/igsc_coreactivities.html#intesc) is aimed at assessing recent experience in developing safety cases and to identify areas of consensus and divergence, as well as ongoing challenges and emerging trends, by comparing the approaches and results achieved in the various Member States.

The development of a safety case is an iterative and recursive procedure that aims to optimise overall safety, taking into account the natural situation, engineering features and the applicable regulatory requirements. There may be several pathways to safety and different mixes of safety functions

that arrive at the same overall level of safety. For instance, repositories to be built in argillaceous or salt formation can put less emphasis on the long-term performance of waste forms, packages and the engineered near-field than a repository to be built in fractured hard-rock. Using, for instance, dose as a measure, different repository concepts in different host rocks will achieve different levels of safety. However, all currently investigated disposal concepts are capable of achieving dose levels below current regulatory requirements.

NEA is undertaking a review of safety assessment methods and first results are expected in 2009; the project will be coordinated with PAMINA, and one possible product is a joint OECD-NEA/EC brochure on the topic. These issues will also be discussed in more detail in the companion report on the Safety Case.

Additional references: IAEA (1988,1993,1997,1999d,2000,2002,2003c,2005a,2006,in press), OECD-NEA (1997,1999,2001,2004d,2004g,2004h,2004m,2005f,2006c,2007c)

Simplification issues

For practical reasons numerical models that may be used in probabilistic safety assessments have to be based on rather simple mechanistic models. For instance and as discussed above, these models still employ unconditional retardation factors for the radionuclide migration vector that are derived from distribution coefficients (K_d -values), though the conceptual problems and mechanistic limitations of K_d -values are well recognised. It needs to be quantitatively assessed for each case whether and how simplifying assumptions will influence the outcome of performance assessment calculations. It needs to be shown in particular that for a given scenario the underlying assumptions are robust and keep the overall model within a certain envelope, meaning that a more mechanistic model could change the magnitude of the result, but not its basic outcomes, such as calculated pathways.

The project PAMINA will help to clarify the picture on simplification issues.

Upscaling issues

Most natural processes are scale-dependent. Processes and parameter values derived from laboratory experiments have to be extrapolated to field conditions (OECD-NEA, 1997b). Different processes may be dominating at different scales. For instance, in a small rock sample transport processes may be governed by the porosity, while on the field scale transport in the same material may be dominated by fractures that do not occur in the small sample. Drawing conclusions from permeability measurements on the small sample to the host rock bulk permeability would lead to erroneous results. The upscaling issue is closely related to the question of heterogeneity. Given the limitations in resources, accessibility and others, heterogeneous systems cannot be investigated in all details, but their behaviour must be inferred using statistical techniques. ***Respective sampling strategies and required sampling densities as well as a quantitative assessment of the associated uncertainties continues to be the subject of research within and outside of the radioactive waste community.***

Many practical questions around repository design, construction and operation cannot be resolved on a theoretical basis, but practical experience is needed (IAEA, 2001d). For this reason several Member States and other countries around the World have constructed Underground Research Facilities (URFs) or have converted existing mines for this purpose. These research facilities allow to confirm *in situ* concepts and data that have been developed on small sample recovered from drill cores for instance. The facilities are also used to test various emplacement design etc. using non-radioactive mock-ups. Examples include the simulation of decay heat-loads by electric heaters. At some stage the waste emplacement and sealing techniques will be also tested *in situ* using inactive components. Realising that for the various groups of host rocks synergies between the different research undertakings can be generated and with a view to increase the utilisation of URFs by opening them up to partners with less advanced programmes, the IAEA initiated a Network of Centres of Excellence (http://www.iaea.org/OurWork/ST/NE/NEFW/wts_network.html). ***The objectives of the network are to encourage the transfer and preservation of knowledge and technologies, to work on solutions for Member States currently without URFs, to supplement national efforts and promote public confidence in waste disposal schemes, and to contribute to the resolution of key technical issues.***

The issue of timescales

As predictions about the post closure-future of the repository are to be made, two questions about timescales automatically arise, namely for what period of time do we need to make such predictions and over what period of time can we make predictions with some confidence (IAEA, 2000a). **The decision for which time horizon predictions have to be made is largely an ethical one, though it is informed by scientific research into overall future site development and associated probabilities.** For instance, a possible criterion is the development of radiotoxicity of the high-level waste or spent fuel. It will take in the order of 100,000 years to reach natural levels. Implementers will have to show compliance with respective regulatory requirements, which are ultimately based on ethical considerations. In particular the NEA has been discussing this issue (OECD-NEA 2004j, 2006i), but it is concluded that the ultimate decision rests with the national regulators. The issue is closely linked with that of confidence building. Scientist will have to successfully communicate to stakeholders their confidence in their own predictions of site development.

