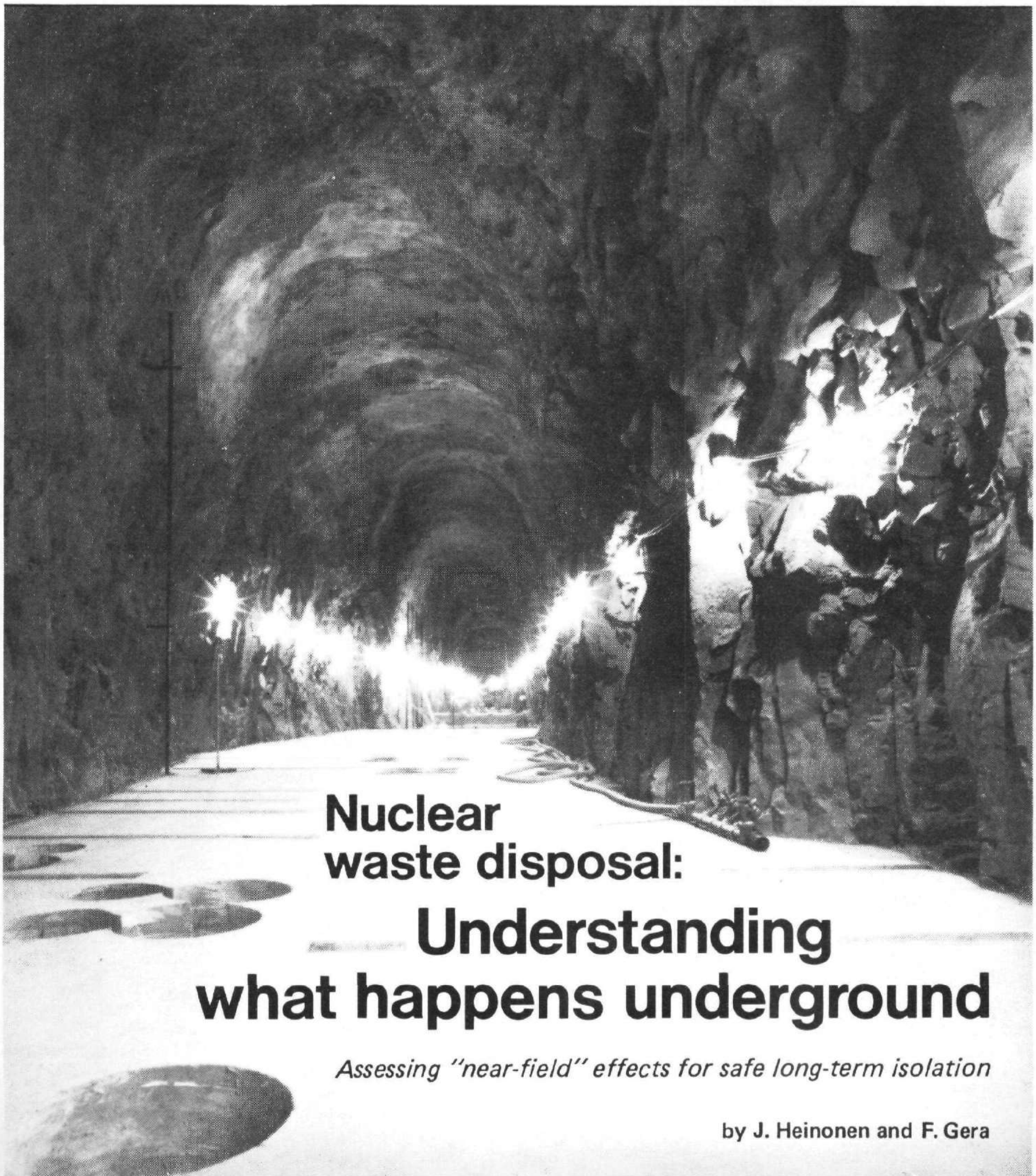


Nuclear waste disposal: Understanding what happens underground

Assessing "near-field" effects for safe long-term isolation

by J. Heinonen and F. Gera

Many different kinds of repository systems are under consideration, development and – for certain types of waste – even in operation. These systems are based on different host rocks and repository designs.

In simple terms, the concept of multiple barriers prevails in radioactive waste disposal. Repositories located in host rocks characterized by a certain potential for radionuclide transport will require that other components of the disposal system compensate for this by preventing or restricting mobilization of radionuclides.

