Identifying and testing indicators for assessing the long-term performance of geological repositories

The European SPIN project
(project FIKW–CT–2000–00081)

Geological disposal is currently a widely studied solution for the long-term management of high-level and long-lived radioactive waste. But how can we assess the resulting level of safety? The European SPIN project identified and assessed safety and performance indicators that are complementary to radiation doses to humans. Besides providing alternative ways to evaluate the safety of future geological repositories, these indicators help understand how such repositories work by visualising both their global performance and that of their individual components.

The most widely studied solution for the long-term management of high-level and long-lived radioactive waste is geological disposal. Geological disposal isolates the waste from human beings and the environment—the biosphere—for as long as is necessary, through emplacement in a repository built in a stable geological formation (Fig. 1), such as a granite, clay, or salt layer. Because the timescales associated with geological disposal are so long—that is, of the order of 10^6 years or more—perfect isolation is impossible to achieve. This solution minimises however the likelihood of radionuclides reaching the biosphere at such a rate and in such quantities that they would be detrimental to human beings and the environment.

Since the relevant timescales make it impossible to resort to classical experiments to prove the long-term safety of geological repositories, specialist teams around the world have developed methods to assess safety by indirect means. These methods use mathematical models to represent possible evolutions of the repository under study and to calculate how radionuclides migrate towards the biosphere. Comparison of the calculated results with appropriate reference values provides an *indication* of the potential radiological impact of the repository.

Historically, most safety assessments have relied on the calculated *effective dose rate* as the main indicator of the level of safety provided by a repository. The calculated dose rate provides a direct measure of the potential health detriment and is commonly used also for assessing the safety of other nuclear activities, such as medical and industrial activities. It is normally compared with regulatory limits that represent the maximum dose that an individual may receive annually. However, the results of dose rate calculations inevitably are subject to some level of uncertainty, which increases with time. Such calculations depend indeed strongly on certain aspects that are inherently unpredictable, such as the evolution of human behaviour and the evolution of the biosphere.

Despite the usefulness of the calculated dose rate, there is thus increasing recognition that safety cases for geological repositories should incorporate a range of additional indicators, including indicators that are particularly suited to very long time frames. Identifying and assessing such additional indicators has been the task of the SPIN project. This project has been sponsored by the European Commission as part of its continuing commitment towards radioactive waste management.

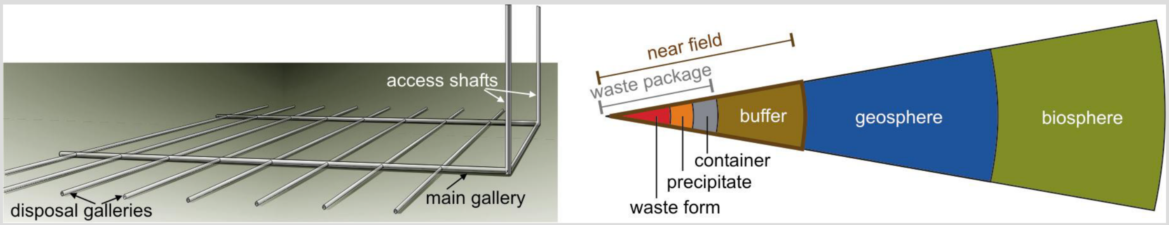

Figure 1 Global and detailed views of a generic geological repository with horizontal disposal galleries. All geological repositories under development apply the multi-barrier principle: they feature several compartments, each one contributing to isolate the waste from the biosphere.

The SPIN project

The SPIN project brought together organisations from seven European countries already dealing with performance assessments of repository projects. After potential indicators had been identified, they were tested by computing them for the repository concepts in granite formations developed in some of the participating countries. Where applicable, the results were compared with indicative reference values derived from regulations or natural processes. The various indicators were then evaluated against a number of assessment criteria, the main criteria being their added value compared to other indicators and their ease of understanding.

Alternative indicators

Twenty-one potentially useful indicators, including the effective dose rate, have been identified and then tested through model calculations (see box). Seven indicators are intended to help assess the global performance of geological repositories in terms of their impact on human health, namely *safety indicators*. Fourteen indicators are concerned with how geological repositories and their individual components isolate the waste, namely *performance indicators*. The following explains some of the most significant results of SPIN, with special emphasis on the type of information these indicators convey.

