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Geological Disposal of Radioactive Wastes Produced by Nuclear Power

... from concept to implementation

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Geological Disposal of Radioactive Wastes Produced by Nuclear Power

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Preface

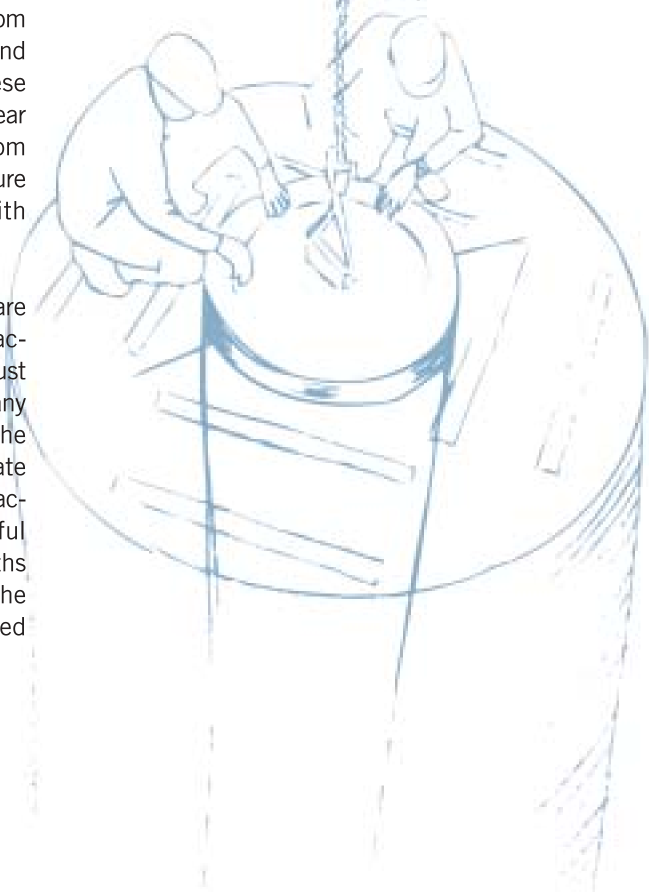
Secure electricity supply is one of the most vital requirements of modern life. Like all human activities in the developed world, the production of our electricity generates wastes – although less than 5% of the total volume of waste that society generates every year. In the European Union, we generate about 35% of our electricity from nuclear energy, although this has historically only produced about 0.05% by volume of our power production wastes. Like all wastes, those from the nuclear industry have to be managed responsibly. The scale of their potential environmental and health hazard varies considerably, in the same way as for wastes from other industrial activities, such as the manufacture of chemicals. A very small proportion of radioactive wastes are extremely hazardous, compared with almost all other industrial wastes, and require very special provisions to ensure their safe and secure management.

We also produce radioactive wastes in hospitals – from diagnosis and treatment of the sick; in universities – from vital research in biology, chemistry and engineering – and from many types of industry. The amounts of these wastes are much smaller than those produced by nuclear power generation. We all derive immense benefits from the use of radioactivity and it is our responsibility to future generations to manage the wastes we produce with both our own and their safety in mind.

The radioactive materials that we use in everyday life are all derived, directly or indirectly, from natural radioactive minerals that we mine from the rocks of Earth's crust – we live in a naturally radioactive environment. For many years, since the development of nuclear power in the 1950s, it has been proposed that the most appropriate and natural way of dealing permanently with our radioactive wastes is to return them to the ground. Careful burial in well-engineered 'repositories' at various depths below the land surface at specially selected sites is the favoured solution in every country that has decided how to handle the problem.

Burial at several hundreds of metres depth in stable rock environments – so-called 'geological disposal' – is the option for disposal of the most hazardous radioactive wastes because it will provide permanent safety – not just for ourselves, but for future times very much longer than the whole of past human history. Although we currently store all our wastes safely and make every effort to minimise the amount of radioactive waste that we produce – and Europe is researching ways of making further reductions – it is inevitable that there will always remain some wastes that have to be disposed of deep underground.

The European Union has been researching geological disposal for almost 30 years and is on the verge of constructing its first deep repositories. This document explains the current status of development and highlights in particular the achievements of the most recent Euratom work in the Fifth Framework Programme.



Radioactive wastes from nuclear power production

The vast majority of Europe's radioactive wastes come from nuclear power production. They fall into three main groups:

- spent fuel (SF) removed from nuclear reactors after its useful life;
- high-level waste (HLW) residues from reprocessing spent fuel;
- intermediate-level waste (ILW), mainly from power reactor operations and from reprocessing.

Most reactor fuel is in the form of fuel elements comprising pellets of ceramic uranium dioxide sealed into thin metal tubes, a number of which are bundled together in a fuel assembly. After it has been involved in the nuclear fission process, the fuel becomes intensely radioactive as a result of the formation of new radionuclides – mainly 'fission products'. The build-up of fission products in the fuel reduces its efficiency. After a few years, it must be removed from the reactor and replaced. After removal from a reactor, one or more spent fuel assemblies will be sealed into a metal container for emplacement in a repository.

HLW originates as a liquid residue from reprocessing SF to extract uranium and plutonium for reuse. The liquid contains most of the radioactivity from the original SF. It is evaporated and the dry residue containing the radionuclides is melted with a much larger volume of inert glass-forming material to produce a homogeneous, solid, vitreous waste form. The glass is cast in stainless steel containers that are sealed and may be placed in a further metal container for emplacement in a repository.

ILW arises principally from reactor operations, from reprocessing SF (e.g. the metal tubes that contained the fuel, and other parts of fuel elements) and from decommissioning nuclear facilities. ILW is generally embedded in a matrix of cement or bitumen inside steel or concrete drums or boxes, to produce monolithic waste packages for disposal.

Apart from developing disposal options, Euratom is also researching the potential to reduce the amounts of some of the longest-lived radionuclides in some of these wastes. This involves chemical separation of these radionuclides followed by nuclear transmutation in particle accelerators or nuclear reactors. This is a very long-term research programme. If it proves economically and technically possible to implement, it will require continued access to nuclear power facilities and it will not remove the requirement for geological disposal.


(Courtesy SKB)


(Courtesy BNFL)


(Courtesy BNFL)

Cutaway illustrations of (top) spent fuel in a copper container – about 5 m long; (centre) vitrified HLW in a stainless steel container (about 1 m long); and (bottom) a 500-litre stainless steel drum of ILW fragments embedded in a cement matrix. The pictures are not to scale.

Introduction

Geological disposal of radioactive wastes is based on the principle that the deep rock environment is stable and largely unaffected by environmental change for hundreds of thousands – even millions of years – times that are longer than those since the appearance of modern humans in Africa and their spread across the globe, during and after the last ice age. Materials that are carefully emplaced deep underground will be well isolated from people and the environment in which we live (see Box 1).

Unlike many of our other industrial waste products, radioactive wastes have a useful characteristic. Their hazard progressively decreases by natural processes of radioactive decay – the very mechanism that makes radioactivity useful in the first place. As a result, many of the radioactive isotopes (radionuclides) in our wastes will decay to a few millionths of their original activity over the first few thousand years after burial and they will present no future hazard. Even for the most hazardous wastes, it is estimated that more than 99.9% of their original activity will never escape from a repository.

In the far distant future, only the most long-lived (that is, weakly decaying) and mobile radionuclides will be able to move out into the rock by natural processes. These will be diluted and dispersed by the slow movement of groundwaters in fractures and pores deep in the rock, and their presence will be lost among the natural variability of Earth's radiation 'background'. Essentially, in the far distant future, geological disposal returns a small, residual amount of radioactivity back to nature. *How can we know this?*

The science and technology of geological disposal originated and has grown over the last decades – about the last 25 to 30 years in Europe (see Box 2). There has been an energetic international effort to develop and research the concept. It is aimed at designing repository systems that will provide good containment, at identifying the right types of geological environment in which to locate them, and at evaluating how the radionuclides will behave over long periods of time in the future.

All of this information is brought together in models of the future evolution of repositories that indicate how each barrier will behave (called 'performance assessment') over thousands of years. The overall long-term safety of a repository is determined in part from such assessments, but also by more readily understandable analogies drawn from the observable behaviour of natural geological systems and materials over equivalent periods of time.

Repositories must be practical and effective (see Box 3). It is essential that they can be built, operated and closed using robust, secure technology. Most of all, scientists and technologists must be able to show with confidence that the radioactivity will be adequately contained and that the disposal system will function as intended for immensely long periods of time. They must be able to explain convincingly why there is scientific and technical confidence in safety, both today and in the far future.

This last topic is vitally important. Our society, which has benefited from the use of radioactivity, has to make decisions about how to handle the wastes it has produced. In our developed social structures, people want to be involved in the decision-making process so we need to be informed and to understand the issues well.

The European Commission began funding basic R&D into geological disposal in the early 1970s and, in 1975, started to foster co-operation between European laboratories and institutions and help develop concepts suitable for the wastes and the natural environments of Europe. There has been almost 30 years of Commission-supported work since then (see Box 4), the most recent being within the Commission's Fifth Framework Programme (FP5), a five-year, highly co-ordinated exercise that was completed in early 2004. During this time, many questions have been raised and answered and a mature scientific and engineering basis has evolved.

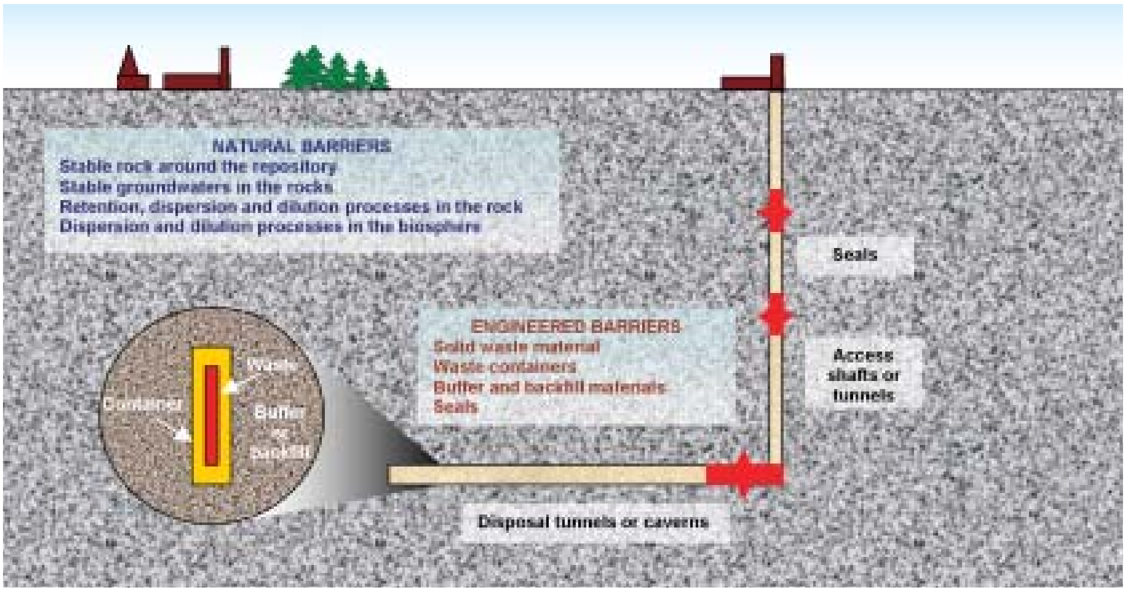
This document summarises and puts into context the achievements of the FP5 work and evaluates the scientific and technical status of geological disposal today. The European Union moved to enlargement in mid-2004, with five more countries joining the nine that already require geological disposal facilities for nuclear power production wastes. The first European geological repositories, in Sweden and Finland, will be close to construction around 2010-2015 – making the European Union and the USA the most advanced programmes in the world. We conclude by looking forward to the support and integration work that will lead up to this point, in the Sixth Framework Programme (2004-2006).

BOX 1: Geological repositories

Geological disposal is based on the concept of multiple barriers that work together to provide containment. The barrier concept prevents deep groundwaters, present in almost all rock formations, from rapidly leaching the wastes and transporting radioactivity away from the repository. There are both 'engineered barriers' that are constructed in the repository and 'natural barriers' in the surrounding geological environment. For disposal in hard rocks and clays, the basic engineered barrier components are the solid waste, its container (usually metal and often multi-layered), and a buffer or backfill material (clay or cement) that fills the space between the container and the rock. In salt formations, where there is no groundwater, the buffer is replaced by crushed salt. The natural barrier is provided by the rocks and soils between the repository and Earth's surface.

These barriers work together to provide containment and safety:

- the container protects the waste and prevents any water reaching it for at least several hundred years and, in some concepts, for tens or even a hundred thousand years – by this time, most activity will have decayed inside the waste matrix;
- the buffer protects the container, preventing water from flowing around it and absorbing any mechanical disturbance that might be caused by future deep-earth movements (associated with major earthquakes) – if it is highly impermeable, such as clay, it also contains any radionuclides that eventually escape from the container;
- the rock and the geological environment of the repository provide stable mechanical, chemical and water flow conditions around the engineered barriers for very long times, allowing them to contain radionuclides for much longer than if they were left at Earth's surface – this 'cocoon' effect is due to the very slow rate of natural processes at depth;
- the rocks, soils and waters around and above the repository slow down, or completely immobilise, and dilute and disperse any eventual releases of activity so that they do not cause a hazard in the natural environment.