Effects in the "near-field" – a term that generally refers to the excavated repository itself, the waste package, and the host rock (see accompanying box) – are fairly well understood for certain types of rock and repository

Mr Heinonen is a former staff member in the Agency's Division of Nuclear Fuel Cycle, and Mr Gera is on the staff of the Instituto Sperimentale Modelli e Strutture, S.p.A. (ISMES), Via dei Crociferi 44, I-00187 Rome, Italy.

Photo shows tunnel in basalt rock, which is one geologic medium for nuclear waste disposal. Basalt is a dense volcanic rock deposited by lava flows that slowly covered the earth's surface up to 16 million years ago. (Credit: Atomic Industrial Forum) designs, and when considered separately.* Near-field effects discussed here are waste package corrosion, leaching, chemical and mineralogical changes, modifications of groundwater flow, and transport of radionuclides to the far-field.

These various individual effects have to be considered together to assess the performance of disposal systems in containing radioactive wastes. This coupling is the most difficult part of the assessment and the one where additional work is still required to reduce uncertainties about the performance of the various near-field components.

For example, the thermo-mechanical effects in a hard rock repository may affect the permeability of the rock and the groundwater flow in a way that may be difficult to model satisfactorily. In addition, the chemical environment may be changed by the presence of the waste, and oxidizing conditions may result from radiolysis. On the other hand, the engineered barriers surrounding the waste can be designed in such a way that any uncertainty about coupling of near-field effects and about long-term behaviour of the various components will be counterbalanced by their great capacity to isolate the critical radionuclides.

Deep *in situ* experiments still are needed, for example, to help clarify certain near-field effects, as well as to quantify the impact of certain parameters. All this will aid in the integration of near-field effects in the performance assessment of the entire disposal system. Large projects in several countries should improve the understanding of near-field phenomena and promote dissemination of this specific knowledge. The development of specific disposal systems, in particular for high-level, long-lived waste, necessitates complex and extended site-specific investigations.

In general terms, the safety of waste disposal will be improved by the increased knowledge and maturity of technology, and experimental data will allow the verification of models often based on laboratory experiments and theoretical considerations.

Waste package corrosion

No mobilization of radionuclides — which is assumed to depend on leaching by groundwater — is possible as long as the waste package maintains its integrity. The waste package consists of the waste form, the canister and, when applicable, other barriers such as overpack, absorber material, and chemical conditioners, provided they are integral parts of the package. It is possible to design waste packages that are expected to last for almost any length of time. Designs for lifetimes in excess of 100 000 years have been considered, but most waste packages are expected to last much shorter times.

Different kinds of materials can be used in waste packages. Some concepts rely on materials that are thermodynamically stable in the environment of the

"Near-field" effects — defining terms

In assessing a geological disposal system for long-lived radioactive waste, it is necessary to understand the long-term behaviour of the various components contributing to waste isolation. It is obvious that the important characteristics of an isolation system are those affecting overall performance, in particular from the safety viewpoint.

However, to facilitate the performance assessment of underground repositories the relevant phenomena are divided into near-field and far-field ones. This is an arbitrary distinction since no well-defined physical boundary exists between the two. This article discusses processes taking place in the near-field in different host rocks and with different disposal concepts. The near-field is defined as "the excavated repository, including the waste package, filling or sealing materials, and those parts of the host medium whose characteristics have been or could be altered by the repository or its contents."

The number and nature of components actually present in the near-field is specific to particular disposal systems and depends on the nature of the host rock and the waste and on the engineering aspects of the repository. Most near-field effects discussed here are relative to disposal of high-level vitrified waste and spent fuel, but, whenever appropriate, effects specific to other types of waste have been considered.

Specific components

The components of the near-field can be grouped as the waste package, the repository, and the host rock.

The **waste package** includes the waste form, its container, and any additional barriers, provided they are integral parts of the package.

The **repository** is the underground facility into which the waste packages are emplaced. It includes any engineered barriers that separate waste packages from host rock, structural materials such as tunnel lining and hole liners, and materials used for backfilling and sealing.