Process relevance

It is important that all relevant features, events and processes (FEPs) that might affect the safety case are adequately captured. The basis for this is a catalogue of FEPs. Which processes from the catalogue of FEPs will be relevant is also closely related to the questions of scale and simplifications made. The NEA developed such a catalogue on a generic basis (OECD-NEA, 2000a) and recently updated it. Such catalogue will be universally applicable to all types of host rocks in all countries, though not all actual FEPs are expected to occur in any one country. **The catalogue of FEPs will serve as benchmark for testing national safety cases for relevance and completeness.** The use of 'safety functions' is emerging as an important tool to assess the relevance of various processes and to define key scenarios to be assessed.

If the output variability of a system, such as the results of transport calculations, can be explained with a reasoned variability of input parameters at a given scale level, then processes at a more detailed level would not need to be investigated, if they do not result in a change in the variability of the output at the higher level. Again the project

PAMINA (<http://www.ip-pamina.eu/>) is currently investigating such issues and a cohesive strategy for dealing with this aspect will be developed at European level.

Performance indicators

The traditionally used overall safety and performance indicator is dose. Dose, however, depends on the scenario and receptor chosen, the evolution of which over large timescales is highly uncertain. In recent years this concept has been criticised for being not very robust and because it may not necessarily protect species other than humans (http://www.nea.fr/html/rwm/safety_case/). More direct and exposure scenario independent measures are provided by radionuclide concentrations in environmental compartments or respective fluxes of radionuclides. The latter could also be compared with natural (geochemical) fluxes of comparable elements. The project PAMINA is currently critically reviewing the complex of performance indicators (BECKER & WOLF, 2008).

For certain radionuclides and depending on their concentration not radiation dose but chemotoxicity can be of concern. Except for uranium in some countries, there are no regulatory standards for radionuclide concentrations in environmental compartments. Therefore, no performance indicators can be built currently on this basis. **This may require some action on EU level.**

Conceptual and parameter uncertainty

Each safety case will have a range of different uncertainties associated with it. Some of the uncertainties are reducible, e.g. the magnitude and distribution of permeabilities, while others essentially are not reducible, such as the future development of the climate. Reducibility is bounded by numerous considerations, such as economical feasibility, the desire not to disturb the host rock in question, or practicability of obtaining data. In addition, there remains always a certain level of uncertainty over whether the chosen conceptual models are adequate and sufficient.

Thus, it will not be possible to investigate in every detail a repository site for reasons of limited resources and in order not to disturb the natural system unduly. It will also not be possible to quantify

in 3-D space all features and processes that may influence repository performance and development over time. Therefore, the conceptual model for the system as well as its parameterisation has a certain amount of uncertainty associated with it. Quantitative methods to describe system variability (OECD-NEA, 1998) and to decide on what level of confidence is needed for an acceptable safety case are required. Undue safety margins can be very costly.

These uncertainties impact on the safety case in a variety of ways. It is important to quantify this impact in order to ensure that the system performance remains within the expected limit for all interactions of the system components and for all states of the system parameters. It may be noted that propagation of uncertainties is likely to result in 'variant explosion', which is usually contained by expert judgement.

Current internationally sponsored research aims to minimise the range of uncertainties, to capture them quantitatively and to develop strategies to handle them and to facilitate regulatory decision making (IAEA, 1997c; OECD-NEA, 2005f). This research includes the activities under PAMINA (<http://www.ip-pamina.eu/>) and work sponsored by the NEA. ***Hopefully, this work will result in greater confidence that uncertainties have been adequately captured.***

The management of the safety case

Much of the current work around safety cases is concerned with the management of its development. The scientific communities that develop the safety case as such and its modelling tools are different from the communities that develop the supporting scientific process and materials knowledge. Strategies and mechanisms have to be put into place that ensure that all the available (geo-) scientific knowledge is utilised in developing the safety case. This includes quantitative as well as qualitative information. The information has to be utilised in a structured way so that individual elements of information are given due weight and to avoid bias. Conversely, knowledge gaps identified from the perspective of the safety case have to be translated into research programmes. The AMIGO series workshops (OECD-NEA, 2007e), for instance, is intended to sample Member States practice and experience in this particular area. The workshops

are organised in the context of the NEA task group on Integration Group for the Safety Case (IGSC). ***In the interest of confidence building among stakeholders, harmonised guidelines to the management of safety cases and harmonised objectives may be desirable.***

Emerging issues

Best Available Technology (BAT)

This term originates in the engineering and project management field, where it refers to the process that is designed to ensure that the best technical solution is selected and implemented. The process formalises technology selection according to a predefined set of criteria. The purpose is to ensure that e.g. technology selection is need driven, rather than vendor driven.