BOX 2: The development of geological disposal

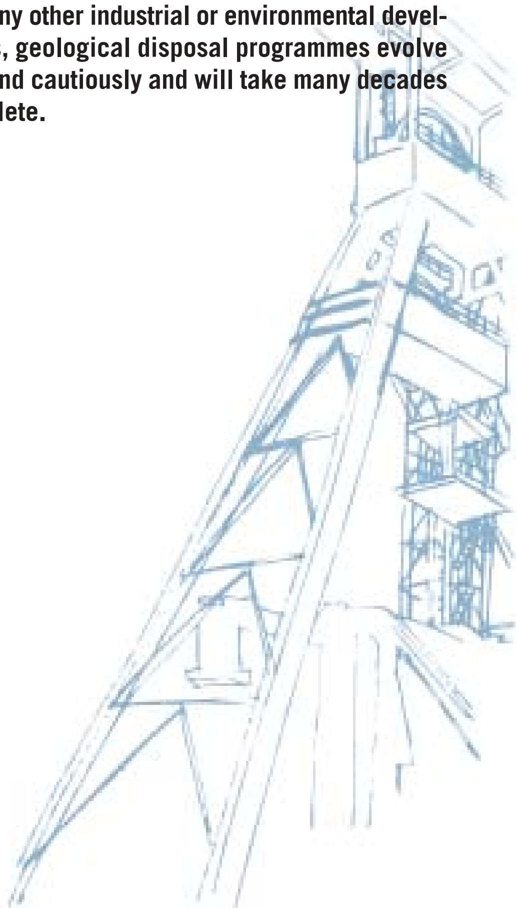
The earliest work on geological disposal originates from the USA in the 1950s and 1960s, when deep salt formations were first considered as host rocks in which to build waste repositories. Rock salt provides a dry environment for construction and operation underground, easily conducts heat away from the waste and is impermeable to groundwater that could leach the wastes. Whilst there were limited practical tests of the properties of such environments in the USA, the first concerted work internationally only began in the 1970s. In 1975, the EC commissioned work to identify potentially suitable rock formations in Europe, producing an atlas of hard igneous and metamorphic rocks (such as granite and gneiss), clay-rich rocks and salt formations that might be considered for disposal. All were identified for their stability, low permeability and good containment properties.

Since then, work has been focused around these three geological environments. The European countries involved in disposal R&D have opted to look at one or more of them, depending on their national geological conditions. Each country has developed its own active research and development programme, with elements of the work partially supported by the European Commission – first acting to promote studies and then to integrate them.

Basic R&D in the field and in the laboratory has been augmented by practical tests and experiments in specially constructed underground facilities that have operated for more than 20 years. The practical implementation of disposal has, however, been slow, owing to the political and social problems associated with selecting repository sites. This stems from a widespread fear of radioactivity and nuclear energy, arising from their association with nuclear weapons and compounded by the long period of innate secrecy of the nuclear industry, from which it is only just emerging. This atmosphere was prevalent throughout the 1980s and 1990s. Now, the first national repository programmes to have overcome these setbacks (Sweden and Finland) have narrowed down to potential repository sites and hope to begin construction in the next ten years.

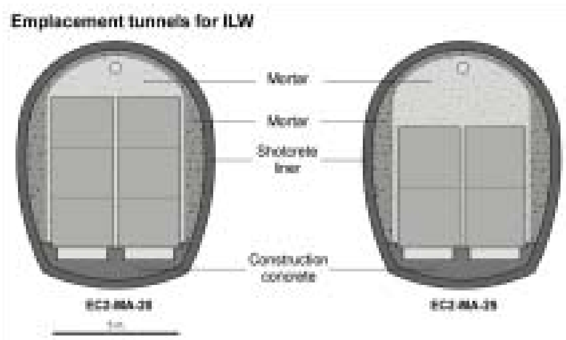
The steps from concept to implementation will thus have taken many decades and the further operational steps leading to final closure of geological repositories are expected to take at least as long.

Unlike any other industrial or environmental developments, geological disposal programmes evolve slowly and cautiously and will take many decades to complete.

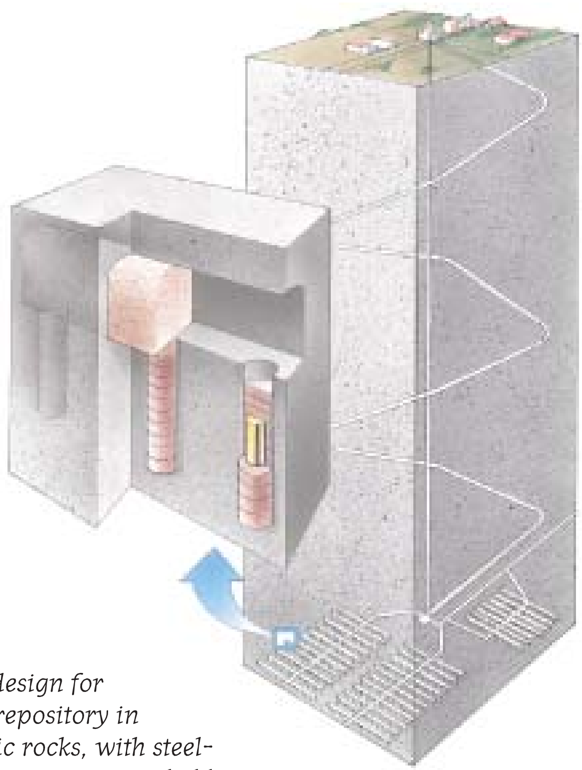


BOX 3: What will geological repositories look like?

The multi-barrier design of a geological repository reflects the types of waste to be contained and the nature of the geological environment. The two fundamental designs that are being widely developed involve large, often concrete-lined caverns for large packages of intermediate-level wastes and narrow tunnels or boreholes for canisters of the more radioactive high-level wastes, which also emit heat for some hundreds of years after they are buried. The illustrations show examples of these basic designs.



Cross-section of a typical conceptual design for a repository for large-volume containers of ILW using concrete-lined caverns (courtesy Nagra).



Conceptual design for a spent fuel repository in hard, granitic rocks, with steel-copper containers surrounded by compacted bentonite clay (courtesy SKB).

BOX 4: The development of R&D in the EC

Euratom began work on geological disposal in 1975. The EC shares the costs of work with EU Member States and organises work in programmes that normally last about five years. The earliest work focused on identifying potentially suitable geological formations in Europe. Since 1979, work has effectively fallen into two main categories: scientific and technical studies on the long-term safety of disposal – which has involved an extremely diverse range of projects – and experimental and engineering work that is carried out in underground laboratories, such as the Asse salt mine in Germany and the Mol facility in clay in Belgium, in support of design and safety studies. Through agreements with non-EU countries, work has also been carried out in other underground facilities (e.g. in Switzerland) and there has been a long and profitable scientific exchange with Canada, Japan, Switzerland and the USA, among others.

Working together in EC programmes has provided tremendous added value by bringing together numerous academic and professional scientists, waste disposal organisations and regulatory agencies, and the involvement of the EC has resulted in wide and efficient dissemination of results to all end-users. The two most recent R&D programmes (Fourth and Fifith Framework Programmes: 1994 – 2002) saw the evolution of the original concept of co-ordination of national activities, which had driven earlier programmes. Today, as the geological disposal concept moves to maturity and implementation, the emphasis is very much on integration of efforts in order to rationalise and optimise solutions that can be achieved in Europe.

To this end, current programmes are built around 'Thematic Networks' which bring expertise from many countries together to work on common 'Integrated Projects'. The EC also launched Cluster (Club of Underground Storage Testing and Research facilities for underground waste disposal). Groups and networks working on related issues have been brought together in Cluster workshops – for example, on all types of underground laboratory activity (at a conference in Belgium in September 2001), and on the topical issue of excavation disturbance to the rock (at a conference in Luxembourg in November 2003). These organisational structures will form the core of FP6, which takes the programme through until 2006.

Themes and achievements of FP5

Building on the logical breakdown of work in FP4 and earlier programmes, the principal achievements of FP5 can best be explored under the following thematic headings:

- Development of repository technology
- Long-term behaviour of wastes and containers
- Groundwater and radionuclide movement around repositories
- Safety assessment of geological disposal
- Public Involvement in repository programmes

The following section highlights the main achievements in each of these themes and more detail is provided in the boxes on each topic.

Development of repository technology

As we move closer to the construction of repositories, a key theme has been the large-scale testing and demonstration of the technologies that will need to be deployed in a few years time. Until recently, repository designs were essentially concepts on paper – plans and layouts showing how the wastes and the barriers can be arranged to provide the required performance. These had served for identifying the processes that control rock and materials behaviour and as a basis for designing experiments in underground laboratories, but there had been relatively few projects aimed at testing the practical feasibility of handling the engineered components under realistic repository conditions.

The Prototype Repository Project, carried out in Sweden, was the first full-scale demonstration and test of the machinery that would be used for placing waste containers and the surrounding bentonite clay buffer vertically in boreholes, in the floor of disposal tunnels in hard rocks such as granite. In hard rocks, the disposal concept involves a durable metal waste container (copper and steel in this project) surrounded by pre- manufactured (blocks) or *in-situ* compacted bentonite to form the buffer. As the buffer slowly absorbs water naturally present in the rock, it swells and, after some decades, seals the container permanently from contact with the slowly moving groundwaters.

A major 'prototype repository' project in Sweden has tested the engineering methods needed to place full-scale model spent fuel containers into disposal locations in a deep underground laboratory in granite – a dummy (non-radioactive) copper container can be seen being rotated for emplacement in a disposal hole in the floor of a tunnel (courtesy SKB).

A related project, carried out in an underground laboratory in Switzerland, simulated the horizontal emplacement of waste containers and the clay buffer along the axis of disposal tunnels. This closely instrumented test also reproduced the heating of the buffer and the rock that will be caused by the radioactive decay of waste and looked at the way the buffer absorbs water from the rock. It was possible to test and to begin

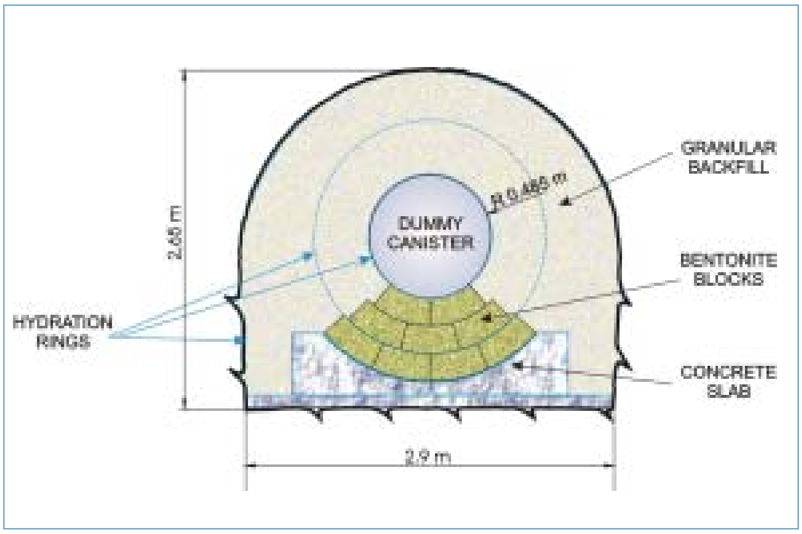
Pictures of a heater, inserted inside highly compacted bentonite clay blocks in a 2.5 m diameter tunnel in granite before and after their heating. This full-scale test of heat and water movement has been used to simulate the period immediately after a waste container and its clay buffer are emplaced in a repository (courtesy ENRESA).

to validate, under realistic disposal conditions, the mathematical models used to predict how these processes occur.

In clay repositories, the buffer material will comprise bentonite clay pellets, rather than blocks. An equivalent full-scale test in an underground laboratory in clay in Switzerland evaluated the mechanical procedures for emplacing the buffer. After artificially accelerating the uptake of water by the pellets – it would take many hundreds of years for water to enter the engineered barriers in this very dry rock – it was possible to examine the isolation and barrier properties of the final clay mass

Important practical lessons were learned in each of these three projects about how to handle materials and engineered barrier components under deep underground conditions. In a repository, the operators will need to be able to adapt to working routinely in restricted space, under natural temperature and humidity conditions. Eventually, it will also be necessary to perform demonstrations of how to handle fully radioactive waste containers remotely.

A heated, dummy waste container being emplaced into a tunnel in clay, where it will be surrounded by pelletised bentonite clay buffer material. The container is initially supported on blocks of compacted bentonite (courtesy ENRESA).



An important factor in the long-term behaviour of a repository is the disturbance of the rock around waste disposal tunnels and boreholes by the excavation method – the 'excavation disturbed zone' (EDZ), which could include the formation of small, open fractures. Typically, civil engineers use drill-and-blast in hard rocks, mechanical excavation in softer rocks such as clays, or tunnel-boring machines (TBMs) in any rock with reasonable strength. A disturbed zone could affect how water moves around the engineered barriers. It was recognised that TBMs cause the least disturbance in hard rocks, but there was limited knowledge about the EDZ in clays, where it was believed that the plastic or swelling nature of the rock could cause disturbances to heal naturally. Such healing has now been observed under a range of conditions and appropriate mathematical and physical rules developed to describe it.

BOX 5: Key repository technology achievements

- Full-scale testing of high-precision drilling for container deposition holes in granite.
- Demonstration of full-scale, inactive canister and bentonite clay buffer emplacement.
- Emplacement of bentonite clay tunnel backfill above deposition holes with high homogeneity and density.
- Industrial-scale manufacture of preformed blocks of clay buffer material of the quality needed for waste disposal and full-scale testing of bentonite pellet emplacement.
- Full-scale emplacement of clay and concrete shaft seals.
- Validation of models used to predict the thermo-hydro-geochemical and mechanical development of the clay buffer at large-scale under simulated disposal conditions.
- Acoustic emission tests of self-healing in clays as water enters open fractures caused by excavation disturbance.
- Simulation of excavation disturbance healing around tunnels in clay caused by swelling back-fill material and observation of natural healing with time after excavation, even in open tunnels.
- Testing models for salt deformation around heated waste containers at full-scale, over eight years, confirming earlier laboratory tests.
- Long-term tests on instrumentation used in salt, allowing development of operational monitoring systems for repositories.

As a result of these large-scale tests under real conditions, repository designers and engineers are now increasingly able to develop operational plans for repositories that can be refined over the years before construction work begins.

Repositories will remain open for many decades as waste is emplaced – possibly even long afterwards if society decides that it wishes to maintain an option to monitor the waste disposal zone directly or to be able more easily to retrieve them for some purpose (see Box 5). Prolonged exposure of the disposal and access tunnels to the atmosphere could also disturb the rock properties, especially in clays, which are prone to drying. This effect has now been examined in detail by accelerated ventilation of a test tunnel in the Swiss underground laboratory in clay.

Like some clays, rock salt also tends to creep and heal naturally. Since 1990, a full-scale experiment had been carried out in a salt mine in Germany, using six inactive, but electrically heated waste containers, each weighing 65 tonnes. The disposal tunnel around the simulated containers had been filled with crushed rock salt and the natural creep of the host rock had sealed the containers into place. After eight years, the whole system was excavated and the material properties studied, allowing good validation of many of the predictions made about the development of the salt properties over time.