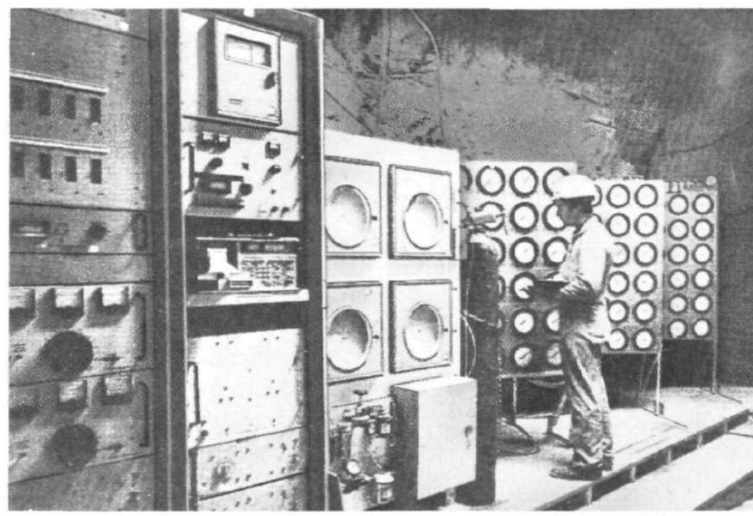
The **host rock** included in the near-field is that part of the disposal medium where physical properties and chemical conditions are significantly modified by the repository. The actual extension of this altered zone will vary depending on waste type, repository design, and host rock, but it will range up to a few tens of metres at the most.

The near-field is surrounded by that section of the host rock where repository-induced changes are minor and by any additional geological materials that may exist between the host rock and the ground surface. The geological environment around the near-field, or the far-field, is not the subject of this article. But it has strong interactions with the near-field since near-field processes determine the source term for transport of radionuclides in the geosphere. Conversely, the migration potential in the far-field determines the number and nature of barriers installed in the near-field.

The types of rocks presently considered as potential host rocks for long-lived radioactive waste include rock salt; granite and similar crystalline rocks; argillaceous rocks; tuff; and basalt.

* For fuller technical information, see "Deep Underground Disposal of Radioactive Waste — Near Field Effects", the draft of an IAEA Technical Report, June 1984; and "Effects of Heat from High-level Waste on Performance of Deep Geological Repository Components," the draft of an IAEA Technical Document, October 1983.

During a series of experiments from 1977–80 at the Stripa mine in central Sweden, scientists assessed the deep underground disposal of nuclear waste in hard crystalline rock. Above, ultrasonic measurements were performed during a full-scale heater experiment. Below, the macro-permeability experiment measured water pressures in about 100 sections and 15 boreholes.
(Credit: SKBF KBS, Stockholm).



repository. Other materials, although unstable, would form a protective coating that would drastically reduce further attack. Finally, it would be possible to use relatively thick layers of materials that corrode with a known rate. Decisions about waste packages in specific repository conditions will depend on a number of factors. These include regulatory requirements, the isolation capability of the other barriers, and economics.

Leaching by groundwater

After failure of the packages, waste will eventually come into contact with water or brine. Reactions between the waste matrix and the water will cause some radionuclide dissolution. The rate of reaction will depend on the waste form, the waste composition, the ratio of water volume to exposed surface area, the effective flow-rate of the water past the waste, the temperature, and some other factors, such as radiolysis. The composition of the water contacting the waste depends on the composition of the interstitial water in the host rock. It can be modified by substances derived from buffer and backfill materials and from the waste package. The flux of water past the waste is determined to a large extent by the groundwater flow in the far-field, as this will control the amount of water which reaches the repository. The flow-rate past the waste packages may be further limited by low-permeability materials placed around the waste. These additional barriers can reduce the water flow to very low values and reduce significantly leaching of many radionuclides.

Radiation effects

The near-field environment can be modified by radiation by way of three different primary effects: alteration of the waste form and any buffer material, of any fluids present around the waste, and of the host rock. Due to the shielding capacity of solid matter, gamma radiation will be adsorbed completely within about one metre from the waste containers. Beta and alpha radiation, which are much less penetrating, will be adsorbed within a very small volume of material. However, radiolysis may produce corrosive substances resulting in accelerated corrosion of containers and enhanced leaching of waste. Other radiation effects such as energy storage and changes in physical properties of both rocks and man-made materials have been found to be irrelevant in the context of waste disposal.