As the concept of BAT is also being referred to in the Directive on Integrated Pollution Prevention and Control (CEU, 1996) some cross-reference between this Directive and regulations for geological disposal of radioactive waste might be needed.

One could argue, however, that the whole process of developing a safety case together with the feedback into repository design in fact constitutes a process to select BATs, though not the same terminology is being used. Implicitly, the concept of BAT may also be present in ICRP Publication 81 (ICRP, 2000). Recently the NEA Radioactive Waste Management Committee's Regulators' Forum has taken up the subject and produced a first review of pertinent literature (OECD-NEA, 2008b).

In order to put safety cases into perspective, it may be worthwhile to examine and compare BAT selection processes applied to other environmental projects. This might also contribute to confidence building.

There are, however, a number of conceptual questions around BAT. For instance, how is it defined what constitutes a 'best' technology and how is 'availability' defined? In the past this has led to exaggerated demands by certain groups of stakeholders. For this reason in some countries the BAT concept has been replaced by the BPO (Best Practical Option) concept. This in turn leads to a discussion of what is to be considered 'practical'. In all cases there will be elements of judgement that are

driven by budgetary constraints as well as societal negotiations on acceptability.

It should be noted that some countries that originally championed this approach, which was borrowed from the well-established construction engineering realm, are now backing away from the use classical BAT/BPO concepts in emerging fields such as radioactive waste disposal. However, as relying on numerical performance indicators is also being questioned considering the long timescales involved, procedures are being developed that intend to demonstrate that sound scientific and engineering principles have been applied.

Other parameter optimisation concepts and policies borrowed from adjacent fields of science and industry include ALARA (As Low As Reasonably Achievable), which suffers from similar quantification issues as BAT and, hence, may not offer any advantages over the processes and criteria used in developing safety cases.

Optimisation

In the context of radiation protection this term refers to a very specific process of judging various costs and benefits that should lead to a minimisation of exposure while not resulting in other societal detriments. In the wider context of geological

disposal this term may describe other features or processes that are weighed against each other.

Thus optimisation should be an inherent result of the safety case and the process leading to its development and implementation.

Feedback from operational safety

As several national waste management programmes move closer to implementation, the aspect of operational safety becomes more relevant, which is also reflected in the 2009ff work programme of e.g. the NEA IGSC. An operating repository will be a licensed nuclear facility and subject to regulations in accordance with the Basic Safety Standards of European Union (EURATOM, 1996) and/or the IAEA (FAO *et al.*, 1996). The safety case has to consider any feedback from operational safety requirements into the design and layout of a repository and its infrastructure. For instance, the need for ventilation may worsen the effects of the EDZ and therefore have repercussions on the (long-term) performance of the repository. In the same way the actual feasibility of construction is to be considered. ***Within the scope of generic workplace and industrial safety standards there will be scope for a Europe-wide harmonisation in safety requirements for repository construction and operation.***

6. Alternative Concepts

As has been recently emphasised by a collective statement of the NEA RWMC (OECD-NEA, 2008d), the preferred concept for the end point of radioactive waste management is disposal in inland deep geological formations (see also IAEA 2007f, in prep. f). For many countries deep geological disposal is the reference long-term management solution. Nevertheless, it may be worthwhile in the interest of confidence building to periodically re-assess the overall reasoning that lead to this concept. In the past other concepts have been discussed and investigated, such as now abandoned deep-sea seabed disposal. Deep borehole disposal concepts are considered as a disposal solution for certain types of wastes and may be applicable in countries with very limited waste

generation (e.g. http://www.iaea.org/OurWork/ST/NE/NEFW/documents/BOSS_Flyer.pdf). Indeed, the NEA LTSC group has considered the various options from different perspectives, recognising that isolation or dispersal strategies over geological timescales are two end-members of a strategy to re-distribute risks in time and space (OECD-NEA, 2007d).

When scientific and societal knowledge have grown, it may be valuable to re-visit decisions that have been made mainly on the basis of technical or political considerations. A step-wise decision making approach during the implementation allows to accommodate scientific, technical and societal developments.