A long-term test of the behaviour of a non-radioactive, simulated high-level waste container in an experimental gallery in a mine in a deep salt formation in Germany. The container can be seen as crushed rock salt is being excavated from around it, after the test (courtesy DBE).

Eventually, repositories will have to be closed and sealed. Although this is still many decades into the future, underground tests have already been under way for some years to begin evaluating appropriate designs for seals, especially for the access shafts from the surface to the repository. Full-scale bentonite clay and concrete seals have been emplaced in an experimental shaft in an underground laboratory in clay in Belgium. The work has tested the development of seal properties that aim to prevent water movement in and around the seal zone. An important factor was the removal of the shaft support system – temporary engineering intended for the operational period of the repository – so as to ensure a good seal directly with the surrounding rock.

One of the common advances made in all of the tests of repository technology has been in the field of instrumentation to measure a wide range of rock and material properties. Instruments need to be able to operate for long periods, sometimes in adverse conditions of high temperatures or aggressive chemistry. Advanced, fibre-optic techniques for data transmission underground have been developed and tested within the current programme.

Much has been learned that will be useful when considering how to monitor real repositories through their operational lives and beyond. A Thematic Network on monitoring began to look at technical and societal requirements for such activities – a truly cross-cutting issue where there are diverse views on what is needed and how and when monitoring data could be used. This is closely linked to the whole issue of 'phasing' repository development so as to establish a broad consensus of confidence before moving from one step of disposal to the next (see Box 6).

BOX 6: Phased repository development

Because repository development programmes will take many decades from inception to completion, it is important that they are robust and responsive enough to whether the ever-changing backdrop of social and political change, scientific and technological development and the inevitable turnover of expert staff and decision-makers as the years pass. We will not be involved in many of the key, but distant decisions that need to be taken before a repository is closed.

This has led to the concept of 'phasing' or 'staging' in which the programme is broken into manageable steps that can be completed and handed along with confidence to future generations, while leaving them able to modify decisions taken today if they so wish. Each phase should enhance the overall safety and security of the wastes. Some of the questions that arise in phasing, and which are being addressed by networks within the EC programmes, are:

- how long should we store wastes before taking them underground and can we do this securely?
- can the option to retrieve wastes be incorporated into designs without affecting their isolation performance?
- how long can a repository remain open for inspection of the disposal zone and can it be readily closed?
- can and should specific repositories be flexible to adapt to changing rates and amounts of waste production over future decades?
- what type of monitoring of the repository and its environment should be carried out, and when?
- how can monitoring contribute towards understanding and how can the results be used?
- what type of surveillance may be required to ensure the permanent security of disposed nuclear materials?

Many of these issues are philosophical in nature, but each has a practical implication. In many cases, there is no requirement to reach decisions today, but we must all be aware that choices will always exist and it is our responsibility to be aware of them and be prepared to make decisions when required.

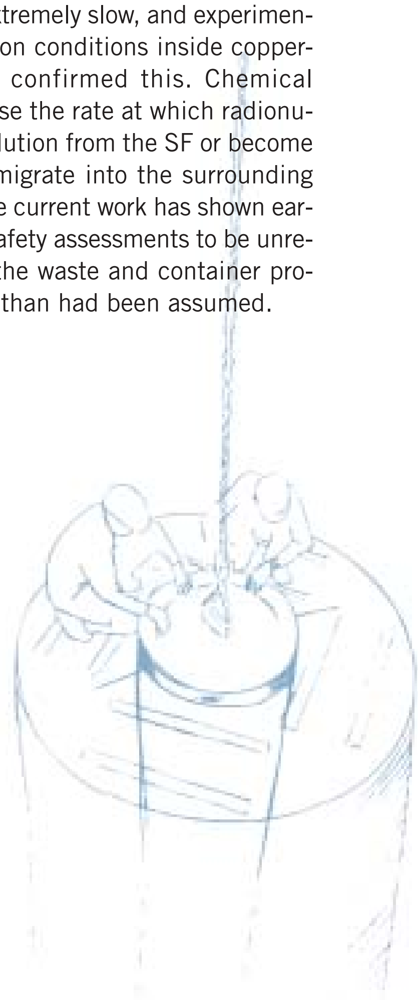
Long-term behaviour of wastes and containers

Europe's most highly active radioactive wastes destined for geological disposal comprise spent fuel (SF), taken from power reactors and stored to cool for several decades before disposal, and vitrified high-level wastes (HLW) from reprocessing spent fuel to extract reuseable uranium and plutonium. SF comprises uranium oxide fuel elements that contain accumulations of highly active fission product radionuclides. HLW consists of the same radionuclides that have been separated from the uranium oxide and incorporated into a solid glass matrix.

Euratom's earliest work in the 1970s and 1980s was on characterising HLW and how it will behave in a repository. This work is essentially complete and a solid understanding is now in place. Only limited studies continue to refine some of the chemical data on how radionuclides are slowly leached from glass in contact with groundwaters. The emphasis today is on fully integrated studies of how all the material and chemical components in and around the waste will interact over long times. The results enable many of the earlier conservatisms on radionuclide leaching to be removed – glass is a very durable material under disposal conditions.

The corrosion rate of the metal waste containers controls the time of first release of radionuclides into the surrounding engineered barriers. The rate depends on the type of metal used – some concepts place little weight on the container as a barrier and use relatively short-lived materials such as iron and steel, while others utilise very resistant metals such as copper and titanium. These two conceptual approaches to the role of the container in the multibarrier system are called respectively 'corrosion allowance' and 'corrosion resistance'. The mechanism of corrosion – general, localised or cracking as result of stresses in the metal – as well as the chemistry of the porewaters around the container, are also critical factors. FP5 continued to examine metal corrosion, focusing in particular on the behaviour of a wide range of possible container metals in saline waters that are present in many deep geological environments. There is now so much information available that this work is able to make state-of-the-art recommendations for the most appropriate container materials for use in salt, clay and granite repository rocks.

Once containers are breached by corrosion, the SF or HLW can also be corroded or dissolved by porewaters that penetrate inwards from the surrounding rock and the engineered barriers. This may take thousands, even tens of thousands of years to initiate. The chemical conditions inside a breached waste container are complex, being controlled by the salinity and oxidising capacity of the water, the products of metal corrosion and the radiation from the waste. Waste corrosion – especially SF breakdown – is extremely slow, and experimental work in the laboratory on conditions inside copper-steel SF containers has confirmed this. Chemical conditions tend to minimise the rate at which radionuclides are released into solution from the SF or become mobile so that they can migrate into the surrounding buffer material. In fact, the current work has shown earlier assumptions used in safety assessments to be unrealistically conservative – the waste and container provide much better barriers than had been assumed.



BOX 7: Key achievements in waste and container behaviour

- Improved understanding of how glass alteration products themselves act to adsorb, precipitate and thus help immobilise radionuclides leached from the glass by groundwaters and pore waters in the repository.

- Validation of complete resistance of titanium-palladium container materials to localised and stress corrosion in brines, as well as its negligible general corrosion rate (0.2μm/year).

- Confirmation of suitable 'corrosion allowance' canister materials with high pitting corrosion resistance for use in salt – such as TStE 355 carbon steel; of the suitability of Hastelloy C-22, copper and copper-nickel alloys and carbon steel for disposal in granites with bentonite buffers; of chromium-nickel steels as the most promising container material for repositories in clay.

- State-of-the-art recommendations on the most appropriate container materials for different geological disposal environments.

- Experimental confirmation of extremely low dissolution rates of spent fuel under realistic conditions replicating those inside corroded copper-steel containers – much lower than values that had been used in safety assessments to date.

- Confirmation that the chemically reducing conditions inside copper-steel waste containers will considerably reduce the mobility of uranium and neptunium released from corroding spent fuel, before they can leave the container – again reducing the conservatively calculated impacts of previous safety assessments.

Spent fuel and HLW are extremely stable materials and will remain so in the deep, stable environment provided by geological disposal. As a result of many years of study, their properties and behaviour are well understood. We have a range of suitable metals in which to contain them so that they can be deposited and isolated inside the buffer and the rock of a deep repository.

Groundwater and radionuclide movement around repositories

Radionuclides that move slowly out of the degraded engineered barriers may become mobile in groundwaters in the rocks surrounding the repository. How they move through fractures and pores in the rock and are slowed down or immobilised by interaction with the minerals in the rocks has been extensively studied for many years. The root of understanding the 'transport' process is to be able first to estimate the movement of water through the rock, then to superimpose the chemical behaviour of the radionuclides as they interact.

FP5 focused its transport studies on fractured hard rocks, such as granite. Both water flow and radionuclide transport in this environment are now well understood and one of the remaining challenges is to be able to capture the natural variability of these processes in models and in field measurements. Whilst we can already do this conservatively enough for safety assessments (see later), it is recognised that increasing field data and progressive advances in science will enable us to do this more accurately and realistically as the years go by.

The water in deep geological environments often displays high salinities that reflect the 'age' of the water, or how long it has been present in the rock and interacting with it. Saline waters are dense, which tends to make them less mobile, and most deep environments contain heterogeneous bodies of water of different chemistry, age and origin. Our ability to model groundwater flow and to relate it to water chemistry needs to be tested by looking at these natural flow systems, because they have operated for very long time periods – similar to those we are concerned with for waste containment. This type of study involves looking at the distribution of water of different composition in large volumes of rock –

typically over tens of square kilometres and down to one or two kilometres depth – the scale of a repository site. Detailed chemical and natural isotope measurements of the waters and the rock minerals tell us much about how long water has resided in the rock, where it came from and how stable the flow system would be if a repository were to be placed at depth.

Water chemistry controls how radionuclides behave in deep groundwaters – whether they are in solution in organic or inorganic form and whether they can attach themselves to tiny colloid particles. Much work in FP5 has focused on what controls the behaviour of the actinide series radionuclides (such as plutonium, neptunium and americium), as well as the most mobile radionuclides, such as radioactive iodine. New analytical techniques are providing ever increasing understanding, and the improved databases, combined with integrated reactive transport and geochemical evolution models, should progressively reduce the conservatism with which we frequently model many aspects of radionuclide movement.

All of this information and modelling can be tested using 'case studies'. Two exercises have been completed recently – one looking at the organic chemistry of actinide radionuclides in the pore water environment of the boom clay in Belgium, a potential repository host rock, the other at historically contaminated deep environments in Russia. This latter project examined evidence for the mobility of mainly shorter-lived radionuclides that had been injected deep into the ground as liquid waste – a practice that would not be accepted today in Europe. Nevertheless, the sites provided a useful insight into transport and retention processes.

BOX 8: Key achievements in groundwater and radionuclide movement

- Significant gaps in the thermodynamic database for the tetravalent actinides were filled, and understanding of their complexation with organic species much improved.
- Molecular scale modelling and quantum chemical tools applied for the first time to evaluate the coordination chemistry of actinides in natural waters.
- New X-ray spectroscopic techniques used to look in great detail at mineral surface sorption of actinides.
- Increased understanding of the important role of mineralisation (e.g. in cement degradation products) in fixing radionuclides inside the repository barriers.
- Demonstration of the large-scale barrier effect of thick clay layers in preventing radionuclide migration at depth in a contaminated site.
- Demonstration of the immobility of uranium colloids in a clay formation as a result of ultrafiltration.
- Detailed characterisation of americium colloid instability and americium interaction with organic complexants in clay.
- Broad agreement between performance assessment modellers and experimental and observational scientists on the current 'fitness for purpose' of the representation of transport processes in safety assessments – including identification of 'closed' and low-relevance issues/processes and areas where representation can and will be improved in future.
- Identification of ways to move forward with integrated reactive pathway evaluation linked with time-dependent geochemical evolution – giving more realism to performance assessments and allowing a reduction in conservatism.

Our understanding of the most important aspects of radionuclide chemistry in natural waters continues to improve and we are filling important gaps where there have been questions for many years – the key example being colloid behaviour. New analytical techniques will provide ever-increasing detail in our knowledge and realism to our models – but in the meantime, the safety assessment modellers are generally content with the adequacy with which they can represent chemical transport aspects.

Safety assessment of geological disposal

All of the processes discussed above control the way in which a repository behaves over thousands of years into the future. We need to understand how all the processes fit together and what the fate of each radionuclide in the waste will be. Most will never leave the waste matrix or its container, decaying *in situ*. But some mobile and very long-lived radionuclides will eventually begin to disperse into the rock. Evaluating what happens to them and their possible impacts on people and the environment far into the future is called *'safety assessment'* (SA) and has formed a focus for EC programmes for the last 25 years.

The methodology for carrying out safety assessment is now thoroughly developed and tested – indeed, it is a routine exercise used regularly, at various programme stages, to compare alternatives: designs, layouts, materials, geological environments and repository sites. Safety assessment looks at the behaviour of the whole disposal system to evaluate possible radiological impacts on people. Its cousin, *'performance assessment'* (PA) models the behaviour of components of the system – perhaps comparing the suitability of different container materials, or combinations of container materials, under different conditions. Performance assessment is itself based on connected *'process models'* that reflect detailed scientific understanding. PA generates the building blocks of a complete safety assessment, often by producing simplified models of processes in parts of the disposal system, or simplified datasets that can be more easily managed in a full SA.

Bentonite is one of the most important components of most engineered barrier and seal designs; a major exercise in FP5 looked at every aspect of the behaviour of this material at a process model level and at how these are translated into PAs, focusing in particular on the consistency of the data and the evaluation methods. The key role of bentonite buffer is to 'slow down' the movement of chemicals and radionuclides around waste containers to a rate controlled by diffusion – an exceptionally slow chemical transport mechanism.

The important barrier functions of bentonite can be affected if it is attacked by the alkaline pore fluids found in the cements and concretes that will inevitably be used in repository construction. Repository host rocks. too, could react with these fluids. These interactions have been extensively studied both experimentally and by thermodynamic modelling. It was found that the depth of reaction penetration into bentonite buffer and clay host rocks is not significant enough to affect their performance.

Process models that describe materials behaviour in a repository need to consider all of the driving mechanisms – thermal, chemical, hydraulic and mechanical ('TCHM') resulting from the radioactive decay heating of the wastes, the chemical composition of materials and pore waters, and the rock stresses. These can each be affected by external events, too – for example, in the distant future, some European countries will be covered by thick ice sheets in a new ice age – with thermal and mechanical load impacts being transmitted even to repository depths and changes in groundwater flow and chemistry.