The twenty-one indicators tested

Safety indicators

Effective dose rate	[Sv/y]
Radiotoxicity concentration in biosphere water	[Sv/m^3]
Radiotoxicity flux from geosphere	[Sv/y]
Radiotoxicity outside geosphere	[Sv]
Time-integrated radiotoxicity flux from geosphere	[Sv]
Relative activity flux from geosphere	[–]
Relative activity concentration in biosphere water	[–]

Performance indicators

Activity in compartments	[Bq]
Activity outside compartments	[Bq]
Activity flux from compartments	[Bq/y]
Time-integrated activity flux from compartments	[Bq]
Activity concentration in compartment water	[Bq/m^3]
Radiotoxicity in compartments	[Sv]
Radiotoxicity outside compartments	[Sv]
Radiotoxicity flux from compartments	[Sv/y]
Time-integrated radiotoxicity flux from compartments	[Sv]
Radiotoxicity concentration in compartment water	[Sv/m^3]
Transport time through compartments	[y]
Portion of not totally isolated waste	[–]
Time-integrated flux from geosphere / initial inventory	[–]
Concentration in biosphere water / waste package water	[–]

Safety indicators aim to show how safe a geological repository is

Safety indicators are calculated for the full set of radionuclides and apply either to human beings directly or to the environment. To be meaningful, safety-relevant reference values are required, to which the calculated quantities can be compared. Such values may already have been determined by regulatory authorities, for instance dose constraints. They may also be derived from what is commonly found in nature, applying the premise that natural values in general can be considered to be safe. The safety indicators found most useful for assessing the safety of a geological repository were the effective dose rate, the radiotoxicity concentration in biosphere water, and the radiotoxicity flux from geosphere.

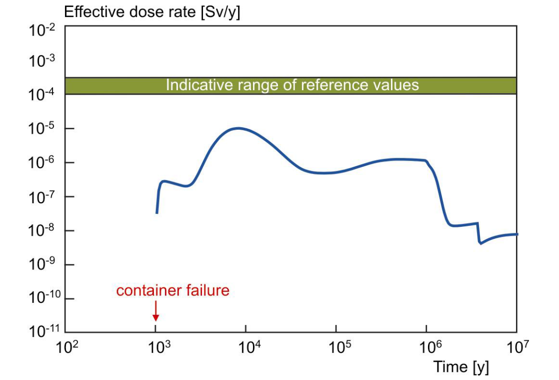

Figure 2 Effective dose rate (GRS).

The **effective dose rate** represents the annual effective dose to an average member of the group who would be most exposed to radiation due to the repository. Its maximum value can be compared easily with the regulatory limit. However, because calculated dose rates rely strongly on the model of the biosphere used in the calculations, the level of uncertainty in these calculations increases with time. Though useful for all time frames, the baseline safety indicator "effective dose rate" is therefore most directly relevant to early time frames. Figure 2 shows that the effective dose rate, as computed in the German study, lies below the range of regulatory limits applied in the countries of the participating organisations, namely 10^{-4} to $3{\cdot}10^{-4}$ Sv/y.

The **radiotoxicity concentration in biosphere water** is a measure of the potential radiological impact on human beings of the use of biosphere water that has been contaminated by radionuclides. This indicator does not consider the biosphere pathways, but depends on the aquifer system, that can evolve significantly over long time frames, in particular as a result of climate changes. Though useful for all time frames, it is therefore most directly relevant to medium time frames. An indicative reference value has been derived from natural radiotoxicity in a broad range of groundwaters. Figure 3 shows that the maximum radiotoxicity concentration in biosphere water is about two orders of magnitude below the indicative reference value.