7. Confidence Building

Closing the issue

A repository project is likely to go ahead when all groups of stakeholders – scientists, engineers, operators/implementers, regulators, local administrators and the general public – are sufficiently confident that the repository will perform as designed (OECD-NEA, 2002e). In other words, confidence needs to be established so that enough is known to close the respective scientific and technical issues. There is no room here to enter into a discussion of the epistemology of the science that provides the basis for geological disposal. Much of the controversies over geological disposal is centred on issues of truth, belief and trust. In practice, confidence building is made up of various elements, including quality management, outreach and stakeholder interaction activities, management of uncertainties, and monitoring. NEA's Forum on Stakeholder Confidence (FSC) attempts to elucidate experience in confidence building by "promoting open discussion across the entire spectrum of stakeholders in an atmosphere of trust and mutual respect" (OECD-NEA, 2002f). Confidence building and providing multiple lines of evidence are essential components supporting safety cases.

No clear mechanisms and criteria exist to date to determine quantitatively when an issue can be closed. One also needs to distinguish between site specific and generic aspects for which closure needs to be sought. While in practice closure of generic issues is indicated by diminishing numbers of new research proposals in the field, this may not be a sufficient criterion from a regulatory point of view. Notwithstanding the epistemological dimensions, in practice more quantitative guidelines can be derived from probabilistic performance assessment, whereby sensitivity analyses can demonstrate whether a more precise knowledge would improve the level of certainty in the safety case or not. From a harmonisation and stakeholder trust point of view, it would be desirable that the same level of confidence in scientific and technological knowledge be achieved at international level. The development of closing criteria and mechanisms is one of the open issues for the NEA and will be addressed in 2009.

There are quantitative (geo)statistical methods that can help to decide on the scope and extent of site investigation needed (cf. PAMINA, <http://www.ip-pamina.eu/>). However, there is also a considerable amount of expert judgement involved as

to when a site is understood well enough. The use of such non-quantitative methods and criteria is being critically reviewed in the context of the IGSC of the NEA. As each site is different, it would be difficult to develop generally applicable closing criteria. It is likely that closure of scientific issues will be an iterative procedure whereby a case is presented to the regulator/stakeholders once the implementer has enough confidence in the scientific findings and technical solutions to proceed. If not accepted by the regulator and/or stakeholders, a further round of refinement would be necessary. As far it concerns site-specific properties, this process is largely driven by the local regulatory and political situation and, hence, may have limited scope for harmonisation. Nevertheless guidance on how to proceed in generic terms might be helpful for those Member States that enter this phase. International fora and research projects help to define the state-of-art of generic scientific issues and whether they can be considered 'closed' for the purpose of the safety case.

Confidence is the result of trust in the implementing organisation. Trust is built by providing the assurance that the organisation is set up appropriately to meet the requirements and to cover all the relevant issues.

The use of natural analogues

Natural (and anthropogenic) analogues have been used for several decades in the development of process understanding and to test conceptual and process models (e.g. MILLER *et al.*, 2000; IAEA 1989, 1999f, 2005c). More recently the potential value of analogues for communicating with stakeholders has been recognised.

While in the early years the use of natural analogues concentrated on understanding and parameterising processes as such, in more recent years local and regional fluxes of natural (radioactive) geochemical constituents are being used to deduct information on long-distance and long-time migration phenomena (e.g. IAEA 2005a, in press; HELLMUTH *et al.*, 2007) and the long-term behaviour of the geological systems in general. For obvious reasons these phenomena are not accessible in another way.

Nevertheless, detailed process analogues continue to be studied under various programmes (e.g. IAEA

2005c). In these newer studies research focuses *inter alia* on how well the analogues actually represent the processes for which they are chosen.

It is expected that analogue studies will continue throughout the implementation phase and there will be various synergies with generic material flux and element cycling studies.

Monitoring

There is some confusion in the usage of the term ‘monitoring’, which sometimes is applied to certain phases of and activities under the site investigation process. Indeed, it can be difficult to discern between e.g. baseline environmental monitoring and site investigations, as the two would run concurrently.

Strictly speaking monitoring activities are carried out in order to confirm that individual natural or engineered system features or the system as a whole behave as expected. Thus in the early phases of implementation engineered systems may be monitored for their performance, e.g. for settling or the re-establishment of the natural hydraulic situation. Monitoring is particularly carried out during those phases of the implementation where there is still the possibility for intervention (e.g. OECD-NEA, 2005n).

