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GENERAL CONCEPTS OF SUPPORTING THE SAFETY CASE BY MEANS OF SAFETY AND PERFORMANCE INDICATORS
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Foreword

The work presented in this report was developed within the Integrated Project PAMINA: **P**erformance **A**ssessment **M**ethodologies **IN** **A**pplication to Guide the Development of the Safety Case. This project is part of the Sixth Framework Programme of the European Commission. It brings together 25 organisations from ten European countries and one EC Joint Research Centre in order to improve and harmonise methodologies and tools for demonstrating the safety of deep geological disposal of long-lived radioactive waste for different waste types, repository designs and geological environments. The results will be of interest to national waste management organisations, regulators and lay stakeholders.

The work is organised in four Research and Technology Development Components (RTDCs) and one additional component dealing with knowledge management and dissemination of knowledge:

- In RTDC 1 the aim is to evaluate the state of the art of methodologies and approaches needed for assessing the safety of deep geological disposal, on the basis of comprehensive review of international practice. This work includes the identification of any deficiencies in methods and tools.
- In RTDC 2 the aim is to establish a framework and methodology for the treatment of uncertainty during PA and safety case development. Guidance on, and examples of, good practice will be provided on the communication and treatment of different types of uncertainty, spatial variability, the development of probabilistic safety assessment tools, and techniques for sensitivity and uncertainty analysis.
- In RTDC 3 the aim is to develop methodologies and tools for integrated PA for various geological disposal concepts. This work includes the development of PA scenarios, of the PA approach to gas migration processes, of the PA approach to radionuclide source term modelling, and of safety and performance indicators.
- In RTDC 4 the aim is to conduct several benchmark exercises on specific processes, in which quantitative comparisons are made between approaches that rely on simplifying assumptions and models, and those that rely on complex models that take into account a more complete process conceptualization in space and time.

The work presented in this report was performed in the scope of RTDC 3.

All PAMINA reports can be downloaded from http://www.ip-pamina.eu.

1. Introduction

The disposal of radioactive waste in deep geological formation implies a potential hazard to man and the environment. Therefore the most important task for the process of siting and designing a disposal system is to assure that the disposed waste causes no harm for human health and the environment.

A safety case is the synthesis of evidence, analyses and arguments that quantify and substantiate a claim that the repository will be safe after closure and beyond the time when active control of the facility can be relied on [8]. An important part of every safety case is the computational proof of long-term safety for a variety of relevant scenarios that seem possible or, at least, cannot be excluded. The primary outcome of such calculations is radionuclide activity fluxes, which themselves have no direct relevance for safety. To allow an assessment of long-term safety, it is necessary to calculate from the fluxes at least one safety-related measure and to compare it with a suitable reference value. Such magnitudes are called safety indicators.

Most national regulations give safety criteria in terms of dose and/or risk, which are evaluated for a range of evolution scenarios for the disposal system using mathematical analyses. Dose calculations include complex exposition paths depending on biological characteristics of different species as well as on human behaviour. There is a high level of uncertainty about the assumptions that are used when calculating doses to humans. Besides the near-surface processes, which are difficult to predict over long time-scales, in particular the usual assumption that the biosphere properties remain unchanged for the next one million years is highly questionable. Consequently, a safety statement based solely on dose or risk calculations is not very robust.

The robustness of the safety case can be strengthened by the use of multiple lines of evidence leading to complementary also qualitative safety arguments that can compensate for shortcomings in any single argument. One type of evidence and arguments in support of a safety case is the use of safety indicators complementary to dose and risk.

Complementary safety indicators can avoid, to some extent, the uncertainties of doses and risks. In contrast to near-surface and biosphere properties, the possible evolutions of a well-chosen host rock can be predicted with reasonable confidence over much longer time scales, i.e. about one million years into the future. Hence, there is a trend in some recent safety cases towards evaluating safety indicators, in addition to dose and risk, such as radiotoxicity fluxes out of the geosphere, which do not rely on assumptions about human behaviour and can support the safety statement and increase the robustness of the safety case, e.g. [7].

Safety indicators provide statements about the overall safety of a repository system. Additionally it can be valuable to investigate the functioning of the repository system and its components on a more technical level by calculating quantities that describe the effectiveness of individual barriers or parts of the system. Such quantities are called performance indicators. Typical performance indicators are radionuclide concentrations and fluxes in or between different parts of the system. They provide a good means for understanding and communicating the functioning of the system and can support the safety case in an illustrative manner.