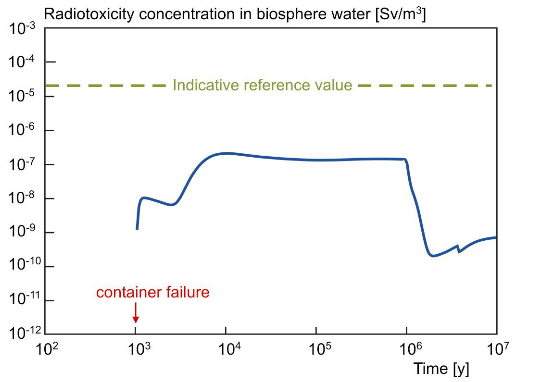

Figure 3 Radiotoxicity concentration in biosphere water (GRS).

The **radiotoxicity flux from geosphere** is a measure of the annual radiological impact on human beings associated with the hypothetical ingestion of all the radionuclides released to the biosphere (Fig. 4). It does not take account of radionuclide transport in the biosphere and in the aquifer system and is therefore most relevant to long time frames. An indicative reference value has been derived from radiotoxicity fluxes found in two potential host environments.

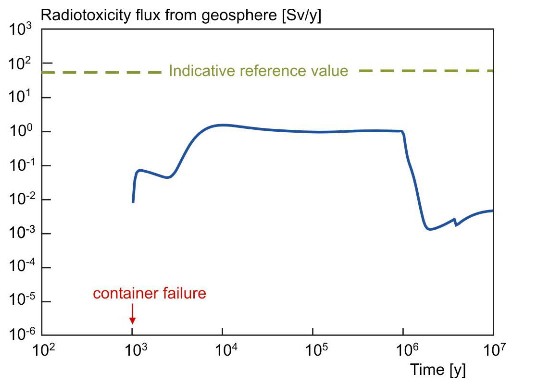

Figure 4 Radiotoxicity flux from geosphere (GRS).

Performance indicators aim to show how a geological repository works

Geological repositories are designed to minimise the radiological impact of the disposed waste. They must thus isolate the radioactive waste from its surroundings for as long as possible and delay the migration of radionuclides when waste containment is no more effective. Groundwaters and surface waters further contribute to reducing the impact on individuals of the fraction of the initial radionuclide inventory that will eventually reach the biosphere.

The fourteen performance indicators identified help understand *how* the different barriers—the engineered barriers and the host formation—contribute to the overall safety of the geological repository. In this way, they can provide input to the design process. Five of these performance indicators are expressed in terms of radiotoxicity and have a counterpart expressed in terms of activity.

It is often not meaningful to sum together activities from different radionuclides, as their toxicity level varies. Performance indicators based on activities are better used for single radionuclides: they enable a comparison to be made of how a geological repository works for different types of radionuclides (short-lived versus long-lived, sorbing versus non-sorbing, highly-soluble versus poorly-soluble) or, conversely, how different subsystems work for the same radionuclide. Performance indicators based on radiotoxicities, in turn, can be used to show how the repository works for all radionuclides together. Some examples are explained in the following.

The performance indicator **activity in compartments**, for instance, shows where the radionuclides are at any time. It enables the retention capacity of the successive barriers to be assessed. This is illustrated by the behaviour of ^{126}Sn as computed in the Spanish study (Fig. 5). After container failure, the ^{126}Sn activity in the waste form starts to decrease. Precipitation inside the waste package and strong sorption on buffer and geosphere materials are such that only a very small fraction of the initial ^{126}Sn inventory reaches the biosphere, with decreasing activities from compartment to compartment. This performance indicator thus illustrates the physical containment and the delaying functions of the geological repository: the repository allows radionuclides to decay as much as possible before they reach the biosphere and limits their release rate.

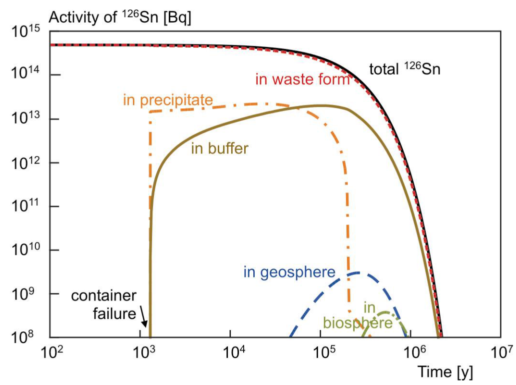

Figure 5 Activity of ^{126}Sn in compartments (ENRESA).