(Environmental) monitoring is also carried out as a confidence building measure with a view to demonstrate to stakeholders that the disposal system performs as expected, for instance to demonstrate that no releases of radionuclides occur. While such monitoring can be hardly justified on scientific grounds, it can provide considerable reassurance to the public.

Long-term monitoring does provide considerable challenges for a variety of reasons: the probes have to perform over very long periods of time under very difficult conditions and without the possibility for maintenance or replacement. The necessary connections from the surface to metering equipment also must not provide preferential pathways for radionuclides. In other words the monitoring installations must not compromise safety functions. However, it forms an integral part of the licensing procedure in some countries. For instance, Switzerland plans to operate a special section of the repository as underground research laboratory for monitoring its performance.

In the context of phased repository implementation and delayed closure, for instance in the interest of retrievability, monitoring may become an important management measure. Here it has to be shown that the repository does not degrade prematurely and that the safety functions are not compromised by its prolonged open phase.

Monitoring has also been included in the current FP7 call for proposals. It will be also addressed, to a degree, in the upcoming NEA RWMC project on reversibility and retrievability. In addition a possible NEA IGSC workshop would focus on technological aspects and advancements in monitoring techniques.

Step-wise decision making

It becomes increasingly recognised that a step-wise decision making process that allows for review and modification or even reversal of previous decisions is likely to increase confidence into the overall project (OECD-NEA, 2004i). A step-by-step approach is also endorsed by the relevant draft IAEA Safety Requirements (Requirement 12; IAEA, in prep. f). While a step-wise approach has several benefits for both implementer and regulator, as it reduces the reliance on strict compliance with protection criteria at each step, it has also been accused of a sneaking approach to implementation without overall assurance of compliance, as in practice certain decisions are difficult to revert. Overall, a step-wise approach, however, will make the complex implementation process more tractable and therefore more transparent. Similar approaches are current practice in licensing complex projects, such as nuclear power stations. It should be noted that still a clear vision of the process, a ‘road map’, is needed right from the beginning.

A stepwise decision making process that can span several generations may be also seen in the ethical context of intergenerational equity. ***A step-by-step approach allows succeeding generations to modify decisions according to their expectations and needs, thus not prejudicing their freedom of choice.***

Continuing research

The notion that an issue can be closed for the purposes of building a safety case leading to a license application does not necessarily mean that research on this particular issue will stop completely.

It is just an indication that there is sufficient confidence to proceed. As science continues to develop in related and adjacent areas, an issue may need to be revisited taking into account these new scientific insights. This revision will help to decide, whether there is still enough confidence to further proceed with implementation in the chosen way, or whether the issue needs to be reopened. **Thus continuing research in particular areas that have been designated as 'closed' is not a sign of lack**

of understanding or confidence, but rather a confidence building measure. This message needs to be conveyed to stakeholders (OECD-NEA, 1999a). Continuing research also ensures that at any one time the best available technical solution is chosen and helps to increase safety margins by reducing uncertainties. Furthermore, continuing research in all relevant areas is necessary to train new generations of scientists, who will be working on the safety cases in decades to come.

8. Knowledge Management

Knowledge management has become a fashionable term, but it lacks a clear definition. It appears that three distinct, but related processes are covered by this term: first, the maintenance and preservation of knowledge within a particular organisation, i.e. corporate knowledge; secondly, preservation of scientific knowledge about processes and phenomena in general, with a view to prevent 're-inventing wheels'; lastly, the passing on of information about a specific repository to 'future' generations.

The issue of how knowledge about a repository site might (need to) be communicated to future generations has been debated in various fora extensively, but no final conclusions on the best way forward have been drawn. There are numerous examples from thousands of years of human history where people have left to posterity written or symbolic messages, but now we often cannot read them anymore or do not understand their meaning. Even in the case of symbols the effectiveness is rather questionable – who understands all the pictograms (e.g. for 'Exit', 'Elevator' and so on) that are so fashionable today? The same symbol may have different meanings in different cultures. All this does not instil a great deal of confidence in our capability to transfer knowledge intentionally beyond a few centuries and across significant cultural borders. Semiotics will have to go a long way to arrive at messages and symbols that are universally understood. An emerging and important way to preserve the knowledge about a site is by building an active and durable relationship between it and the hosting community (OECD-NEA 2007b; MAYS & PESCATORE, 2007).