The use of complementary safety indicators for assessing the overall safety of a repository as well as performance indicators for demonstrating the functioning of the system has been widely discussed in international fora and projects, e.g. [2], [3]. In the SPIN project [1], it has become clear that the terms “safety indicator” and “performance indicator” are not at all used in exactly the same sense throughout the literature. Therefore, specific definitions were established for the purpose of SPIN. In view of newer developments, however, it seems necessary to refine these definitions. Moreover, there seems to be a variety of similar terms used in different national programmes and by different international organisations with more or less different meanings. The IAEA Safety Glossary [4] provides definitions for many of these terms, which seem, however, to be made from a more general point of view and are sometimes too unspecific, not very helpful, or even misleading for the purpose of PAMINA. Therefore, some definitions are given in this paper in order to create a common basis for PAMINA work package 3.4. These definitions are neither intended to replace any existing definitions nor to anticipate the results of any discussions on the subject going on in PAMINA or elsewhere. It has become clear that that they are not fully in line with the views of all organisations. Nevertheless, the outcomes of WP 3.4 may contribute to the discussion.

After the definitions of safety and performance indicators and related terms in chapter 2, chapter 3 deals with the concept of safety indicators and chapter 4 with the concept of performance indicators. Chapter 5 summarizes the paper by presenting an overall concept for the use of supporting the safety case by means of safety and performance indicators.

2. Definitions

The following definitions are meant as basis for the purposes of PAMINA WP 3.4, in order to propose a sound concept for assessing long-term safety of repositories by means of safety and performance indicators. Only those terms that are necessary for a clear view of the subject are discussed. A top-down approach is pursued, starting with a definition of the overall goal that is to achieve by using the indicators.

2.1 Long-term safety

For each repository, the long-term safety has to be proved. Regardless of what is meant here by “proof” and how it can be provided, it must at least be clear *what* should be proved.

Long-term safety of a repository means that over a very long (in principle unlimited) period beginning with the closure of the repository, there are no effects originating from the repository that impair human life and health or disturb the natural state or evolution of the environment outside a technically unavoidable minimal zone of influence.

This definition specifies two basic safety concerns: Protection of human life and health and protection of the environment. The mentioned zone of influence refers only to the second concern. It describes the region in the host rock that is unavoidably influenced by the construction of the repository. The two safety concerns discriminate two possible basically different lines of argument in a safety assessment. It will, however, be nearly impossible to assess one of them completely by one single investigation. Therefore, it is helpful to further focus such investigations to specific well-defined aspects that cover a smaller or larger part of the respective safety concern.

2.2 Safety aspects

Safety should not be reduced to one single aspect like human health. This may be the most important and comprehensive safety aspect but is not the only one. Sometimes it is claimed that the protection of man automatically includes all other protection goals, but this does not seem to be an acceptable assumption, as influences to the environment that do not directly and in a known manner interact with human health remain unconsidered. The concept defined in the following is intended to focus on the identification of indicators to specific safety statements.

A safety aspect is a specific subarea of the total field of long-term safety that can be addressed independently of others. A repository can be safe with respect to one aspect but unsafe with respect to another.

Safety aspects might be, e.g.,

- Human health,

- Human fertility,
- Quality of human life,
- Groundwater quality,
- Surface water quality
- Seawater quality,
- Balance of biological species,
- Health of non-human biota,

Safety aspects can be more or less comprehensive. An aspect that is totally covered by another one can be called a sub-aspect. Often, however, there is some overlap between different aspects without one being a sub-aspect of the other. For example, groundwater quality is clearly relevant for human health, but also for health of non-human biota. On the other hand, human health is not at all covered by groundwater quality.

It should clearly be stated in a safety case which safety aspects are addressed.

2.3 Safety indicator

To assess the long-term safety with respect to a specific aspect by means of model calculations, calculable quantities are needed that are related to safety and can be compared with reference values.

A safety indicator is a quantity, calculable by means of suitable models, that provides a measure for the total system performance with respect to a specific safety aspect, in comparison with a reference value quantifying a global or local level that can be proven, or is at least commonly considered, to be safe.

A safety indicator should give an indication of whether a repository can be considered safe regarding some safety aspect. Such a safety statement requires a numerical measure as well as a reference value defining a safe level. A safety indicator without a reference value cannot be used to assess the long-term safety of a repository system. It is recommended not to speak of a safety indicator without a reference value specified.