The performance indicator **radiotoxicity flux from compartments** shows the releases from each compartment as a function of time. Usually, peak release rates decrease from compartment to compartment. The studies have indeed shown that long-term radiotoxicity fluxes from the near field are one to two orders of magnitude below those from the waste packages, as illustrated for the Swiss study in Figure 6, and that long-term radiotoxicity fluxes from the geosphere are two to five orders of magnitude below those from the near field. Peak radiotoxicity fluxes from the geosphere are always very small. This indicator is therefore useful to show that the releases are increasingly delayed and spread in time.

Finally, the **time-integrated activity flux from compartments** shows the total amount of a given radionuclide released from each compartment up to a given time. For a given compartment, the amount released is usually smaller than the amount received. The results obtained for ^{126}Sn illustrate this: being highly sorbed, ^{126}Sn migrates very slowly through buffer and geosphere. Since it is relatively short-lived, it decays significantly before reaching the biosphere (Fig. 7). This is because of delay and radioactive decay, the decayed amount in each compartment being given by the difference between the values of the time-integrated activity fluxes from adjacent compartments after infinite time.

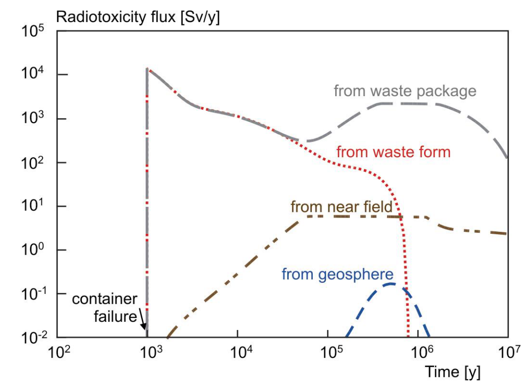

Figure 6 Radiotoxicity flux from compartments (NAGRA/Colenco).

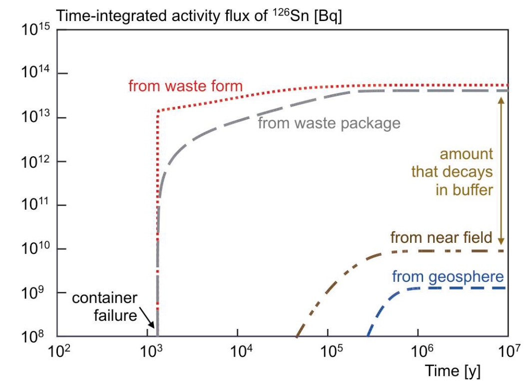

Figure 7 Time-integrated activity flux of ^{126}Sn from compartments (ENRESA).

Conclusions

The SPIN project has successfully identified and assessed a series of indicators that are complementary to the effective dose rate. Safety indicators show *how safe* a geological repository is, provided relevant reference values are available. The alternative safety indicators provide useful additional information about the overall performance of the repository and, since they relate to the behaviour of the engineered and geological barriers—which are less liable to uncertainties than the biosphere—they are more reliable than calculated dose rates in the far future. Performance indicators, in turn, show *how* the repository *works*. Both types of indicator used in combination should thus contribute to enhancing the level of confidence in performance assessments. The effective dose rate remains nevertheless the baseline safety indicator.

Safety and performance indicators also appear as a useful communication tool, likely to help public acceptance of geological repositories. Specialists can indeed use these indicators to show how such repositories work and are thus better equipped to convey to the public their assessments of the safety of those repositories.

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Participating organisations

Germany, *coordinator*

Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS)

Belgium

Belgian Nuclear Research Centre (SCK•CEN)

Belgian Agency for Radioactive Waste and Enriched Fissile Materials (NIRAS/ONDRAF)

Czech Republic

Nuclear Research Institute Rez plc. (NRI)

Finland

Technical Research Centre of Finland (VTT)

The Netherlands

Nuclear Research and Consultancy Group (NRG)

Spain

Empresa Nacional de Residuos Radioactivos SA (ENRESA)

Switzerland

Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (NAGRA)

Colenco Power Engineering Ltd. (Colenco)

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