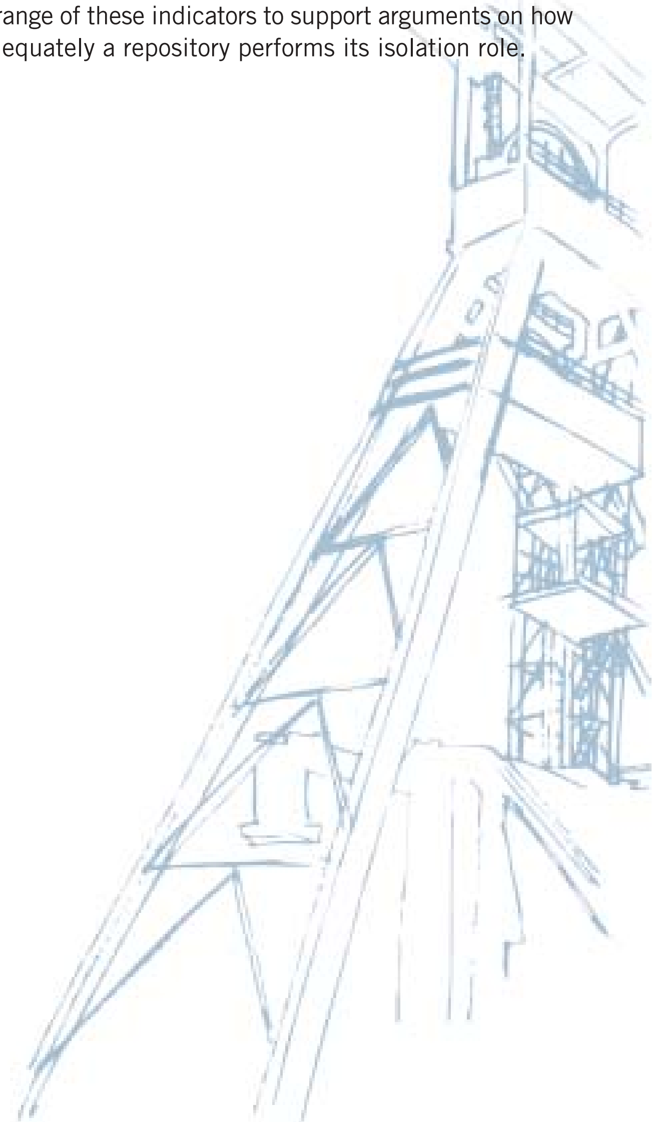
Coupling these TCHM process models together is an area where much work is continuing in EC programmes. The constant growth of scientific and computational capacity means our ability to make ever-more realistic and integrated models of system evolution should contribute to a continued, progressive reduction in the conservatisms that have been used in PA and SA.

When some metals corrode under the anaerobic conditions inside closed engineered barriers, it is possible to generate large amounts of hydrogen gas. Other gases produced in the wastes might also be radioactive – 14C containing methane, for example. The pressures produced if hydrogen gas cannot slowly disperse through the rock could damage the engineered barriers, so there has been much study of how gas is generated and how it moves in a repository. FP5 launched a Thematic Network on this topic that was able to integrate present knowledge and identify several areas where more work will be needed if we are to be able to include better-characterised gas impacts in safety assessments, instead of having to use overly conservative assumptions.

Any radionuclides that do escape from the rock and deep groundwaters could find their way into the biosphere. Pathways for radionuclides through surface waters, soils, plants and animals to people are complex. Nevertheless, the ability to identify and evaluate them is a key aspect of safety assessment as the biosphere pathways and processes ultimately control the potential human radiation doses we calculate and these are compared with regulatory standards to decide whether a repository provides sufficient safety. The biosphere is a very complex and constantly changing natural system, especially when looked at over thousands of years – not least, as a result of changing climate and human habits. Consequently, there are numerous uncertainties about future biosphere states. Safety assessors seek to get round this problem by identifying present- day biosphere models that can act as reference states covering the main environmental conditions that could occur over the next hundreds of thousands of years.

One project in FP5 has taken the approach of identifying five specific biosphere models that cover a range of climate and land use conditions – in Hungary, Spain, Belgium, Germany and Sweden. Comparisons were made between the behaviour of critical radionuclides in a range of exposure pathways in each environment. This work was linked to a climate change modelling exercise that used global-scale climate models to evaluate how each of the reference biosphere sites could evolve.

Owing to uncertainties about the biosphere and human behaviour in the distant future, many people suggest that radiation doses should not be used alone or as the main measure of repository performance or safety after a few thousand years. A major FP5 project considered more than 20 possible alternative indicators of safety – or of the performance of various parts of the repository system that show how well it is functioning at different times in the future. Future safety cases are likely to use a range of these indicators to support arguments on how adequately a repository performs its isolation role.



BOX 9: Safety assessment achievements

- Simulation of the complex coupled processes occurring as bentonite clay buffer becomes saturated with water and swells during the early thermally active period of a repository: but there are still uncertainties – the interaction of bentonite with cement and the movement of gas in bentonite both need further study.
- Experimental and modelling studies of cement interaction with clay and granite – insignificant impacts found on repository performance.
- Testing of fully and partially coupled TCHM process models for hard, fractured rocks – particularly important in the resaturation and heating phase, a few hundred years after waste emplacement.
- Examination of stress effects of rock permeability and evaluation of hydromechanical conditions in a repository during glacial periods.
- Identification of uncertainties about gas generation and behaviour in repositories, allowing structuring of the next stage of EC studies.
- Development of reference European biosphere models covering a range of climate and environmental states, to help assess possible radiation doses to people in the future.
- Application of global- and regional-scale climate models to evaluate the evolution of reference biospheres in Europe.
- Testing of the utility of alternative (to radiation dose) performance and safety indicators – including radiotoxicity fluxes and concentrations in water, distribution of radioactivity in 'compartments' of the repository, the rock and the biosphere and the flux of activity between them.

Safety assessment is an established, everyday activity. Today, it takes a practical and conservative approach (it overestimates impacts) – future developments will allow it to become more realistic.

Public involvement in repository programmes

Many people see radioactive waste disposal as a complex, difficult and dangerous technological activity that can only be understood by a few experts and which is likely to cause insidious, long-lasting damage to our own and our children's environment. Whilst the same fears might be engendered by many other activities, we are more familiar with them and much less concerned – we have a particular fear and a widely felt distrust of anything associated with radioactivity and radioactive wastes.

Fear and mistrust stem from lack of information combined with a feeling of powerlessness to affect developments. This situation must be overcome by ensuring that we are properly informed about the issues and actively involved in making decisions about them. The whole of the Euratom programme is now focused on energetic efforts to ensure that information is advertised and accessible.

Today, enhancing transparency in radioactive waste management activities and encouraging citizen participation are top-level concerns in all European organisations concerned with the issue. Two of the FP5 projects with the broadest participation have looked into and tested methods for communicating the technical complexities (especially those surrounding safety assessments), and receiving and responding to feedback in a process of public dialogue. For a specific disposal project, both local people and the national population might wish to be involved and this must all be done in the framework of national and social and economic European interests.

One project focused on the difficulty of making complex performance assessments transparent to those elements of the non-scientific community which need to be involved in decision-making. One finding was that PAs would benefit from broader involvement – beyond the specialists. Concerned people ask questions that PA can help to answer, if it is properly structured and designed to be responsive. The setting of regulations for waste disposal also benefits from public dialogue. National waste management programmes thus need to set aside resources to allow such broader public participation – a set of lessons that ought to be valued far beyond radioactive waste management, in addressing any complex policy issue.

A major step forward in real public involvement was seen in the EC project which brought together 30 communities across Europe to share views and experience. A key theme of the seminars was public involvement in setting national radioactive waste management frameworks and regional policy, and in local decision-making. Local people are extremely interested in taking a role in decisions on how repository projects could develop. The results of the shared experiences of these groups will undoubtedly identify good common practices and stimulate local empowerment over coming years, as geological disposal moves from concept to reality in the European Union.

Looking forward to the next five years: the Sixth Framework Programme (FP6)

Science and technology grow and develop – a never-ending process of learning and improvement. Requirements for radioactive waste management will change as national and European programmes evolve. The prospect of change is inevitable and does not prevent rational, informed decisions and actions being taken at any point in time – if it did, our advanced society would never have developed. Thirty years of European R&D have now brought us close to the first implementation of radioactive waste disposal, putting the final piece in place to give us a complete and sustainable system for one of our most important sources of everyday energy.

However, in implementing geological disposal, we must always be aware of developments, be able to respond to change and to make the best use of new advances when it is appropriate. The European context, too, will change, as the Union expands and new Members, with their own specific waste management problems to solve, enter the arena.

The next five year programme FP6 (2002-2006) pinpointed these issues – the need to identify and answer outstanding questions, to pursue appropriate and promising new developments and, above all, to integrate national activities to reach commonly applicable solutions. The overall theme is the sustainable integration of European research in the geological disposal of radioactive waste. The programme has thus become still more focused. The future will see yet more integration, with fewer, larger projects, involving more partners. This is in common with European Union research policy in general.

The first group of such topics that will be studied, mainly within Networks of Excellence and Integrated Projects, has already been identified (see Box 10). Networking will develop a common European view on the main issues, strengthen the scientific basis, evaluate practicalities, build structured knowledge transfer and management methodologies, and provide a forum for training – the latter being a vital matter, given the decades' long timescales of waste management projects and the consequent need to ensure that knowledge and experience is propagated from one generation to the next.

This large-scale integration is clearly timely as the next five-year programme will bring Europe to the threshold of actual repository construction, which may commence around 2010. More than 30 years of concerted European research and development will have come to fruition.

BOX 10: The first group of projects for FP6

- The **NF-PRO** project will establish the scientific and technical basis for evaluating the safety function "containment and minimisation of release" of the near-field of a geological repository for high-level radioactive waste and spent fuel. It will investigate dominant processes and process couplings affecting the isolation of nuclear waste within the near-field, and apply and develop conceptual and mathematical models for predicting the source-term release of radionuclides from the near-field to the far-field. The results and conclusions of experimental and modelling work will be integrated in performance assessment.

- **COWAM 2** will build on the highly successful first COWAM project. It aims to improve the governance of radioactive waste management by addressing societal expectations, needs and concerns in radioactive waste decision-making processes, notably at local and regional levels. It will also increase societal awareness of, and accountability for, the management of radioactive wastes, develop guidance on innovative democratic governance, and develop best practices and benchmarking on practical and sustainable decision-making processes recognised as fair and equitable by the stakeholders involved.

- Some small nuclear power programmes in the expanded EU may not have the resources or the full range of expertise to build their own repositories for long-lived radioactive wastes. Even for countries that could potentially implement national projects, there are environmental and economic advantages in co-operation. The prospect that countries could work together to explore shared regional solutions has been much discussed in the EU. Such solutions raise new transnational issues not so far addressed by national programmes: nuclear security, safety of multi-user repositories with diverse waste types, national and European public acceptability, trans-boundary waste transport, and national and European economics and law. The **SAPIERR** project is a pilot initiative that will help the EC to begin to establish the boundaries of the issue, collating and integrating information in sufficient depth to allow concepts for potential regional options to be identified and scope given to the new RTD needs.

- In recent decades, the actinide sciences have stagnated and become less attractive to young scientists. Europe has seen basic research in this area dramatically reduced. Only a few national research institutions and one international institute (JRC) are able to maintain the necessary research infrastructure. The **ACTINET** project aims to revitalise the subject and make it attractive to students so that a new generation of actinide scientists and engineers can develop. It will reinforce links between national nuclear research institutes, the JRC, and the radiochemistry laboratories of academic research organisations – 27 partners in total within the network. The project will significantly improve the accessibility of the major actinide facilities to the European scientific community, form a set of pooled facilities, improve mobility between member organisations, merge and optimise parts of their research programmes, and strengthen European excellence through a selection process for joint proposals. By reducing the fragmentation of the community and putting a critical mass of resources and expertise into shared challenges, it will help Europe to remain a world force in the field of actinide sciences.

- The **ESDRED** project provides the opportunity for radioactive waste management organisations to work together efficiently to generate and share solutions, systems and technologies for constructing, operating and closing a deep geological repository. It will make practical scientific and engineering studies of four topics that are not well addressed by existing or easily adaptable mining, civil and nuclear engineering technologies: buffer manufacturing and construction for horizontal disposal drifts, waste canister transfer and emplacement into horizontal and vertical disposal locations, heavy load emplacement in horizontal disposal drifts, and reinforcing and plugging drifts with low-pH cementitious materials. Monitoring and retrievability at all steps of repository construction, operation and closure will be integrated into relevant technical modules. Each module will provide access to various industrial solutions compatible with national repository concepts and geological environments.

Further reading

The volume of literature on geological disposal is enormous, not least in the extensive series of Euratom reports that have been published over the last decades. These recently published books provide a lead into the general subject area for those wishing to know about geological disposal in more depth.

- Chapman, N.A. and McCombie, C. (2003) Principles and standards for the disposal of long-lived radioactive wastes. Elsevier (publisher), 277 pps

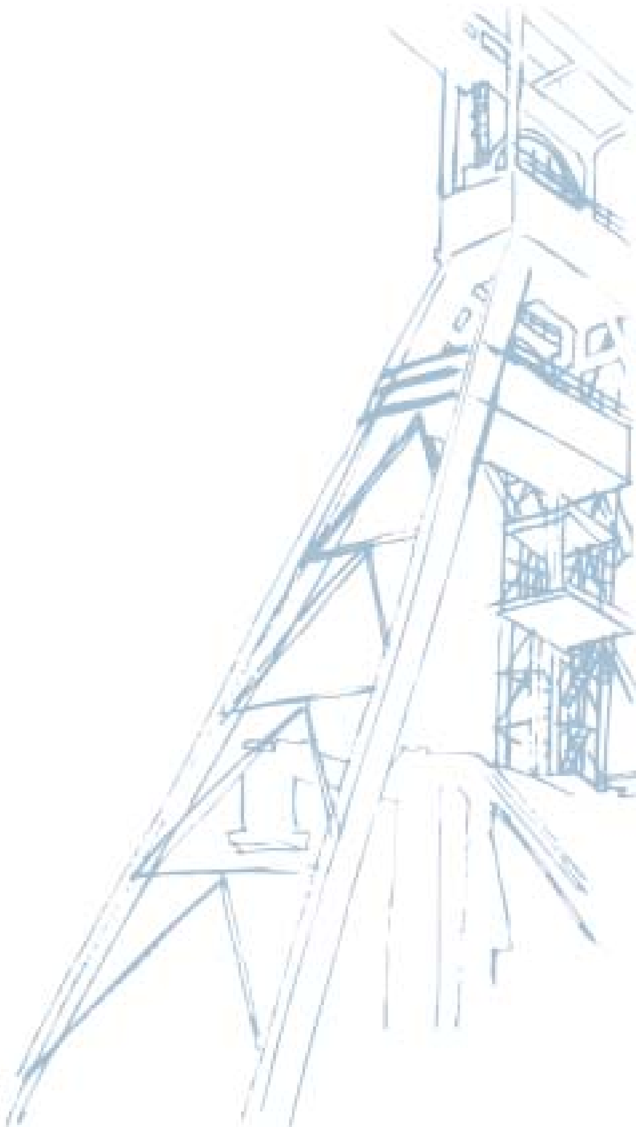
- EURADWASTE'04-Radioactive waste management. Community policy and research initiatives, Proceedings of the sixth EC conference, Luxembourg 29 March - 1 April 2004, Publications Office of the European Communities, EUR 21027 EN

- Euratom-Nuclear Fission and Radiation protection projects selected for funding 1999-2002, Punlications Office of the European Communities, 2003, EUR 20617 EN

- NEA (1999) Geological disposal of radioactive waste. Review of developments in the last decade. OECD Nuclear Energy Agency, Paris.