Sometimes it is clear which quantity is to be used as reference, but its numerical value is still unknown or depends on local conditions. This should, however, not discourage from defining a safety indicator. In such cases, the term “reference parameter” or “reference quantity” could be used, but in the following we simply stick to “reference value”.

It is essential to take account of a specific safety aspect when determining a reference value. The same numerical measure for repository safety, even when calculated in exactly the same way, can yield different and independent safety statements if referred to different safety aspects and combined with the appropriate reference values. For example, one can consider the safety measure “radiotoxicity flux to groundwater”. What is a safe level of this? Probably there is a river near the repository and all the radionuclides released will finally reach it. When considering the safety aspect “health of river fauna” or, somewhat nearer to human health, “integrity of drinking water from the river”, it is a good idea to compare the calculated flux with the natural radiotoxicity flux of the river. In big rivers, however, the natural flux can reach thousands of Sieverts per year, meaning that even a rather bad repository is ‘safe’ with respect to this specific aspect. On the other hand, if the safety aspect “integrity of water from a well” is considered, the natural radiotoxicity flux in the local groundwater should be taken as reference, and this is normally several orders of magnitude lower than that of a river. Since the safety statements derived from these two reference values are completely different, the respective safety indicators should also be seen as different, even though based on the same calculated quantity.

Reference values can be valid globally like the concentration of radiotoxicity in drinking water that is harmless for human health. The value may not yet be known exactly, but it is unlikely that it differs in Finland and Spain. Other reference values have a very local character and are only valid in a specific environment, e.g. natural radiotoxicity flux in groundwater.

Risks, typically compared with accepted social risks from smoking, driving or other areas of life as reference values, can also serve as safety indicators as long as they are calculated in an adequate way. As “risk” is a statistical term, this kind of safety indicators has a somewhat different character than others. Even if, under very specific conditions, the repository causes considerable harm to a part of the environment, the risk may be low if these conditions are very improbable or the consequences concern only a very limited part of the environment. The concept of risk indicators is addressed in the annex.

2.4 Performance indicator

It was shown in SPIN [1] that performance indicators are a good means to visualise the functioning of the system and to help understanding the coaction and interaction of its components. The definition given in SPIN, however, is broader than needed and seems to interfere with terms used by others for other purposes. Therefore, the following definition is used, which is more restrictive.

A performance indicator is a quantity, calculable by means of appropriate models, that provides a measure for the performance of a system component, several components or the whole system in comparison with each other.

Performance indicators are useful for optimisation of the disposal system, comparison of different options, improving the understanding of the role played by different system components and communication of these things, both to experts and the general public. This kind of performance indicators does not need reference values or technical criteria.

2.5 Safety function, safety function indicator

In SPIN, the term “safety function” was used for three basic tasks of a repository system: physical containment, delay and decay, dispersion and dilution. Generally spoken, a safety function in this sense is a functionality the system should provide as a whole, in order to prohibit or reduce detrimental effects.

In the concept developed and applied by SKB, a “safety function” is a local functionality for characterising a component of the repository, like the isolation potential of a container or the retardation capability of a barrier. A safety function indicator is a quantity that characterises numerically the safety function under consideration and can be compared with a given criterion. Each safety function indicator is associated with a specific criterion and can be assessed independently of others. These criteria have a technical character, and satisfying them is neither sufficient nor necessary for the regulatory requirements to be fulfilled. Nevertheless, this concept seems to be a good means to split the performance assessment into separate parts, each with its own well-defined requirements.

A similar concept has already been indicated in SPIN (comparison of performance indicators with technical criteria). This type of indicators was included in the performance indicators, though not really addressed in the investigations. It seems, however, sensible to distinguish between these terms. Therefore, the definition of performance indicators given in the previous section is restricted to the type of indicators currently investigated within PAMINA. Definitions of the terms “safety function” and “safety function indicator” are not established in this report.

2.6 Other terms

There are several other similar terms, which are used in the literature, like “condition indicator”, “function indicator”, “functional indicator”. There seems to be some confusion about these terms and they are not used in this report.

3. Safety aspects and safety indicators

In this chapter some possible safety aspects are defined and explained in order to illustrate the concept of safety indicators. For each safety aspect one or more safety indicators are given that can be used to address the safety aspect specifically. The list does not claim to be complete or to cover all imaginable aspects. It aims rather at identifying some important safety aspects and safety indicators that seem promising to be considered..