Thermal effects

Radiation energy absorbed in matter is transformed into heat. Heat generation is highest in spent fuel and high-level waste but some heat is generated in all types of radioactive waste. In a repository, heat will flow from the waste through container and buffer materials to the host rock, thus raising the temperature of all components of the near-field and affecting their physico-chemical properties. The actual temperature distribution in the repository depends on many factors, including:

- Type and age of waste
- Dimensions and distributions of waste containers
- Volume and nature of buffer and backfill materials
- Repository design
- Type of host rock

Peak temperatures in the repository will be reached a few decades after waste emplacement. Highly reliable computer programs, capable of predicting the temperature distribution in the repository at any particular time, have been developed and verified.

The effects of elevated temperatures on different waste forms, on buffer and backfill materials, and on host rocks have been and continue to be investigated. A thermal effect of particular significance for repositories located in granite or similar crystalline rocks is the possible modification of groundwater flow. If the rock is fractured and water is contained in the fractures, which is practically unavoidable in this type of rock over the dimensions of a repository, then heating may decrease viscosity and density of water and increase the permeability of some fractures, thereby initiating thermally induced flow of water or even convection cells.

The objective of the studies on thermal effects is to develop thermal criteria for the various repository components. The respect of the thermal criteria should ensure that no effects capable of weakening the isolation capability of the disposal system take place. At this time it appears that the most restrictive temperature limits apply to clay minerals present either in the host rock or in the buffer and backfill materials. It is considered prudent to keep the temperature of clay materials below 100°C. Somewhat higher temperatures would be permissible in rock salt; this, combined with the higher thermal conductivity of salt, means that a significantly greater thermal load could be placed in a salt repository.

Thermo-mechanical effects

A particular effect of heating the host rock is its thermal expansion and the resulting stresses in both near- and far-fields. In an excavated repository the rock is already exposed to overburden stresses and possibly to tectonic stresses, which are locally modified by the presence of the excavations. To this relatively complex stress field, thermally induced stresses are superimposed. A large amount of data exists on thermo-mechanical effects in salt. The fit between calculations and observations is very good. In hard rocks like granite, the strains are absorbed by joints and fractures, which are practically impossible to model successfully. As a result some differences exist between theoretical and experimental data.

As far as clays are concerned, few data are available about their mechanical behaviour at repository depths. Even less is known about their thermo-mechanical behaviour since no deep *in situ* tests have been carried out yet. The same is true for other potential host rocks. No particular difficulty is anticipated as a result of thermo-mechanical effects; however, they must be known in order to optimize the design of the repository.

Chemical and mineralogical changes

The excavation of a repository and the emplacement of waste packages and other materials in the host rock is going to disturb the natural equilibrium between host rock and interstitial water. The excavations will introduce oxygen and cause changes in *in situ* stresses and hydraulic gradients. All these disturbances provide the potential for changes in host rock mineralogy and groundwater chemistry. The potential for chemical and mineralogical changes is enhanced by the temperature rise due to the waste. However, these changes are expected to be minor and restricted to a small volume of material if sound thermal criteria are used in the repository design.