Scientific knowledge appears to have a life cycle of around 10 years, when issues tend to be revisited. Driving force frequently is the rate of innovation in supporting technologies, for instance analytical techniques. Another driving force not to be ignored is the cycle of rejuvenation in academia. Thus we currently see significant numbers of researcher, who have driven the programmes over the past three decades, leave the field to retire, and at the same time scientific subject are being re-opened by younger generations. The problem of diminishing expertise is probably more acute in nuclear engineering and in waste treatment technology than in research into near- and far-field processes. In latter areas a strong cross-linking with the generic geo- and materials science community can be observed so that there is likely to be always a sufficiently large pool of expertise and knowledge.

Maintaining and preserving corporate knowledge can become an issue, if the time of active repository operation would be extended beyond a few decades perhaps (IAEA, 2007b). This type of knowledge preservation is not unique to nuclear waste management organisations. A variety of strategies have been developed for other industries that would be applicable in the present context. The concerns of knowledge management in the nuclear industry have been highlighted by a recent conference organised by the IAEA in conjunction with other major players in the field (<http://www-pub.iaea.org/MTCD/Meetings/Announcements.asp?ConfID=153>).

Additional references: IAEA (2001c, in prep c).

9. Other issues

Retrievability, reversibility and long-term storage

The draft IAEA Safety Requirements (IAEA, in prep. f) state that “Disposal refers to the emplacement of radioactive waste ... **with no intention of retrieving the waste**” (original emphasis). Recent discussions arising from considerations that range from resources conservation and re-utilisation concerns to concerns over our current ability to ensure long-term safety have started to question this paradigm (e.g. OECD-NEA, 2001e). However, the draft Safety Requirements insist that “No relaxation of safety standards or requirements could be allowed on the grounds that waste retrieval may be possible or facilitated by a particular provision. It would have to be assured that any such provision would not have an unacceptable adverse effect on safety or performance”.

Though not necessarily linked conceptually, the terms retrievability and reversibility are often mentioned together. Retrievability refers to technical and management measures that would allow to retrieve waste packages that have already been emplaced in a repository and possibly back-filled (IAEA, 2001a, in prep. g). Conversely, reversibility refers to measures and designs that ensure that each step of repository implementation can be retraced and different decisions taken. Thus reversibility may be an enabling element in stepwise decision making. There are various technical and management as well as political reasons why these two concepts have been brought onto the agenda, but the discussion of which is beyond the scope of the present report. The paradigm of ‘stepwise decision making and implementation’ was developed to reconcile some of the underlying concerns. The safety and sustainability of delaying disposal beyond operational needs is still being debated (IAEA, 2002b, 2003f, 2006d). NEA’s RWMC strongly advised against undue delays (OECD-NEA, 2008d) and the NEA plans to examine strategic and technical aspects of reversibility and retrievability.

These new demands and concepts can have potentially fundamental impacts on the safety case and repository design (IAEA, in prep. g). Most of the original concepts for geological disposal assumed more or less tacitly a comparatively short operational phase between the actual construction of a repository and its final closure; at least the filled parts of a repository would be backfilled and sealed as soon as possible. A repository designed for (easy) retrievability may in fact constitute an underground long-term storage facility. This can have a number of implications for the system performance and needs to be considered in the safety case. **It is important that the system is designed in a way that both, retrievability and reversibility options do not compromise a repository’s long-term safety.** It may be noted that the waste can be always retrieved by ‘mining’ techniques, albeit at significant cost and possibly risk to (underground) workers.

Advanced fuel cycles and partitioning & transmutation

Reactor systems and fuel cycles are under continuous development and new systems may entail wastes and hence waste forms different from those that arise from current nuclear energy systems. Reprocessing, partitioning and transmutation change the type and the amount of wastes that will have to be disposed of as well as the associated thermal loading (IAEA, 2004a, OECD-NEA, 2003a, 2005a, 2006j; EC project RED-IMPACT, <http://www.red-impact.proj.kth.se/>). This can have effects on the layout and operation of a repository. There is a certain inclination to adopt a delayed approach/long-term storage and/or options of retrievability in order to keep waste management options open so that one may eventually benefit from P&T or to accommodate wastes from new fuel cycles. **However, these developments should not be used as an excuse to delay implementation of waste management systems with geological disposal as the end-point for residual wastes** (OECD-NEA, 2008d).

10. Governance

Governance is the process whereby societies or organizations make important decisions, determine whom they involve and how they render account (PLUMTRE, 2006). An European Commission White Paper defined good governance as characterised by excellence, independence, transparency, participation and accountability (CEC, 2001).

A gradual shift from a purely technical to a socio-technical framing of the radioactive waste issue can be observed over the past decades (e.g. BERGMANS *et al.*, 2008). Major crises and events seem to lead to cross-national reactions, but it is striking that similar crises in RWM emerge in several countries in spite of international exchange of information and experience.