3.1 Human health

This is the main and most important safety aspect. Human health should not be impaired directly by radionuclides released from the repository. That means that the total of all biological effects to a human individual must remain so small that no impact on health results. This safety aspect includes the effects of

- incorporation of radionuclides by humans and
- external radiation.

Human health is a very comprehensive safety aspect. It can be influenced also by other aspects, but it should always be seen as the total of all influences to human health. Other safety aspects, like groundwater quality, can also be relevant for human health without being a sub-aspect.

For measuring the influence of radioactive substances to human health, the radiotoxicity, calculated from the activity by multiplying with radionuclide-specific dose coefficients seems best adequate. These coefficients comprise all detrimental effects to a human being, taking account of the human physiology, but are, of course, not automatically valid for human-like beings living in the far future.

Appropriate safety indicators for human health are

The annual effective dose to a human individual (individual dose rate, annual radiation exposure), calculated using standardised exposition paths and conversion factors for each radionuclide, and compared with a level that is well below the natural value and therefore considered to be safe. The equivalent dose is related to man and establishes the relevance for human health. Different indicators of this type can result if different sets of such data are used, such as conversion factors for different ages or exposition paths for different groups of people.

The annual collective dose to a group of humans, calculated using standardised exposition paths and conversion factors for each radionuclide, and compared with a typical natural value that can be considered safe. The collective dose differs from the individual dose as a safety indicator insofar as it addresses the overall health of a population with no respect for single individuals.

The risk of suffering death or a serious health damage from the released radionuclides, compared with natural or technical risks.. It must be clearly defined how the risk is calculated.

3.2 Drinking water quality

The quality of drinking water is also related to human health and may be seen as a sub-aspect of the previous one. It addresses only a part-aspect of human health, but an important one. It can be assumed, however, that future human beings take their drinking water from sources that are also open for other biological species so that this aspect gets a more general meaning. A safety indicator addressing this aspect has to measure the quality of drinking water with respect to radiological effects. Since it is mainly intended to assess the effects on human health, the most suitable measure is the radiotoxicity, calculated from radionuclide concentrations using the ingestion dose coefficients published by ICRP [5].

An appropriate safety indicator for this safety aspect is

Radiotoxicity concentration in drinking water, compared to a value that is definitely known not to harm human health. Such a reference value can be obtained by investigation of water that has been drunk by men (and other species) for centuries and obviously not caused any damages.

3.3 Groundwater quality

The quality of groundwater is essential not only for human health but for the total flora and fauna. Therefore, it can be addressed as an independent safety-aspect. Contamination by radionuclides released from a repository can impair the quality of local groundwater. It is, however, not easy to measure the groundwater quality because the acceptance levels of different parts of the environment can differ considerably. A possible approach is to compare the contamination with that due to natural radionuclides, but this causes some problems. The comparison should not be done on a nuclide-by-nuclide basis because many of the radionuclides released from a repository do not occur at all in natural environments. The contributions of different radionuclides have to be summed up using an appropriate weighting scheme. Such weighting schemes, however, either ignore the physiological relevance of different radionuclides, like energy dose rate/activity coefficients (Gy/Bq·s), or are associated with a specific biological species, like ingestion dose coefficients (Sv/Bq).

Appropriate safety indicators for groundwater quality are:

The radiotoxicity concentration in the local groundwater, compared to the natural value. It is calculated directly from the radionuclide activity concentrations by multiplying with ingestion dose coefficients. One should keep in mind, however, that using this weighting scheme implies a specific relevance for human health. Nevertheless the indicator has some relevance also for other biota, as far as their radiosensitivity is comparable to that of humans. This safety indicator is similar to the radiotoxicity concentration in drinking water, aiming, however, not primarily at human health but at the general groundwater quality. “Drinking water” is not necessarily identical to “groundwater”, but the most important difference between these indicators is that their reference values are established essentially unequally.

The specific radiation power in the local groundwater, compared to its natural value. The weighting scheme consists of a simple physical calculation of the energy radiation power per Becquerel. It is physically unique and independent of any specific biological species, but, on the other hand, has only a limited relevance for biological safety aspects. For the groundwater quality as an autonomous safety aspect, however, this is a good indicator.

The radiotoxicity flux from the repository *to* the groundwater, compared to the present natural radiotoxicity flux *in* the groundwater. This indicator is more robust than the concentration indicators with respect to its calculation, since no knowledge about the evolution of the geosphere is required. The reference values are established on the basis of present conditions. Therefore, these indicators convey different statements than the concentrations. It can, however, be hard to determine radiotoxicity flows in groundwater.