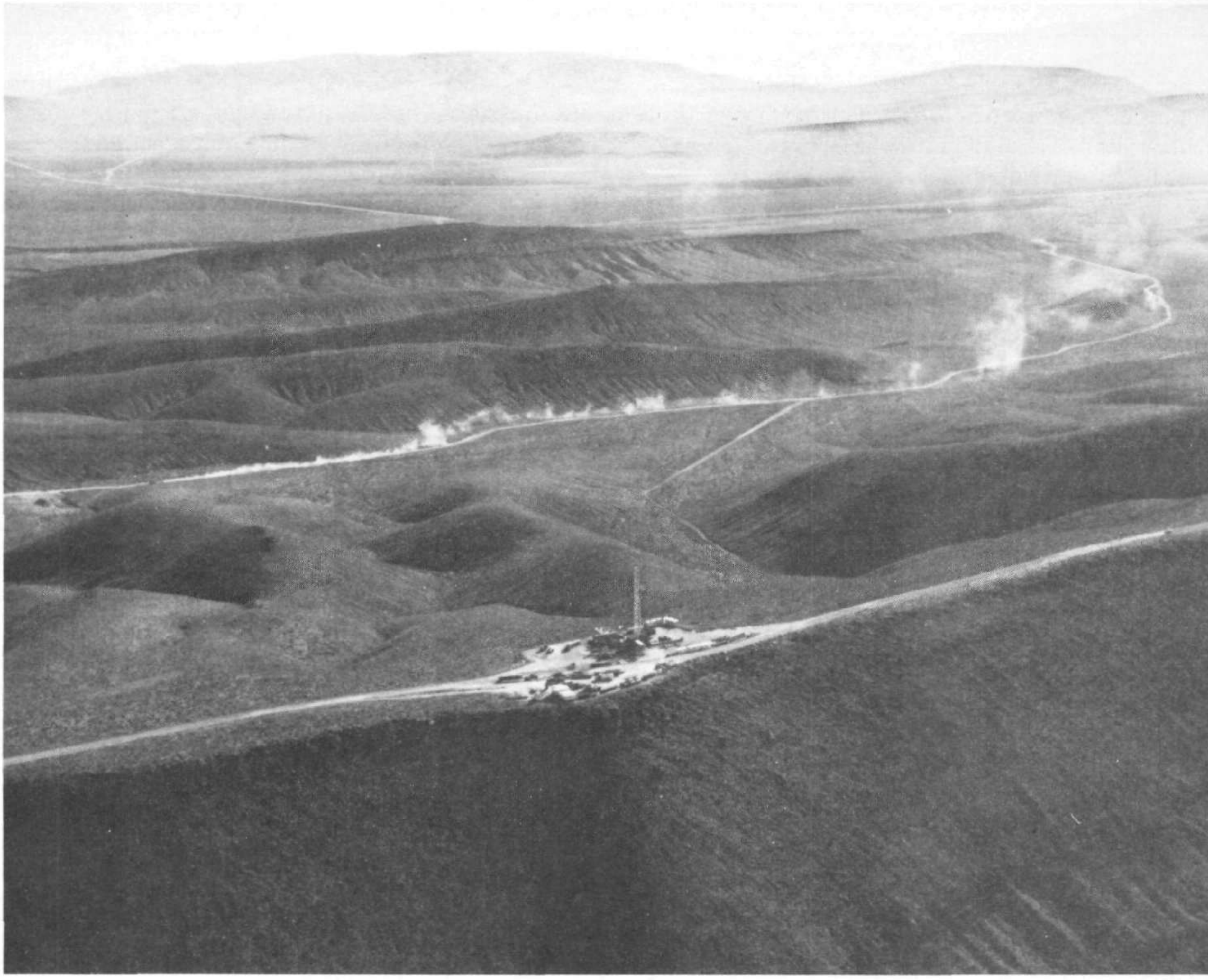
Groundwater flow

Since water is the main transport medium for any radionuclides released from waste packages, any modification of groundwater flow can be of particular interest. As far as near-field effects are concerned, groundwater flow can be modified by four basic mechanisms:

- Introduction of low-permeability barriers
- Draining effect of underground excavations
- Changes in the physical properties of the host rock
- Heating caused by the waste

The potential for water migration in the near-field is different for each of the proposed host rocks. Salt is usually extremely impermeable and free from circulating water. The only water in the disposal zone will be present as brine in small inclusions. The overall water content in salt is normally in the order of 1-to-2% in bedded salt and well below 1% in diapiric salt. The main near-field effect in salt would be the migration of the brine inclusions towards the heat sources. While this phenomenon can have significant effects on the chemical conditions around the waste and on container corrosion, the volumes of brine are too small to cause any significant migration of radionuclides.

Groundwater circulation in granite and similar crystalline rocks is controlled by extent, characteristics, and interconnection of fractures, and by the regional hydraulic gradient. A body of hard rock considered suitable for waste disposal must be characterized by very low hydraulic conductivity; that is, few fractures must be present and they must transmit very little water since



Isolation: Tuff formations at the Nevada Test Site are one of several areas in the US being investigated as potential sites for a geologic repository for disposal of high-level radioactive waste. Tuff is a rock made up of solidified and welded volcanic ash, with separate layers deposited by successive eruptions millions of years ago. (Credit: Atomic Industrial Forum).

they are closed by the overburden pressure, by the accumulation of secondary minerals, or by a combination of the two mechanisms. The excavation of a repository in such a geologic environment will modify groundwater flow even before any waste is placed underground. This will be due to the draining effect of the excavations, which being at atmospheric pressure will act as a point sink, and to the changes in permeability that the modification of the stress field may induce in fractures adjacent to the openings.