- NEA (2002) Establishing and communicating confidence in the safety of deep geological disposal. OECD Nuclear Energy Agency, Paris.

- NRC (2003) One step at a time: the staged development of geologic repositories for high-level radioactive waste. United States National Research Council, National Academy Press, Washington DC.



Projects within FP5

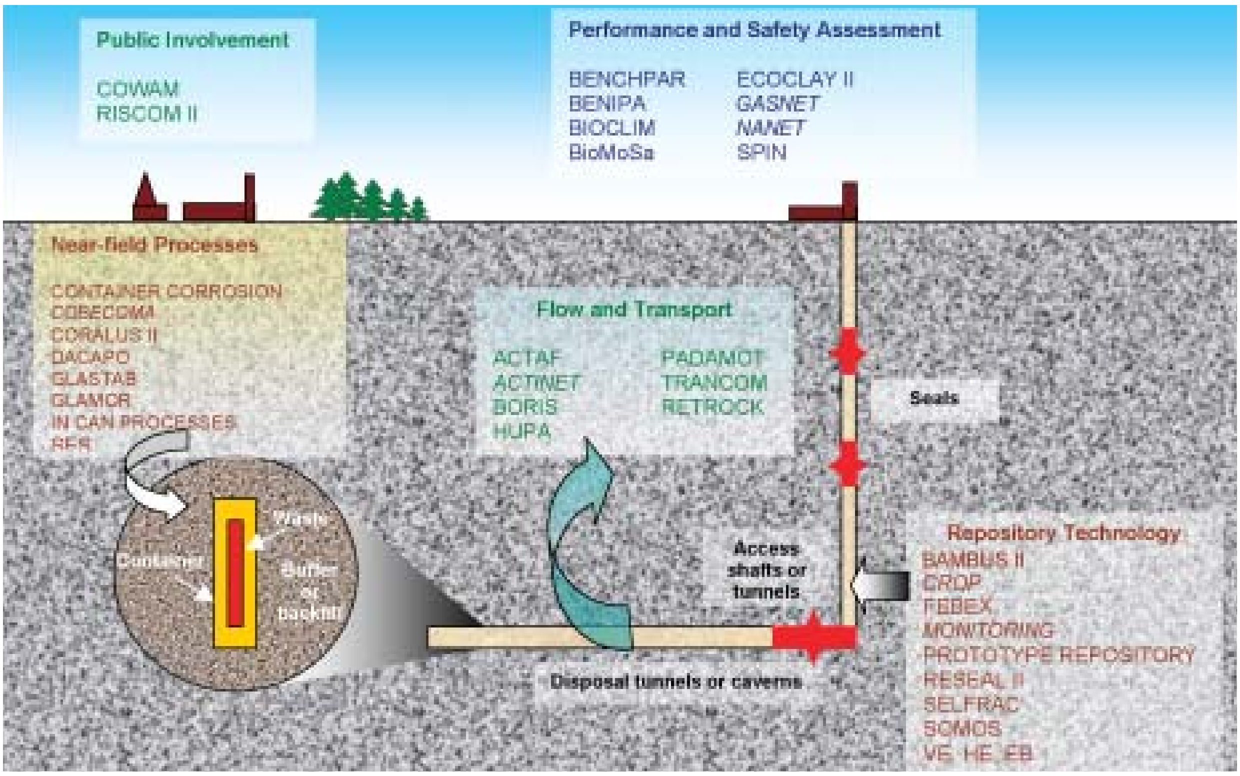
The following pages provide more information on the objectives, challenges and achievements of the many projects that formed components of the Fifth Framework Programme.

The projects are presented in the following pages in tabular form, in two groups:
- RTD projects on:
  - Repository technology
  - Waste and container behaviour
  - Safety assessment of geological disposal
  - Groundwater and radionuclide movement around repositories
  - Public involvement in repository programmes
- Thematic Networks

Where significant results had been published at the time this brochure was prepared, the main findings are indicated in the RTD projects table. The objective of the Thematic Networks has been to review key areas after 10 to 15 years of research and development and thus to identify 'closed' issues as well as those requiring further work.

Overall, the emphasis within the Fifth Framework Programme has been on integration of RTD studies, both within specific topics associated with geological disposal, and by links that improve understanding of the whole disposal system. To put this integration in context, the diagram below shows how each of the project fits into place.

Integration diagram of FP5 RTD projects and Thematic Networks



Repository technology

BAMBUS II

Title: Backfill and material behaviour in underground salt repositories — Phase II

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Abstract: objectives and results to date

This is the last project in a long series of investigations in the Asse salt mine (HAW, TSDE, DEBORA, BAMBUS I) before closure of the mine in the next few years. In Germany, the waste container emplacement concepts in salt formations use backfilling with crushed salt to stabilise the repository. Backfilling provides long-term sealing of the waste from the biosphere as a result of backfill compaction owing to salt creep and consequent excavation convergence. In all the experiments, the waste decay heat was simulated by electric heaters. To determine the achieved backfill compaction in detail, one of the TSDE test drifts and both DEBORA boreholes were uncovered after terminating the experiments. Post-test laboratory analysis of the backfill, as well as measuring the data together with a re-calibration of measuring instruments, confirmed the numerical predictions and thus the material behaviour and 3D-computer models. From these studies, the conclusion can be drawn that the mathematical models, which were developed to simulate the behaviour of backfill and rock formations, are now sufficiently able to simulate the performance of a radioactive waste repository for heat-generating waste in salt. In the process of excavating the test zone, 280 corrosion samples of selected container materials were recovered and their durability assessed by several laboratory techniques. The results showed very low corrosion rates and almost no pitting corrosion effects. The final report on the project has been published under **EUR 20621**.

EB & VE

Title: EB (engineered barrier emplacement) and VE (ventilation) experiment projects in the Opalinus clay at Mt Terri, Switzerland

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Abstract: objectives and results to date

The EB experiment aims to demonstrate a new concept for the construction of HLW repositories in horizontal drifts, in competent clay formations. The principle of the new construction method is based on the combined use of a lower bed made from compacted bentonite blocks, and an upper backfill made with a bentonite-pellets-based material. It has been demonstrated that fabrication of bentonite pellets with the required density, and production of the specified grain sizes (to optimise packing potential) in a continuous industrial line process is feasible. After emplacement testing in a 6 m long, 3 m in diameter tunnel model, of different methods (pneumatic, auger, belt conveyor), it has been demonstrated that auger method provides the highest emplaced dry density without major gaps. The feasibility of a new construction method of engineered barriers in horizontal drifts using bentonite pellets (upper part) and blocks (lower bed) has been demonstrated. Although the artificial saturation situation removes reality from the “in-situ” experiment, and emplaced dry density values are lower than the target ones, the model emplacement results serve to demonstrate achievable densities in a real-world setting. Highly useful information has been obtained for the design of a repository, in relation to drift size and the handling of the bentonite buffer and waste canister. Geophysical and hydrogeological characterisation of the EDZ, both prior and after hydration of the bentonite buffer, has been performed. Data on the hydraulic and mechanical parameters, both in the rock and the EDZ, were gathered and investigated during the 19-month operational phase of the project.

The VE experiment is a ventilation test carried out *in situ* in a 1.3 m diameter by 10 m long horizontal tunnel. The objectives of the test were to estimate the desaturation and resaturation times in clay rock, produced by drift ventilation; the saturated hydraulic conductivity of the rock (macro-scale) and comparison with values obtained at smaller scales and evaluation of the scale effect impacting this important parameter; and the evolution of the EDZ, in terms of changes in hydraulic conductivity and of displacements caused by the generation of cracks on drying. Hydraulic characterisation of the clay rock material has been carried out, namely the water retention curve, relative permeability and saturated hydraulic conductivity. A specific drying test was conducted to measure the rate of evaporation from several core samples under controlled climate conditions. These results have been used for the first calibration of the design model calculations. Geoelectrical and geochemical characterisation has been made of the rock surrounding the test section, before starting the desaturation-resaturation cycle. These non-destructive methods, which use various sensors, have enabled the water content and water potential for a consolidated clay formation to be determined. The resulting database confirms the applicability of the measuring techniques applied to hard clay rocks. The experimental data gathered so far have allowed a

first calibration of the different hydromechanical models used, particularly of CODE-BRIGHT, corresponding to a desaturation phase of the rock. Rock desaturation (i.e. degree of saturation lower than 95%) occurs in a small ring around the tunnel (i.e. thickness about 50 cm or lower), after a very low relative humidity desaturation cycle over several months. It is reasonable to foresee that under real repository construction conditions with much higher relative humidity, the desaturation of this kind of rock will not be a relevant issue. Rock deformations induced by pore water changes (and hence changes in the stress state) are also very small.

FEBEX II

Title: Full-scale engineered barriers experiment in crystalline host rock — phase II

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Abstract: objectives and results to date

The overall aim of the project is to study the behaviour of the engineered barrier components of a high-level radioactive waste repository in granite. The project has so far comprised two phases which include an in-situ test at the Grimsel underground laboratory (Switzerland), a mock-up test (for controlled conditions) above ground in Spain, and a series of laboratory tests and numerical modelling of all the tests. FEBEX I demonstrated the feasibility of handling and constructing an engineered barriers system. It also studied the combined thermal, hydraulic and mechanical (THM) and thermal, hydraulic and geochemical (THG) processes of a repository in this region. FEBEX II extends this work to improve knowledge of the THM and THMG processes, especially in a more hydrated clay barrier, in order to improve, calibrate and validate existing numerical codes. A key objective is to examine the potential changes that may occur in the buffer material – in particular, by their interaction with solutes in porewaters and groundwaters. FEBEX II also looks into gas and radionuclide transport processes inside the engineered barriers as the bentonite properties evolve, and at waste container corrosion processes in reference metals. The heat and bentonite-rock interaction modify the hydraulic regime inside the rock mass, and this is also studied, with special emphasis on the excavation-disturbed zone (EDZ).

Two engineering objectives are also important: evaluation of the long-term behaviour and performance of instruments and monitoring systems – with potential implications for a real repository – and investigation into the technological aspects of canister retrievability, in order to identify potential problems that should be taken into account in this reference repository concept.
The major achievements of the project so far have been:

- The feasibility of constructing engineered barriers for the horizontal storage of canisters placed in drifts has been demonstrated. Specifically, it has been shown that the manufacturing and handling of bentonite blocks is feasible at industrial scale and that the clay barrier may be constructed with a specified average dry density in order to achieve the permeability and swelling pressure required for the barrier. Furthermore, highly useful information has been obtained for the design and construction phase of a repository, in relation to the size of the drifts, the specifications and procedures for the manufacturing and handling of the bentonite blocks, the basic characteristics of the equipment for construction of the clay barrier, and insertion of the waste canisters and construction of concrete plugs, etc.

- The CODE-BRIGHT numerical THM model is capable of reasonably predicting the measured results of the two large-scale tests. During this period, it has been necessary to modify just minor details of the model as it has been observed that its core is based on solid physical laws. Although complete validation is never possible, the checks performed have significantly increased the degree of confidence in the capacity of the model for the performance assessment of the THM behaviour of a repository near field.

PROTOTYPE REPOSITORY

Title: Full-scale testing of the KBS-3 concept for high-level radioactive waste

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Abstract: objectives and results to date

The main objectives of the project are to use engineering, full-scale demonstration and *in-situ* testing to prove the feasibility of a repository concept for hard rock, using the Äspö hard rock laboratory in Sweden. The prototype repository consists of two tunnel sections with four and two canister deposition holes respectively. The outer section should be dismantled after five years of operation, while the other section may be operated for up to 20 years. A concrete plug separates the two sections, and the test is isolated by an outer plug. Electrical heaters inside the canisters simulate the decay heat of the spent fuel and the canisters are embedded in a highly compacted bentonite buffer. A tunnel-boring machine (TBM) with diameters of 5 m for the tunnel and 1.75 m for the vertical holes was used for excavation. The boring of the horizontal drift was based on proven technology, while the vertical boring needed more accurate precisions than ever done before. The outcome was better than expected. The project used "MX-80" bentonite from Wyoming for the buffer. Techniques have been developed, following co-operation between Spain and Sweden, for the compaction of blocks with dimensions ranging from brick size to cylinders with a diameter of 1.65 m and height of 0.5 m. Large bentonite blocks were placed in a column and the canister lowered into the centre hole. Backfilling of the tunnel used a mixture of 70% crushed TBM muck and 30% bentonite (a soda-treated natural Ca-bentonite from Greece). *In situ* compaction gave both better than expected results (in the centre) and worse (close to the rock). Water inflow was a problem, not only because the instrumentation in the backfill required a long installation time, but also because of the high inflows – 5 l/min along a 5 m section of the tunnel. This project is closely related to the FEBEX II project (above) with horizontal canister emplacement. Full-scale testing of a Swedish "in-drift" method has recently been scheduled for the Äspö hard rock laboratory.