3.4 River water quality

In many cases the hydrological environment of a repository is dominated by a single river, and it can be assumed that nearly all radionuclides released from the repository will finally reach this river. The river water is an essential part of the environment and important not only for humans taking their drinking water from the river, but also for fish and other animals living in or near the river as well as for the flora in flooded areas. The quality of the river water should not be impaired by radionuclides from the repository. The natural contamination can be used as reference but, as in the case of groundwater, an adequate weighting scheme is necessary. Bigger rivers can transport enormous amounts of natural radionuclides, and their contamination is not significantly changed even by considerable fluxes from a repository. Therefore, this safety aspect is normally of low relevance, unless a rather small river is known to collect a considerable flux from the repository.

An appropriate safety indicator for river water quality is:

The radiotoxicity flux from the repository, which is assumed to finally reach the river, compared to the natural radiotoxicity flux in the river. By using radiotoxicity a specific relation to human health is created, but nevertheless the indicator has some relevance also for other biota, as far as their radiosensitivity is comparable to that of humans.

3.5 Integrity of highly radiosensitive biota

While the safety indicators mentioned so far either address human health, directly or indirectly, or are at least independent of a specific species (for the price of a reduced relevance for safety), this safety aspect explicitly addresses non-human life forms that are specifically sensitive to ionising radiation. Their radiosensitivity can be higher than that of humans and require stronger criteria. The use of safety indicators addressing this safety aspect, however, requires reliable and detailed knowledge about the radiosensitivity of a wide variety of biota, which is probably not available at present.

An appropriate safety indicator for the integrity of highly radiosensitive biota is:

The annual dose to a hypothetical being that combines the highest radiosensitivities of all relevant species. Similarly to the individual dose rate to humans, it is calculated from the activity concentrations at the interface to the biosphere, but using, instead of dose coefficients for humans, a specific set of factors as a weighting scheme. Theoretically, these factors can be calculated by determining conversion factors for all species, taking into account their specific radiosensitivities to all radionuclides as well as their typical lifestyles. The hypothetical being is then assigned a set of factors consisting of the maximum values for each radionuclide. This, however, would mean a lot of work. For practical reasons, only a few typical species (e.g., a fish, an amphibian, a bird, a mammal, a plant) should be included and assessed with simplified stylised models. The reference value can be derived from the natural exposure. This safety indicator could show interesting results because it is probably stronger than the individual dose rate to humans. It requires, however, a great effort. Therefore, it is not considered within PAMINA.

4. Describing system functionality by performance indicators

Safety indicators are a good means for assessing the level of safety of the total system, but they do not provide information about how the system works and how the level of safety is reached. Such information, however, is of high value for the safety case. For the experts it is essential to understand how the different barriers work together and where the radionuclides are mainly retained. For communication with licensing authorities as well as with the general public it can be helpful to demonstrate the functioning of the system in an illustrative and understandable way. Such demonstrations can improve the confidence in the safety case.

Information of this kind is provided by performance indicators as defined in chapter 2.4. They are typically concentrations or fluxes of radionuclides in or between specific parts of the repository system, or other descriptive measures that demonstrate specific properties of the system.

4.1 Compartment structure

The general idea of the concept of performance indicators is to look in detail at the transport processes at specifically relevant locations inside the repository system. Interesting locations can be, e.g., the interfaces between parts of the system that fulfil different tasks. Comparing the indicators calculated for different locations is often very illustrative for demonstrating the functioning of the system. In view of this purpose, the division into part-systems has to be done carefully. Following the SPIN terminology, we call these part-systems compartments. Compartments can be natural or mined subsystems like the geosphere or the mine building, engineered components like canisters or barriers, or even physically independent phases in specific regions, like the canister water or precipitate. There is no need to have a non-overlapping compartment structure. It often makes sense to consider compartments that contain others. An example is the “canister” compartment, which contains the three compartments waste matrix, canister water and precipitate

When designing the compartment structure for a specific repository system, one has to distinguish whether the processes *in* the compartments or *between* the compartments are to be illustrated. Normally, these two purposes lead to different compartment structures. for example, the distribution of the inventory in the canister to the matrix, the canister water and the precipitate can be meaningful, while fluxes between these phases are of low interest and, perhaps, hard to calculate. For the calculation of fluxes some kind of concentric structure is often preferred, which allows tracing the radionuclides from the inner parts of the repository to the outside.