After waste emplacement has taken place and the repository has been backfilled, the near-field hydrology can be further modified by the thermo-mechanical effects already discussed, and by the presence of buffer and backfill. In conclusion, hydrogeological modelling of a repository in hard rock can be complex. The resulting uncertainties can be compensated either by the great capacity of the far-field to restrict radionuclide migration or by the engineered barriers placed in the repository.

Argillaceous rocks are usually characterized by very low permeabilities. In plastic clays all water flow is through the pores, while in stiff clays and shales some water-bearing fractures seem to be possible. It is anticipated that any argillaceous formation considered suitable for waste disposal would not be intersected by permeable fractures. After waste emplacement and after backfilling and sealing of the repository, near-field conditions will depend on the repository design.

For example, in a repository based on a matrix of boreholes drilled from the surface, each borehole would be isolated from the others and containers would be more or less directly in contact with the clay. In case of a mined repository, the waste containers could be placed in disposal holes drilled from the galleries or within the galleries themselves. In either of the latter two cases, the galleries would be filled with a material with hydraulic properties probably different from those of the undisturbed clays.

Consequently, the near-field hydrogeology would be significantly different from the initial conditions in the formation. However, provided that connections between the repository and the surface are plugged and that no new flow paths are generated by subsequent events, then near-field changes of groundwater flow are local and short-lived and are expected to have little impact on the overall performance of the disposal system.

For a repository located in tuff in the unsaturated zone little effect would be expected on the flow of groundwater as a result of waste emplacement. The thermal field in the disposal area would be expected to drive away water and reduce the flow past the waste packages.

For a repository in basalt the effects on groundwater flow would be similar to those already described for a repository in granite.

Radionuclide transport to the far-field

All near-field effects described so far should not be considered in isolation; on the contrary, the analysis should concentrate on their coupling and lead to a realistic assessment of the potential for radionuclide transport to the far-field.

For a repository in granite and similar crystalline rocks, the release and transport of the radionuclides will mainly be determined by the rate of water flow in the fissures in the rock. The presence of ferrous iron minerals controls the redox potential of the water and may limit the solubility of many of the actinides to very low values. The radionuclides may also diffuse into the matrix of the rock and sorb into pore surfaces. This will withdraw them from the water flowing through the fissures.

For a repository in salt, no transport of radionuclides to the far-field is possible if no additional fluids enter the near-field from outside the repository. In case of flooding of the repository – an event that suitable design can make extremely unlikely – transport of radionuclides to the far-field would be strongly dependent on the repository layout.

For a repository in argillaceous rocks, assuming that no abnormal events take place and no preferential pathways are generated through the formation, the migration of radionuclides would be controlled by diffusion. For a clay formation of suitable dimensions and with representative hydraulic properties, it can be calculated that sorbing radionuclides would decay to insignificant levels within a few metres of the waste packages. On the other hand, non-sorbing radionuclides, such as Iodine-129, could migrate to the far-field and partially escape the disposal formation.

For a repository in tuff the migration of radionuclides through the near-field would depend, as in other rock types, on the rate of mobilization of radionuclides and on the magnitude of fluid flow. Sorbed species will be retarded mostly by reactions with zeolites, which are secondary minerals formed by the alteration of ash. The effectiveness of tuff as a geochemical barrier will depend strongly on the zeolite content. Consequently, any assessment of the potential transport of radionuclides in a particular tuff formation will require specific data about fluid flow and mineralogical composition of the rock.

For a repository in basalt the situation would be somewhat similar to the one described for granite, since radionuclide transport would occur as a result of water flowing through fractures. The same uncertainties about coupling of thermo-mechanical effects with fracture permeability and groundwater flow would exist. The uncertainties can be reduced by site specific data and counterbalanced by effective engineered barriers.

Ongoing and future studies

The following list consists of examples of activities either ongoing or planned, which can contribute to a better understanding of near-field effects:

- Investigations of groundwater flow in different geological environments
- Studies on migration of radionuclides in various rocks and in various hydrogeological conditions
- Verification of models; in particular identification, quantification, and verification of certain parameters
- Investigation of different buffer materials, including buffer mass tests and comprehensive analyses of the results
- Heat transfer experiments in various potential host rocks
- Study of thermally induced rock movements
- Improvement of methods for evaluation of rock behaviour, including effects of rock stress and fracture generation
- Chemical and physico-chemical behaviour of certain important radionuclides, for example mechanisms of dissolution, leaching, and migration of actinides.