Further information available at: http://www.skb.se/prototype

SELFRAC

Title: Fractures and self-healing within the excavation disturbed zone in clays

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Abstract: objectives and results to date

The main objectives of the project are to characterise the Excavation Damaged or Disturbed Zone (EDZ) in clay and its evolution with time, as it may lead either to a significant increase in permeability related to diffuse and/or localised crack proliferation, or (as a result of self-sealing and self-healing) a reduction in permeability with time. Two potential geological formations for deep radioactive waste repositories were studied: the Opalinus clay (Switzerland) and the Boom clay (Belgium). Triaxial and biaxial tests were used to understand and quantify the fracturing process and the increased permeability related to crack proliferation around excavations. The results of these tests allowed sets of parameters to be established for numerical simulation. Other tests characterised self-sealing and self-healing processes by monitoring the evolution of flow properties along a fracture, and by means of acoustic emission. Results of these tests show that in Boom clay self-sealing occurs very quickly after flooding of the fracture. During self-sealing the permeability decreases up to values close to the permeability of intact Boom clay (about 4.10-12 m/s). The first *in-situ* test conducted in Opalinus clay at Mt Terri studied the influence of bentonite swelling pressure on transmissivity in the EDZ. Permeability measurements were performed during the stages of a long-term load test in order to investigate mechanical-hydraulic effects. The assumed healing effect/process, combined with a significant reduction in transmissivity (nearly two orders of magnitude), has been proven. An *in-situ* test in Boom clay at Mol is studying the long-term evolution of the disturbed zone along a gallery. A reduction of the extent of the EDZ with time is being observed. It has been shown that open fractures close progressively. One year after the excavation of the gallery, the extent of open fractures did not go beyond a zone of about 0.6 m around the gallery.

Waste and container behaviour

CONTAINER CORROSION

Title: Long-term performance of candidate materials for HLW/SF disposal containers

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Abstract: objectives and results to date

To determine the influence of essential parameters (e.g. composition of host rock, temperature, gamma radiation) on the corrosion of canister materials and to gain a better understanding of the corrosion mechanisms. In-depth corrosion studies were performed on selected materials in simulated rock salt, granite and clay environments: carbon steel, stainless steels (Cr-Ni steels), nickel-base alloys (Hastelloy C-4 and Hastelloy C-22), the titanium-palladium alloy Ti99.8-Pd and copper (Cu)-base materials. The results obtained in salt brines up to 150°C indicate agreement with previous studies that the passively corroded alloy Ti99.8-Pd is the strongest candidate for the manufacture of long-lived containers (corrosion-resistant concept). Under all test conditions this material was completely resistant to local corrosion and stress-corrosion cracking, and its general corrosion rate was negligible/low (0.2 µm/a). The actively corroded TStE355 carbon steel and the Cu-base materials Cu, Cu-Ni 90-10 and Cu-Ni 70-3070 are promising for the corrosion-allowance concept. They are resistant to pitting corrosion, in terms of an active-passive corrosion element, and their general corrosion rates, although clearly higher than the value of Ti99.8-Pd, imply corrosion allowances reasonable for thick-walled containers. The corrosion rate of the Cu-base materials clearly decreases through galvanic coupling with carbon steel, i.e. the more noble Cu-base materials will be cathodically protected by the less noble carbon steel. The results obtained in granitic water and granitic-bentonite environments at 90°C indicate that the materials Hastelloy C-22, Cu, Cu-Ni alloys and carbon steel are strong candidates for containers to be disposed of in a granitic formation. These materials exhibited a high resistance to stress-corrosion cracking (SCC) and to pitting and crevice corrosion under relevant disposal conditions. Only the alloy Cu-Ni 70-30 has shown a slight susceptibility to SCC under very hard test conditions, i.e. extremely low strain rates of 10-6-10-7 s-1 and a chloride concentration of 50,000 ppm, which is more than seven times higher than the chloride concentration expected in the Spanish granitic-bentonite environment. Electrochemical studies in clay water (anaerobic and aerobic conditions, T=16-140°C, 100-50,000 ppm Cl-) indicate that among the passively corroded materials only Ti99.8-Pd is completely resistant to pitting and crevice corrosion. Hastelloy C-4 and Hastelloy C-22 show slight crevice corrosion at Cl- concentrations higher than 20,000 ppm. The Cr-Ni steels investigated show a lower resistance to pitting corrosion than Hastelloy, but they are resistant to pitting at Cl- concentrations which are relevant for the Belgian disposal concept. Considering material costs and container fabrication aspects, Cr-Ni steels are considered the most promising material for containers to be disposed of in a clay repository.

COBECOMA

Title: State-of-the-art document on the corrosion behaviour of container materials

Co-ordinator: Bruno Kursten, SCK.CEN, Belgium
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Abstract: objectives and results to date

Carbon steels, stainless steels, nickel-based alloys, titanium-based alloys, and copper have been widely investigated as potential container materials, depending on the studied host rock formation. The results obtained in salt environments indicate that the passively corroding Ti99.8-Pd is the primary choice for the thin-walled corrosion-resistant concept, since its general corrosion rate is negligible and it is highly resistant to localised corrosion and stress corrosion cracking (SCC) in salt brines. The TStE 355 carbon steel is the first candidate for the corrosion-allowance concept because it is resistant to pitting corrosion and SCC and its general corrosion rates are sufficiently low to provide corrosion allowance acceptable for thick-walled containers. Stainless steels, Ni-based alloys, and Ti-based alloys are the most important candidate container materials in clay for the thin-walled concept, while carbon steel is considered the main choice for the thick-walled corrosion-allowance concept. Studies performed in granite seem to indicate that copper containers provide an excellent corrosion barrier with an estimated lifetime exceeding 100 000 years. The TStE 355 carbon steel is also a valid option for a thick-walled container concept in granite.

CORALUS 2

Title: Integrated in-situ corrosion test of alpha-active HLW glass – phase II

**Co-ordinator: Elie Valcke, SCK.CEN, Belgium
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Abstract: objectives and results to date

To validate the long-term behaviour predictions generated under the GLASTAB project. This is being done by comparing the GLASTAB experimental and modelling results with the experiments undertaken in the CORALUS project: the alteration kinetics and radionuclide release and migration are being studied *in situ* at Mol (Belgium) in the HADES underground research facility under conditions as realistic as possible to those of disposal.

DACAPO

Title: Development and automation of chemical analytical procedures for the determination of non-gamma emitting radionuclides in radioactive waste

**Co-ordinator: Johannes Fachinger, FZJ, Germany
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Abstract: objectives and results to date

To develop advanced methods for the destructive analysis of conditioned radioactive waste and the automation of these methods. The project aimed to develop reliable methods in order to minimise the risk for the employees, by short analytical procedures or by pre-separation of the main activity, like 137Cs or 60Co. Different decomposition methods have been developed based on pressurised microwave digestion and on combustion. All waste matrices could be disintegrated sufficiently except slag from decontamination melting processes for metals. Methods have been developed to investigate such residues and validated with a cement powder with a known radionuclide inventory. The separation of the radionuclides from the dissolved waste samples was performed by precipitation, liquid-liquid extraction, solid-phase extraction and high-performance liquid chromatography (HPLC). The last two methods could be performed in a completely automated manner, and the last method has the added advantage that the HPLC system can be coupled with an on-line liquid scintillation counter for direct measurement of *a*- and *ß*-emissions. The detection limits of such a system are sufficiently low for most *ß*-emitters, which occur in higher activities in the waste. However, the detection limit for *a*-emitters of 5 Bq/ml is still too high with respect to the required detection limits for destructive waste analysis. In order to reduce the dose rate, several new extracting agents have been synthesised to separate 137Cs and 60Co (the nuclides which cause the highest dose rates in the samples) selectively from all other radionuclides. Furthermore, the extracting agents have been fixed on a polymer resin or silica to get a stable material which could be used in automated chromatographic systems. In general, most of these extracting agents were able to separate Co and Cs but unfortunately at high pH values which will disturb further analysis procedures. Nevertheless, one agent, poly(Terpy-1-co-NBE)-coated silica, was able to extract Co at low pH (1.5 - 2.5). This is an important development because no alternative separation method was available for Co. A model has been developed for calculation of the radionuclide inventory of a waste package based on the gradient between samples from different locations of a waste drum, and has been checked by statistical computer modelling. It could be shown that such a calculation would lead to a conservative estimation for stirred cemented waste for a storage facility, if a sufficient number of waste packages were calculated in this way. However, it could not be used for the inventory estimation of single waste packages.

GLAMOR

Title: A critical evaluation of the dissolution mechanisms of HLW glasses in conditions of relevance for geological disposal

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Abstract: objectives and results to date

To determine whether the observed behaviour of waste glass under disposal conditions (see GLASTAB) is attributable to the selection of the experiments used to develop the models or to the choice of hypotheses incorporated in the models. This concerted action was organised to allow mutual exchanges of experimental work and models among the partners. It is expected to lead to a common European understanding on the approaches used to model the observed dissolution rate decrease with time (combining retention, affinity and diffusion phenomena), and should allow quantification of the uncertainties arising from the choice of one model rather than another.

GLASTAB

Title: Long-term behaviour of glass: improving the glass term and substantiating the basic hypothesis

Co-ordinator: Isabelle Ribet, CEA, France
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Abstract: objectives and results to date

To improve knowledge of nuclear glass behaviour and increase the dependability of source term models and predictions under representative repository conditions. Experimental investigations covering the formation of the alteration gel that develops when glass is exposed to water, the interaction of the glass with environmental materials such as clays or metal canister corrosion products, and radionuclide retention in the alteration products were combined with a two-track modelling approach: the first focused on the alteration rate and provided a better understanding of phenomena responsible for the rate decrease that is systematically observed during glass alteration; the second, an operational approach, has led to performance calculations that can be used by the safety authorities, and has enhanced the degree of realism by limiting the overly conservative aspects of the preceding approaches.

- The nature and properties of the glass alteration layer are highly dependent on both the glass composition and the alteration conditions (temperature, pH, water flow rate, etc.), and they evolve with reaction progress. These observations were corroborated by studies of natural analogues of the alteration gels (palagonite). The formation of the alteration layer systematically corresponds to a significant drop in the glass alteration rate. Various models have been developed for the formation of the alteration gel and for the glass surface alteration rate. The methods range from microscopic approaches, such as Monte Carlo modelling, to macroscopic approaches combining silicon retention in the gel, silicon diffusion in the gel and possibly in the hydrated glass layer, and the onset of silicon saturation at the glass/gel interface. Attempts have also been made to model gel formation based on the use of geochemical models taking account of the formation of solid solutions and, from a texture standpoint, using coupled transport-chemistry models to describe the evolution of the gel porosity. The drop in the alteration rate is indeed modelled according to the alteration conditions, although it is still necessary to use empirical parameters.

- The presence of near-field materials – in particular clays – modifies glass alteration kinetics. A major effort has been undertaken to characterise the properties of these materials in order to progress toward a coupled description of the glass evolution in contact with clay. Significant differences in behaviour can be observed depending on the nature of the materials. The main phenomena likely to account for the effects of clay are silicon sorption on the clay and the precipitation of secondary phases containing silicon. Nevertheless, these phenomena do not prevent very low glass alteration rates from being reached after a time period that depends on the quantity of clay involved.

- Sorption and co-precipitation are two major phenomena considered as accounting for radionuclide retention in the glass alteration products. Experiments in complex glass-gel-solution systems have confirmed that the behaviour of elements and the predominant sorption mechanism depend on the physicochemical conditions: trivalent elements released by glass dissolution are incorporated by (ad)sorption on gels at near-neutral pH. Under basic pH, there is competition between adsorption and aqueous carbonate complexation, leading to decreased retention (the solubility-limiting phases could be carbonates). In MgCl2 brines, the predominant sorption mechanism is ion exchange (low efficiency). Over the long term, the behaviour of actinides and lanthanides is controlled by the precipitation of poorly soluble mineral phases.

All the results were incorporated into an overall view of glass performance to substantiate the hypotheses supporting the operational models of glass alteration: these are simple, robust models with varying degrees of realism, to be coupled with environmental models for performance assessment calculations. The conclusion is that glass performance is highly dependent on the reactivity of the surrounding environment, on the residual alteration rate (i.e. the rate observed over the very long term), and on the hypotheses postulated concerning the repository constituents that must be taken into account. Performance assessments have shown that when the alteration conditions are compatible with the onset of a residual rate, the overall performance of the repository is directly related to performance of the glass itself: its low alteration rate controls the release of radionuclides from the site.

IN-CAN PROCESSES

Title: Rates and mechanisms of radioactive release and retention inside a waste disposal canister

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Abstract: objectives and results to date

To examine the interactions between spent fuel radiolytic dissolution and container corrosion, in terms of the effect of hydrogen overpressure, the retention capability of the corrosion products, and the influence of corrosion products on the redox balance within the container. Experimental work was carried out on both simulated materials (alpha-doped UO2 simulating old fuels) and irradiated fuels using, in particular, the isotopic dilution method to attempt to measure very low dissolution rates. More fundamental approaches were used to understand the chemical reactivity of Fe(II) towards U(VI) and Np(V) by developing RIXS measurements and quantum mechanics calculations. Data on experiments involving uranium dioxide and alpha-doped uranium dioxide were compared with dissolution rates of spent fuel (with the additional effects of beta and gamma radiation doses) under anaerobic conditions using a hydrogen gas atmosphere. In the presence of iron, the dissolution rates are very low and current values used in safety assessments are conservative. Furthermore, the solubility of uranium dioxide is also very low in the presence of iron, with uranium solution concentrations measured of less than 0.02ppb – significantly lower than previously published data in the scientific literature. The second part of the programme, a study of the potential of actively corroding iron to reduce oxidised aqueous U(VI) and Np(V) species to less soluble U(IV) and Np(IV), involved the development and use of an innovative electrochemical cell. There was also a significant development where RIXS – resonant inelastic soft X-ray scattering – spectroscopy was used to study and measure quantitatively the reduction of aqueous U and Np species on to the corroding iron surface. U(VI) reduction can occur in solution instead of at the solid surface, and carbonate complexes are reduced at a quicker rate than hydroxyl complexes. These results were in agreement with a new computer model that calculated from first principles the expected reaction path, and the relative reaction rate for the reduction of U(VI) to U(IV) and Np(V) to Np(IV) in solutions with various ligands. These data show that even if more oxidised (and more soluble) U(VI) and Np(V) species are released into solution from the waste form by radiolysis reactions, the reducing conditions present due to the canister materials are sufficient to reduce them to less soluble products, significantly reducing the inventory of U and Np in the groundwaters that flow away from the repository through the host rock. This will reduce the expected dose to the far field and has significant implications for current performance assessment models for high-level waste disposal that do not take into account the indirect contribution from canister materials.