Often it is sensible to create “logical” compartments that have no physically separated counterpart in the real repository. For example, if there are some hundred identical boreholes with a number of canisters each, one would be likely to define one “canister” compartment, which contains the inventory of all canisters together and one “borehole” compartment comprising all physical boreholes.

In SPIN only granite systems were considered. For all considered studies, the common compartment structure shown in figure 1 was used. Al canisters are assumed to be identical and represented by one “logical” waste package containing the waste form, the precipitate and the canister water. Each waste package is surrounded by a bentonite buffer and an EDZ, which are also represented by comprehensive compartments. Together these compartments represent the near field, which is assumed to be surrounded by the geosphere and the biosphere. Inventories were calculated in waste form, precipitate, buffer, geosphere and biosphere; concentrations in canister water, EDZ and biosphere water. Fluxes were calculated from the waste form, the waste package, the near field and the geosphere.

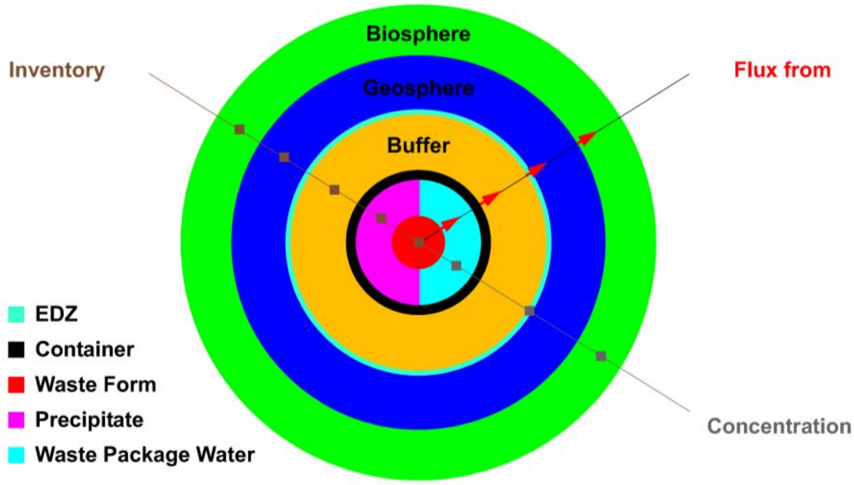

Figure 1 : Compartment structure of SPIN

For clay systems a similar compartment structure may be chosen, though probably it does not make much sense to distinguish between the bentonite buffer and the surrounding clay formation. In such a structure the waste package compartment is directly followed by the geosphere.

Salt systems normally require a different compartment structure. The current German concepts for repositories in salt comprise emplacement fields for different types of waste in different parts of the mine. This excludes the possibility of a strongly concentric compartment structure. It is more suitable to consider parallel compartments representing, e.g., all boreholes or all emplacement drifts. Sometimes it makes sense to divide an emplacement field into several compartments, even if it consists of identical units, because, due to the specific properties of salt, some parts may close earlier than others and behave differently concerning release of radionuclides. The compartment structure used by GRS in PAMINA is shown in figure 2. It contains two SF compartments, one HLW compartment and one ILW compartment. Each of these is subdivided in waste form, canister, borehole and emplacement field. Further compartments are the central field and the overburden. For calculation of fluxes only the canisters, the total near field and the overburden are considered.