The importance of governance issues for the overall implementation process is reflected by a variety of past and current (<http://www.radwastegovernance.eu/>) projects that aim to elucidate the societal processes and to improve interaction between all stakeholders concerned:

TRUSTNET	http://www.trustnetinaction.com/
COWAM	http://www.cowam.org/
RISCOM II	http://www.karinta-konsult.se/RISCOM.htm
RISKGOV	http://www.riskgov.com/
CETRAD	http://www.grc.cf.ac.uk/cetrad/
OBRA	http://www.obraproject.eu/
ARGONA	http://www.argonaproject.eu/
CIP	http://www.cowam.com/spip.php?rubrique28
CARL	http://www.carl-research.org/

It is interesting to note in this context that little interaction between the natural science and social science communities has taken place in the past. Their main interface indeed has become the development of the safety case. Some activities, such as the Forum on Stakeholder Confidence (FSC; <http://www.nea.fr/html/rwm/fsc.html>) of the OECD-NEA feed directly into the process of developing the bases for safety cases (OECD-NEA, 2002f). COWAM in Practice (CIP; <http://www.cowam.com/spip.php?rubrique28>) brings together stakeholders from various horizons to perform collaborative research in five European countries, while ARGONA investigates how approaches of transparency and deliberation relate to each other and also how they relate to the political system in which decisions are ultimately taken. The project aims to study the role that is played by mediators who facilitate public engagement with nuclear waste management issues. Furthermore, the project investigates how well risk communication can be organized taking cultural aspects and different arenas of discourse into account.

Overall these projects indicate that certain lessons have been learnt in the larger context of radioactive waste management. It is now widely understood that appropriate governance processes have to be put in place so that desired final solutions in radioactive waste management can be brought closer to implementation.

Additional references: IAEA (2002c), OECD-NEA (2000,2002c-e,2003e,2003g,2003i-k, 2004a-b, 2004e-f,2004l-m,2005e,2005m,2006f-g, 2007b) VARI & PESCATORE (2007).

11. Conclusions and Recommendations

It can be observed that a certain level of maturity has been reached in many scientific and technical areas relevant to geological disposal. The term maturity means that those features, events and processes that are likely to be of importance have been identified. Maturity does not mean that all of these FEPs can now be sufficiently parameterised. Therefore, research continues and has to continue for some time. By its very nature, research is curiosity driven, but at the same time reflections are undertaken on what we really need to know at what

level of detail or precision. Such reflections and quantitative assessments are the subject of, for instance, the PAMINA project. It is envisaged that the results from this project will provide guidance on when we can proceed to actual implementation with sufficient technical and scientific confidence. The close scientific co-operation on a European and indeed world level ensures that all waste management programmes can draw on up-to-date scientific knowledge. An added benefit is that scientific work contributing to national waste disposal

programmes and that is published in scientific journals is automatically subject to a peer review process.

- ***Overall, it appears that our scientific understanding of most processes relevant to geological disposal is developed well enough to proceed with implementation in a step-wise fashion.***
- ***Scientific co-operation, e.g. through the Framework Programmes, ensures a Europe-wide harmonised level of scientific understanding. Such co-operation should continue to be supported.***

Given the conceptual and scientific maturity of geological disposal in principle, it would appear to be important to proceed to construction in those Member States that have sufficiently advanced the site selection programme. This step is needed to test in practice the paradigm of step-wise decision making. At the same time it allows the real-scale testing of the various scientific and technical hypotheses and proposed technologies.

- ***A real example will demonstrate that implementation of geological disposal is feasible. International support to national programmes that are far advanced are likely to have Europe-wide spin-off benefits.***
- ***For less advanced Member States and for those with more limited resources it would be beneficial to support the development of joint solutions, either in the form of shared repositories or in the form of sharing technology.***

The key element in moving towards implementation is the development of safety cases. A safety case is a structured presentation of the evidence, analyses, and lines of reasoning related to the long-term radiological safety of a radioactive waste repository.