SFS

Title: Spent fuel stability under repository conditions

Co-ordinator: Jean-Marc Cavedon, CEA, France
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Abstract: objectives and results to date

To identify the processes controlling spent fuel alteration in the near-field environment of a deep geological repository, which will act as reference input data for national geological disposal performance assessment exercises. The project aims to obtain a reliable radionuclide source term, including the instantaneous release fraction (IRF) of radionuclides at the time of water ingress and the much slower release from matrix dissolution. The focus is on (i) the potential increase with time of the IRF due to intrinsic spent fuel evolution before water ingress; and (ii) the matrix radiolytic dissolution process, for which no shared alteration model is yet available. Experiments on simulated samples, as well as irradiated uranium oxide and MOX fuels, were carried out in both saline and argillaceous conditions. Significant focus has been put on the effect of hydrogen on the radiolytic process.

Safety assessment of geological disposal

BENIPA

Title: Bentonite barriers in integrated performance assessment

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Abstract: objectives and results to date

To assess the state of the art in the treatment of bentonite barriers in Integrated Performance Assessment, evaluating the methods and data available to justify convincingly the capacity of bentonite to perform its assigned safety functions. An in-depth analysis and cross comparison has been made of the different models available for the numerical simulation of the behaviour of bentonite barriers at different levels of detail. The consistency and availability of data needed by the models has been evaluated. The overall result is a better understanding of the modelling and computer programs related to the performance of bentonite barriers. Numerical simulations have also been carried out at both process and integrated levels with respect to hydraulic, mechanical, chemical and transport processes. Modelling at process level included reactive transport, especially to assess the effects of cementitious degradation products on bentonite minerals, coupled T-H-M modelling, including the growth of canister corrosion products, and radionuclide transport associated with colloids potentially generated by bentonite barriers. For repositories in crystalline rock, the project studies confirmed that as long as the buffer is in place and functions as a diffusion barrier, the release rates of radionuclides from the near field to the geosphere remain low. The simulations indicate that these rates are very sensitive to the water-flow rate around the buffer and much less sensitive to the transport parameters in the bentonite, and are not affected much by changes of the buffer thickness. For a repository in a clay layer, the host rock normally acts as a huge buffer around the engineered barrier. Under the expected conditions, the contribution of the advection in the surrounding rock is very small, with the emplacement tunnels effectively sealed and a low vertical hydraulic gradient, the overall contribution of the bentonite to ensure low release of radionuclides is very small. This is because the host rock above and below the repository horizon is an extremely effective transport barrier, with very low permeability and good sorption properties. Overall, bentonite barriers are able to ensure that transport in the near field is controlled by diffusion. Their resaturation is expected to be completed in a few years while temperatures and stresses remain within moderate ranges. The effect of canister corrosion products should be investigated further. Chemical conditions evolve smoothly, but important uncertainties remain in the presence of cementitious products. The final report on the project has been published under **EUR 21023.**

BENCHPAR

Title: Benchmark tests and guidance on coupled processes for performance assessment of nuclear waste repositories

Co-ordinator: Herbert Henkel, KTH, Sweden
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Abstract: objectives and results to date

To improve the thermo-hydro-mechanical (THM) coupled processes models used in radioactive waste repository performance and safety assessment. The methodology for conducting technical auditing for THM modelling was successfully developed via a questionnaire. In the near-field rock-buffer system, a series of THM analysis was performed on homogeneous and fractured rock masses. The importance of the couplings on the safety indicators was evaluated by comparing the THM calculations to partially coupled ones (e.g. TM, TH, HM). Coupling is most important in the short term (less than 100 years) and it has been concluded that for confidence building and demonstration purposes, a fully coupled approach is necessary to interpret monitoring data correctly that would be collected after repository closure. In the upscaling exercise, methodologies and numerical techniques were developed to determine upscaled H, M and HM properties of highly fractured rocks in two and three dimensions. This demonstrated the impact of stress on permeability under a range of stress conditions. The possibility of increased permeability and enhanced permeability anisotropy under high-stress ratios was recognised for the first time. The results showed the need to acquire very precise fracture geometry data, which emphasises close co-operation between site characterisation and the ultimate users of the data for design and safety analysis of a repository. A synthetic exercise was conducted describing HM conditions during the dynamics of a glaciation cycle. Important coupling to the behaviour of glaciated terrain systems was identified and large-scale deformations and strength of the rock mass were investigated. Modelling of glacial sheet and permafrost were performed and differences between coastal and inland sites identified.

Further information available at: http://www.benchpar.com

BIOCLIM

Title: Modelling sequential biosphere systems under climate change for radioactive waste disposal

Co-ordinator: Delphine Texier, ANDRA, France
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Abstract: objectives and results to date

To provide a scientific basis and practical methodology for assessing the potential impacts of long-term climate change on biosphere characteristics in the context of radiological performance assessments (PA) of radioactive waste repositories in deep geological formations. Climate models that can simulate future climate changes in Europe over very long timescales have been developed and their results linked to an understanding of the pattern of biosphere changes for five selected European regions, in order to address the issue of how to represent future biosphere systems in long-term radiological performance assessments. The project was designed to advance the state-of-the-art of biosphere modelling in four steps:

- Step 1: summarise information on issues that have to be addressed when considering climate change impacts on repository safety, and the current methods used to represent environmental change in repository safety assessments.
- Step 2: use a hierarchy of climate models to derive the climatic changes for selected discrete time periods of interest to radioactive waste management (i.e. selected time slices during glacial and interglacial periods). The outputs from these models consist of climate and vegetation cover scenarios for selected time periods in the future. Statistical downscaling approaches have been developed and evaluated to enable climate model output for large areas to be downscaled to more appropriate scales for the regions of interest.
- Step 3: develop and apply integrated, dynamic climate models, representing all the mechanisms important for long-term climatic variations such as atmospheric forcing, ice-sheet development and ocean changes. The time-dependent results from these models have been interpreted in terms of regional climate evolution using a set of downscaling methodologies.
- Step 4: interpret the complementary outputs from Step 2 and 3 in terms of model requirements for the post-closure radiological performance assessment of deep geological repositories for radioactive wastes. To develop a methodology to demonstrate how biosphere systems can be represented in the long term.

Further information available at: http://www.andra.fr/bioclim/

BioMoSA

Title: Biosphere models for safety assessment of radioactive waste disposals based on the application of the reference biosphere methodology

Co-ordinator: Gerhard Pröhl, GSF, Germany
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Abstract: objectives and results to date

To develop and compare results of generic and site-specific assessment models that were developed for five European sites in Belgium, Germany, Hungary, Spain and Sweden, covering a wide range of living habits and agricultural and climatic conditions. Guidance in model development was given by the Reference Biosphere Methodology that was developed within the IAEA BIOMASS programme. The main objectives of BioMoSA are:

- To identify common and site-specific features, events and processes (FEPs) that need to be modelled
- To identify principal fundamental differences between different sites
- To compare the results and quantify the variability of site-specific models
- To conclude a generic biosphere tool for application in long-term safety studies
- To provide guidance on how detailed specific sites have to be modelled in order to achieve credible and sufficiently reliable results in long-term performance assessment studies
- To identify the possibilities and limitations for applying the generic biosphere tool in different national contexts
- To provide guidance for application of the generic biosphere tool to real sites.

ECOCLAY II

Title: Effects of cement on clay barrier performance

Co-ordinator: Nicolas Michau, ANDRA, France
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Abstract: objectives and results to date

To understand the physico-chemical behaviour of argillaceous and granitic materials altered by the effects of a hyperalkaline plume, and assess the evolution of the confinement performances of these materials, a series of laboratory tests and analysis. Data was acquired on sorption and migration of radionuclides, on mineralogical transformations and modifications to the properties of bentonite, of clay and crystalline host rocks in contact with either alkaline fluids or different kinds of cement. Hydrogeochemical modelling sought to define and optimise a model for hyperalkaline alteration. Simulations were made of the long-term behaviour of clay and crystalline rock under the effect of an hyperalkaline plume, and a performance assessment study was carried out.

SPIN

Title: Testing of safety and performance indicators

Co-ordinator: Dirk-Alexander Becker, GRS, Germany
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Abstract: objectives and results to date

To identify and test safety and performance indicators. The indicators have been tested by recalculating existing performance assessments of disposal systems for high-level waste in crystalline formations in Spain, Germany, Finland and Switzerland. The three proposed safety indicators and their preferred application to time frames are: effective dose rate – most relevant to early time frames; radiotoxicity concentration in biosphere water – preference for medium time frames; radiotoxicity flux from geosphere – preference for late time frames. For the effective dose rate, the data from present regulations were used as a range of reference values. Reference values for radiotoxicity concentration and fluxes were taken from natural environments that are known to be radiologically safe. The project concluded that several performance indicators can be used to show different aspects of the functioning of the individual compartments of the multi-barrier system. These indicators and their preferred applications are: (1) inventories in compartments: showing where the radionuclides are at different points in time, and the retention of radionuclides from the biosphere; (2) fluxes from compartments: showing the decreasing release rates from successive compartments, including radioactive decay and ingrowth, and the delayed release; (3) time-integrated fluxes from compartments: showing decay during delayed transport; (4) concentrations in compartment water: showing the decrease of concentration by dilution, dispersion and decay in successive compartments; and (5) transport times through compartments: showing the potential importance of individual radionuclides to the release of radiotoxicity by comparing them to their half-lives. For investigations relating to the total radionuclide spectrum, performance indicators based on radiotoxicity should be used. For single-nuclide investigations, activity-based indicators can be used. The final report on the project has been published under **EUR 19965**.

Groundwater and radionuclide movement around repositories

ACTAF

Title: Aquatic chemistry and thermodynamics of actinides and fission products relevant to nuclear waste disposal

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Abstract: objectives and results to date

To generate basic thermodynamic data for the actinides with respect to both dissolved and mineral-bound species. A notable breakthrough was the filling of serious gaps in the database for tetravalent actinides. Understanding actinide complexation with small organic ligands, which may serve as a model compound for natural organic matter, has been substantially increased using various spectroscopic methods and theoretical approaches. For the first time, computational methods (molecular modelling) have been applied to chemical problems related to nuclear waste disposal. It is envisaged that quantum chemical tools will play an important role for future investigations on the co-ordination chemistry and thermodynamic of actinides in natural aquatic systems. The co-operation of different laboratories with expertise in either spectroscopic actinide speciation or profound experience in modelling surface sorption reactions provided an improved understanding of actinide interaction at the mineral/groundwater interface. Mechanistic insight into the sorption of U(VI) on iron oxides, including surface-enhanced redox reactions, has been achieved as well as the elucidation of the speciation of trivalent actinides sorbed on to alumina and clay minerals. The first application of the grazing incidence X-ray absorption spectroscopy (GIXAFS) represents a huge step forward towards the spectroscopic characterisation of surface sorbed actinides at even trace concentration level. For the prediction of the U(VI)sorption onto rock minerals, a 'composite' model has been parameterised successfully using sorption data derived for the mineralogical rock constituents. The combination of wet chemical methods, surface analysis and spectroscopic techniques helped to improve the basic understanding of solid solution formation of actinides in calcite, cement degradation secondary phases and phosphates. Such mineralisation processes are believed to be of cardinal importance for the actinide reactions in the near- and far-field of a nuclear waste repository. The results gained in the ACTAF project indicate that inclusion in secondary phases can lead to strong actinide retention in the repository or the surrounding geosphere.

BORIS

Title: Building confidence in deep disposal: the borehole injection sites at Tomsk-7 and Krasnoyarsk-26

Co-ordinator: Stephen Wickham, Galson Sciences, UK
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Abstract: objectives and results to date

To utilise data from real examples of radionuclide movement in the deep underground, to improve understanding of the processes involved, that can then be transferred to performance assessment of deep geological repositories. Two sites in Russia – Krasnoyarsk-26 and Tomsk-7 – where liquid wastes had been injected were used for the study. The results indicated that clay layers formed an effective barrier to vertical migration of radionuclides, that groundwater sampled only a few metres away from waste injection points has significantly reduced levels of radioactivity compared with the original injection solutions, and that colloids and naturally present bacterial populations occur in the groundwaters and could influence radionuclide transport processes. The final report on the project has been published under **EUR 20615.**

HUPA

Title: Effects of Humic Substances on the Migration of Radionuclides: Complexation and Transport of Actinides

Co-ordinator: Gunnar Buckau, FZK, Germany
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Abstract: objectives and results to date

To quantify the impact of humic colloid mediated transport for the assessment of the long-term safety of nuclear waste disposal. For this purpose, actinide ions are being studied and the required database is complemented to generate data for the interaction of actinides and iodine with dissolved and surface-bound humic substances. The overall approach is to generate knowledge and process understanding for the generation of humic substances under natural conditions, as well as the generation from clay organic matter under perturbed geochemical conditions in the near-field.

PADAMOT

Title: Palaeohydrogeological data analysis and model testing

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Abstract: objectives and results to date

Because the long-term safety of an underground repository depends on the continued performance of the repository environment, in- sufficiently isolating the wastes and attenuating any releases, demonstrating that climatic impacts do not degrade containment properties is important. Scenarios for groundwater evolution relating to climate change are currently poorly constrained by data and process understanding. There is some criticism that current hydrogeological models are over simplified and do not address the full variability inherent in natural systems over time. PADAMOT is using mineralogical and hydrochemical data to investigate changes in groundwater conditions over time, as a result of changing climate, to develop improved process understanding and process models from these quantitative data. This work includes innovative modelling of reactions coupled with transport.

Minerals and groundwater at sites in Spain, the Czech Republic, Sweden and the UK are being investigated to relate their evolution to the environmental record. Isotopic signatures of fracture minerals from near-surface rocks are being compared with deep fracture minerals to find out the differences between deep and shallow impacts of past environmental conditions. Samples are being used to evaluate analytical techniques that were not previously available, e.g. ion probe and laser ablation. These new techniques are helping PADAMOT scientists to distinguish between specific groundwater episodes. It is anticipated that the data will give information that will enable zones to be compared with the chronology of past climatic events.