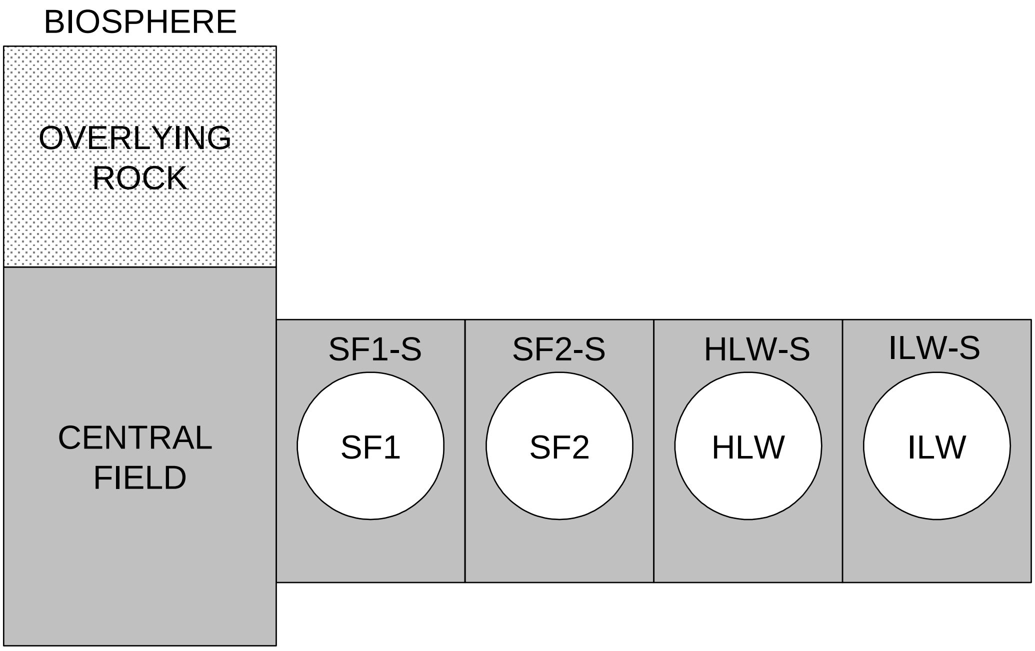

Figure 2 : Compartment structure used by GRS for a salt rock formation

4.2 Performance indicators

In SPIN several performance indicators were calculated and tested. Except for some specific indicators like travel times through the compartments, all of them can be calculated either on a radionuclide-specific or an integrated basis. The former technique is helpful in assessing the effects of barriers to individual radionuclides or groups of radionuclides, for example those with high or low sorption, and to point out the differences between them. For this purpose the inventories and fluxes can be measured directly in terms of activity. The latter is preferable if the retaining capabilities of the system are to be considered as a whole. In this case a suitable weighting scheme is needed to consistently take into account the contributions of the different radionuclides. The ingestion dose coefficients provide such a weighting scheme, which is, of course, related to human health. Using this scheme means to consider inventories and fluxes in terms of radiotoxicity.

It was found in SPIN that all considered performance indicators are helpful for specific purposes and tell their specific stories about the repository system. In the following the indicators are briefly described with their advantages and disadvantages.

4.2.1 Activity / radiotoxicity inventories in compartments

The time development of the inventories in the different compartments shows where the radionuclides are at each point in time. This indicator is clear and easy to understand and allows an assessment of the retention capabilities of the barriers. If calculated for the biosphere compartment it can reach rather high values, due to the fact that the biosphere is considered to comprise everything outside the geosphere. This may be misleading and should not be misinterpreted. Altogether, this is a useful indicator to show the functioning of the system with respect to accumulation of radionuclides in specific parts.

4.2.2 Activity / radiotoxicity inventories outside compartments

Alternatively, the inventories outside the compartments can be calculated. This indicator conveys a similar message as the previous one, but in a somewhat different way. The time-curves start at zero. The indicator is useful to show the combined performance of all barriers inside a boundary. It can show especially which barriers are ineffective.

4.2.3 Activity / radiotoxicity concentrations in compartments

Calculation of concentrations only makes sense in water compartments like the canister water or the biosphere water. If these two concentrations are compared it shows the dilution of the radionuclides caused by the disposal system. It is a direct quantification of the safety function “dispersion and dilution”. The time-development of this indicator can be illustrative but somewhat hard to interpret because there is normally a time-delay between the curves. Concentrations in compartments like buffer and geosphere water can vary within the compartments and are therefore not well-defined.

4.2.4 Activity /radiotoxicity fluxes from compartments

The time-development of the fluxes between adjacent compartments shows how the radionuclides move within the repository. This is different from what the inventories show, but equally illustrative and easy to understand. This indicator is useful to show decreasing release rates from compartment to compartment, which is a direct visualisation of the barrier function of individual compartments and the whole system.

4.2.5 Time-integrated activity / radiotoxicity fluxes from compartments

This indicator is obtained by integrating the fluxes from the compartments over time. This results in time curves that can only increase and finally reach a constant value. If compared to or divided by the initial inventory of the compartments these values show how much of the inventory has been retained by or decayed in the compartment, which is a very meaningful piece of information. This indicator is useful to show where the radionuclides are most effectively retained. It quantifies the safety function “delay and decay”.