- ***In the interest of confidence building in the process as such and among stakeholders, a harmonised strategy to the management of safety cases would be desirable. Support to the various harmonisation initiatives should continue.***

An important element in confidence building is interaction with stakeholders. Owing to major set-backs in some Member States on the road to

implementation, the importance of involving stakeholders in an effective way has been recognised. The objectives and means of effective stakeholder involvement are reasonably well-established for at least some socio-cultural contexts. However, certain scientific concepts are intrinsically difficult to communicate, most notably the concepts of probability and risk. As the Berne Conference (<http://www.icgr2007.org/>) and the NEA RWMC (OECD-NEA, 2008d) concluded, it is important and worthwhile to take the time necessary for an inclusive and rigorous process of stakeholder involvement. Both, the EC and the NEA are addressing this decisive issue explicitly. Within cultural limits, it seems to be important that the same concepts of governance be applied throughout the EU.

- ***The awareness of the need to involve all stakeholders in the decision making processes towards implementation of geological disposal is now high throughout Europe.***
- ***Experience on how to involve stakeholders in practice is still being built up.***
- ***Design and operational requirements (such as e.g. retrievability or access for monitoring) introduced through the public participation process may not compromise (long-term) safety.***

The regulator has the task to balance the needs and interests of the public and the implementers. The main objective of regulations is the protection of humans and of the environment from potential adverse effects ensuing from the chosen nuclear waste management solution. The ultima ratio in regulation is the respective national law, which has to be in place before any implementation can take place. A harmonised European regulatory framework could be of some advantage, but would be difficult to bring about, considering the diverse regulatory 'cultures' and that some Member State already have national regulations in place. Re-opening this process would certainly set back some national programmes and entail considerable expenditure.

- ***Mechanisms to demonstrate that regulatory objectives in the different Member States are comparable will help to increase confidence among all parties concerned. Respective Europe- and world-wide initiatives should be supported.***

- ***Mechanisms to demonstrate that Member States' regulations provide comparable protection might be a more efficient way forward than fully harmonised or unified regulations.***

One aspect of concern can be the question whether regulators in Member States are actually ready and capable to handle license applications. The application review process requires that adequate numbers of staff with an appropriate training are available. Enabling and resourcing regulators is likely to become an important task in the near future in some Member States and could become an obstacle to implementation, if not addressed in due time.

- ***The European Commission needs to ensure that National regulators are capable to perform the needed tasks. Joint programmes between the international organisations aimed at enabling the regulators in less advanced countries would help to reach an adequate level of preparedness in all Member States.***

There is a considerable overlap between the constituencies of the EC, NEA and IAEA. All EU and NEA Member States are members of the IAEA, while the majority of EU Member States are in turn also members of the NEA. While for this reason an overlap in the interests and working areas between the three organisations can be expected, in practice the mandate and working practices are quite different.

The EC, unlike the other two organisations, has legislative powers (right of initiative) and EU 'Directives' have to be implemented in national legislation. In its role as defender of the Treaties, the EC has executive powers that can be exercised e.g. via sanctions. The EC also has considerable

financial means that can be used to fund targeted research. Many important nuclear waste disposal R&D projects have been co-funded over the past decades by the Euratom Framework Programmes.

The IAEA is formulating technical guidance and regulatory guidance based on consensus. In addition, Member States may subject themselves voluntarily to binding agreements, such as the 'Joint Convention' (IAEA, 1997d) for which the IAEA provides the secretariat. IAEA guidance is frequently used to inform and in drafting national guidance and (binding) legislation. However, the IAEA does not have executive powers and non-compliance can only be sanctioned by publicly exposing the culprit. The IAEA has limited amounts of funds that can be used to stimulate research in particular areas for instance in the form of 'Co-ordinated Research Projects' and to provide seed money for joint projects funded by national means.

The NEA provides more of a forum of exchange and a 'think tank'. It does not issue documents that are intended to inform or draft national regulation or guidance documents, but rather documents that intend to conceptualise the issues under discussion. These issues can be of scientific, technical, governance or regulatory nature. The NEA does not have any research budget of its own, but solicits voluntary contributions from interested parties in member states to fund targeted research.

- ***Thus the de facto roles of the EC can be seen as providing the policy framework and R&D funding, of the IAEA as providing regulatory and technological guidance, and of the NEA as compiling and analysing national experiences in terms of strategic principles and scientific and societal aspects of implementation.***

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Abstract

The present report reviews the current state of science and technology that form the basis for implementing geological repositories for high-level nuclear waste and spent nuclear fuel. It is concluded that enough is known about the relevant natural and man-made systems to proceed with a step-wise implementation. The scope for harmonisation of procedures and regulations on a European level is investigated. Public acceptance of the scientifically preferred solution of deep disposal is still low in many European countries and more needs to be done to involve stakeholders in decision making processes in a meaningful way. It also needs to be ensured that national regulators are enabled to adequately process license applications for deep repositories.

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