Results will provide guidance and data on varying geosphere conditions in response to changing environmental conditions and climate. Knowledge will be interpreted and synthesised in order that it can have direct application to safety assessments. The enhanced understanding will have generic value for all radioactive waste management agencies and regulators, as well as site-specific significance.

Further information available at:
http://www.bgs.ac.uk/padamot

RETROCK

Title: Treatment of geosphere retention phenomena in safety assessments

Co-ordinator: Mikko Nykyri, Safram Oy, Finland
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Abstract: objectives and results to date

To examine how the retention and transport of radionuclides are and should be recognised in PA models for deep geological repositories in saturated hard fractured rock. The project judges in depth the available concepts, their applicability for simplified PA models, and seeks the proper measuring approaches and data abstraction schemes (data "up-scaling") for the utilisation of experimental data. The main focus is on examining whether simplifications frequently adopted in PAs can be defended with more complex process models, experiments, and other scientific knowledge bases. Information was solicited through a questionnaire. In the next stage, the scientific basis of the modelling concepts, their applicability for integrated PA models, measuring approaches and data up-scaling for the utilisation of the experimental data were evaluated. In-depth discussions examined the most important and contentious concepts. An additional aim is to enhance the communication between the various disciplines, especially between PA modellers and other researchers. RETROCK has already directed attention to a number of PA modelling issues that probably require future developments.

TRANCOM II

Title: Transport of radionuclides due to complexation with organic matter in clay formations

Co-ordinator: Norbert Maes, SCK.CEN, Belgium
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Abstract: objectives and results to date

To develop and demonstrate a conceptual model for the description of the migration of radionuclides in natural organic matter (NOM) rich, chemically reducing clay environments (using the Boom clay) that can be implemented in performance assessment models. The project addresses the migration behaviour of radionuclides identified as important for long term safety (U, Se, Pu). The transport mechanism of the radionuclide species studied is mainly dominated by an immobilisation process (reduction-precipitation in case of U and Se, or a strong quasi-irreversible interaction with the solid phase for Am) combined with a constant release of a low concentration of the radionuclide. For Se and U, constant release is controlled by a solubility limit of the precipitated phases and the transport is independent of NOM. The dominant effect of NOM on U was the formation of colloids. The formation of organic complexes could not be demonstrated. These colloids (> 2 nm) did not increase the U mobility as they were immobilised in the host formation by ultrafiltration. Am (analogue for trivalent Pu) becomes immobilised upon interaction with the clay solid phase but this is not controlled by solubility. Am complexes easily with mobile NOM, but upon interaction with the clay, the bulk of these complexes dissociate instantaneously and only a small part persists as a "stabilised" complex with slow dissociation kinetics. In the presence of an Am inorganic solid source, this results in a constant release of "stabilised" Am-OM complexes at a concentration level some orders of magnitude lower than its solubility. For Pu, the underlying processes are not understood and the question remains whether Pu will be present as Pu(IV) or Pu(III) under reducing clay conditions but the behaviour in the migration experiments resembles that of Am. Colloids were found to be either unstable in, or filtered by, the Boom clay. A transport model, POPCORN, was developed to describe and evaluate the influence of NOM on radionuclide transport in clay. The methods, results and conceptual models developed for the Boom clay also serve as a reference for other clay formations and waste types (chemo-toxic wastes). The final report on the project has been published under **EUR 21022**.

Public involvement in repository programmes

COWAM

Title: Nuclear waste management from a local perspective

Co-ordinator: Gilles Heriard-Dubreuil, MUTADIS Consultants, France
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Abstract: objectives and results to date

To empower local actors through a networking process between different local contexts, countries and cultures; to gather and discuss the experiences of decision-making processes at the local level within their national context in Europe; to set up an arena for balanced exchanges between local actors, NGOs, regulators and implementers; and to promote new approaches to decision-making in national contexts in Europe. Two hundred and thirty delegates from ten countries met. Thirty local communities were involved and local communities and NGOs represented 65% of the audience. In each seminar, case studies in different local and national contexts were reviewed. They were presented by people coming from different positions and playing different roles in the decision-making process. Five main issues were identified: local democracy; expertise in the local decision-making process; influence of the local actors on the national nuclear waste management framework; regional development policy; and site selection process. Local people and representatives are interested in playing an active role in the discussions over nuclear waste management issues. The usual technical divisions between types of waste or between options are not very relevant when trying to understand the issues faced by communities. This sharing of experience points out good practices which can be adapted from one country to another or used to stimulate local empowerment.

The conclusions are available at:
http://www.cowam.com/final.htm

RISCOM II

Title: Enhancing transparency and public participation in nuclear waste management

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Abstract: objectives and results to date

To support transparency of decision-making processes by means of a greater degree of public participation. The findings are expected to be relevant for decision-making in complex policy issues in a much wider context. Performance assessment (PA) in particular has been an activity where experts communicate with other experts. Now, the users of PA have widened to include members of the public, concerned groups and communities involved in site selection processes. The experts thus have to communicate facts and values with stakeholders and decision-makers. As regulatory standards and criteria set the framework for PA, it is important to open them up for public input. It was shown by organised hearings that the RISCOM model can be used to support the design of public events and decision processes for the sake of transparency. The project found that evidence from dialogue processes suggests that the actual use made of information is minimal. This suggests that great care should be taken in targeting information resources where they will be most useful. A nuclear waste management programme must have resources to allow for citizen participation. Proper resources will encourage positive engagement, improve decision-making, and increase public confidence.

Thematic Networks

ACTINET

Title: Network of excellence for actinide sciences

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Abstract: objectives and results to date

To sustain and disseminate knowledge and expertise, as well as to maintain a threshold level of research activity in actinide sciences in Europe. This particular research area requires reinforced links between national nuclear research institutes, the JRC, and radiochemistry laboratories of a number of academic research organisations: networking will not only facilitate the co-ordination and utilisation of available facilities, but will also consolidate, optimise, and give the necessary impetus to enliven the research and training activities in actinide sciences in Europe. The Thematic Network ACTINET has been used to launch a sustainable network gathering a number of institutions from large national laboratories to university departments, within the broad area of actinide science, with the following objectives for FP6:

- significantly improve the accessibility of the major actinide facilities to the European scientific community, and form a set of pooled facilities that will evolve to a multi-site user facility, as the cornerstone of a progressive integration process
- improve mobility between the ACTINET member institutions, in particular between academic institutions and national laboratories holding the pooled facilities, facilitate mobility of young researchers within the Network, and promote doctorate students
- merge part of the research programmes conducted by the member institutions, and optimise the research programmes and infrastructure policy via the ACTINET management procedures
- strengthen European excellence through the internal selection process of the joint programme proposals, and reduce the fragmentation of the community by putting critical mass of resources and expertise on shared challenges, in order for Europe to remain or become a world force in the fields of actinide sciences
- disseminate knowledge on actinide sciences through various databases, communications in workshops and seminars, and joint activation of research tools (e.g. modelling and code development).

COMPAS

Title: Comparison of alternative waste management strategies for long-lived radioactive wastes

Co-ordinator: Mark Dutton, NNC Ltd, UK
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Abstract: objectives and results to date

To compare strategies that have been adopted or are being considered for the management of spent nuclear fuel and long-lived radioactive waste, involving individuals from the waste management organisations of 15 countries. The project was organised around a series of four workshops. At each of these, the strategies, approaches and data relevant to each country were presented and discussed. The first workshop addressed the historical basis of the existing waste, its categorisation and the amount of spent nuclear fuel and waste that will have to be managed as a result of the existing nuclear power programmes and the other sources of radioactive waste. The roles of reprocessing and partition and transformation in affecting the waste to be managed were also addressed. The second workshop looked at the issues that determine the strategies that had been adopted or were being considered by each country. These included international treaties, European directives, technical and financial issues as well ethical issues. The third workshop determined which issues affected key decision points in the management of the fuel and materials in both the short- and long-term. It also identified the generic strategies that are being implemented or being considered and the reasons for them. The final workshop identified the key issues that affect the success or otherwise of implementing a long-term management solution, such as a repository, and, based on the experience of the participating counties, identified the key aspects of the process leading up to a successful selection of a site. Other issues, such as the potential use of multi-national repositories were also addressed. The final report on the project has been published under **EUR 21021.**

CROP

Title: The cluster repository project

Co-ordinator: Christer Svemar, SKB, Sweden
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Abstract: objectives and results to date

To review and collect information on design, construction and modelling of engineered barrier systems (EBS) as well as on experimental procedures within various types of geological environments in nine networking countries.

Several national underground research laboratories (URLs) for studying the possibility of safe deep disposal of radioactive waste have been in operation for different periods of time and have formed the "Cluster" of URLs in this project. They represent various geological media, such as crystalline rock in Sweden (Stripa and Äspö), Finland (Olkiluoto), Switzerland (Grimsel) and Canada (Pinawa), bedded salt and salt domes in the United States of America (WIPP) and Germany (Asse), respectively, and sedimentary clay formations in Belgium (Mol), France (Bure) and Switzerland (Mt. Terri). The various geological situations have led to different design and instrumentation of the aforementioned URLs. However, the engineered barriers have a similar function and, despite some obvious differences, many of the solutions and techniques are believed to be applicable to disposal concepts in various rock types. The results from tests conducted in many different geological media and involving a large number of engineered barrier system components are expected to be valuable to all organisations involved in repository development.

The project notes that all studied repository concepts fulfil very high demands on long-term safety, and reports on areas where lessons have been learned, issues remain, and has indicated areas of high potential for technical improvements of repository concepts and the testing of them.

MONITORING

Title: Monitoring in a Stage Approach to Disposal

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Abstract: objectives and results to date

To improve the understanding of and the options for monitoring within a phased disposal concept and to identify how monitoring can contribute to decision-making, operational and post-closure safety, and overall confidence in safety. The chosen methodology will be motivated by the monitoring needs at each step of a phased approach, but constrained by technical difficulties and by the available technology. The aim of monitoring is to provide information for making decisions. This could include: acceptability of operating conditions for personnel and general population; provision of an environmental database on the site and its surroundings for current and future generations; confirmation of the understanding of some aspects of system behaviour used in developing the safety case, and to allow further testing of assessment models or provision of additional information to give society confidence to take decisions on the major stages of the repository development programme. It will also strengthen confidence, for as long as society requires that the repository has no undesirable impacts after closure. In determining the duration of certain monitoring activities, the evolution of the repository needs to be considered, as well as this societal component. The final report on the project has been published under **EUR 21025**.

NET EXCEL

Title: Networking for research on radioactive waste geological disposal

Co-ordinator: Christer Svemar, SKB, Sweden
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Abstract: objectives and results to date

Concerns the forming of a network of European end-users for analysing the present status and future needs in research, technological development and demonstration (RTD) for the disposal of highly radioactive waste in the three classical rock media: salt, clay/clay sediments and crystalline rock. The aim is to generate value additional to that gained by the individual participants. The expected results of the project are a common and systematic basis for prioritisation and co-ordination of future European research and development work for radioactive waste management, and suggested areas and priorities for joint European projects.

In general, there are differences in the type of high-level and long-lived radioactive waste (for instance, either spent fuel or vitrified waste if the reprocessing option is considered by utilities) that the participating organisations have responsibilities for, and the time schedules for their work. The national regulatory framework may also induce some differences. One of the initial issues of the project is to shed light on the rationale for these observed differences.

In contrast, the practical way to carry out the necessary RTD activities and the principles behind the process is to establish priorities for the necessary RTD-work is quite similar. Common ground is analysed for the role/responsibilities of the participating organisations, for the establishment of priorities for the RTD work, and for the *modus operandi* of the organisations to carry out the RTD. The issue of prioritising the potential RTD activities is addressed and the factors taken into account by the participating organisations have been summarised and analysed with respect to the common denominator in the project. The expected results of the project are a common and systematic basis for prioritisation and co-ordination of future European research and development work for radioactive waste management, and suggested areas and priorities for joint European projects.

GASNET

Title: Gas issues in safety assessment of deep repositories for radioactive waste

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Abstract: objectives and results to date

To evaluate the present treatment of gas issues in safety assessments of deep geological repositories for radioactive waste, and to improve the translation of scientific information on these issues into safety arguments for such repositories. The emphasis of the work was on the requirements of safety cases rather than on reviewing understanding of gas generation and migration processes, as this had already been addressed in recent work that provided the background to the GASNET project.

The end result of the project is a report that documents the current approaches used in dealing with gas issues in safety assessments and the strengths and limitations of these approaches. By considering the general requirements for dealing with gas issues in safety cases, the work was also intended to strengthen the foundation for assessing gas issues in safety assessments. The final report considers requirements for the treatment of gas issues in the context of a safety case for a deep repository, with documentation of current approaches and discussion of the strengths and limitations of these approaches, where appropriate. Only the effects of gas generation after repository closure from the wastes and repository construction materials that are present are specifically addressed, although the influence of processes occurring prior to closure on the inventory of gas-generating materials remaining at closure, does fall within the scope of the study. The concluding section of the report contains a summary of the principal general uncertainties identified in the GASNET project in assessing the effects of gas generation in repositories, and of those gas-related issues for which it currently remains difficult to provide a satisfactorily robust treatment. The final report on the project has been published under **EUR 20620**.

NAnet

Title: Natural analogue studies and their applications to repository safety assessment and public communication

Co-ordinator: Bill Miller, ENVIROS Ltd, UK
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Abstract: objectives and results to date

To review past and present use and understanding of natural analogues with the intention of promoting more considered applications of them in future safety assessments and for public communication. This involves a comprehensive and critical re-examination of published studies.

In addition to true 'natural' analogues, the NAnet project also considers archaeological and industrial analogues (e.g. the degradation of old man-made materials) and anthropogenic analogues (e.g. where radionuclides have been deliberately or accidentally released into deep or shallow environments).

The scope of the project includes analogues that are relevant to the most common radioactive waste repository design and concepts, including surface and near-surface repositories for LLW and deep repositories for HLW or ILW. The project considers the potential wide-ranging applications of qualitative and quantitative analogues information to safety cases which employ multiple lines of reasoning, rather than just to the more restricted scope of mathematically based radiological performance assessments. The project also examines attempts that have previously been made to use natural analogues to communicate with the stakeholders on radioactive waste management issues.

In the light of this, NAnet has a clear aim of recommending how a more thorough use and understanding of analogues in future safety assessments can be achieved and how better utilisation in terms of 'added value' is possible from previous analogue studies.

Further information available at:
http://www.enviros.com/zztop/nanet/

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