4.2.6 Transport times through compartments

It can be illustrative to calculate the transport times of different radionuclides through the compartments and to compare them with their half-lives. This gives a qualitative overview of the potential importance of the different nuclides. Due to dispersion effects, however, it is not easy to calculate and requires a well-defined calculation scheme.

4.2.7 Proportion of not totally isolated waste

This indicator was specifically introduced in SPIN to quantify the safety function “isolation and physical containment”. Normally, a large portion of the initial inventory is finally retained or decays inside the repository and never reaches the environment. The isolation potential of the total system can be best illustrated by dividing the released inventory by the initial inventory.

5. General concept

Finally, this chapter summarizes the concepts presented in chapter 3 and 4. Figure 3 illustrates the work flow for the overall concept.

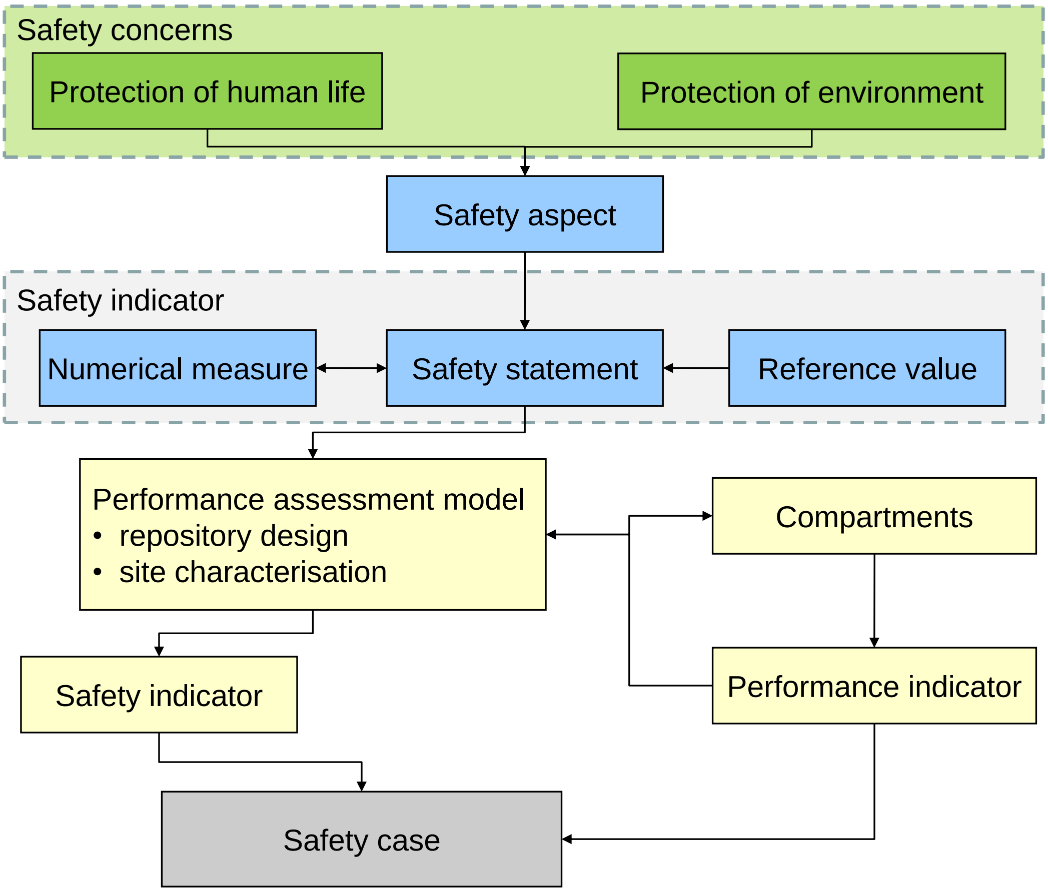

Figure 3 : General concept for the use of safety and performance indicators for supporting the safety case

Every safety indicator that is applied for the safety case must be defined by a safety statement, based on a previously defined safety aspect. These safety aspects are based on at least one of the two safety concerns “protection of human life” and “protection of environment”. A safety statement could for example be that all biological effects to a human individual, i.e. the incorporation of radionuclides released from a repository by humans via different exposition paths, remain so small that they have no impact on human health. The corresponding safety aspect is the human health. For a complete safety statement as defined in chapter 2.3 a numerical measure is required, by which the biological effects due to incorporation of radionuclides can be calculated, as well as a reference value in order to define a safe level. A common measure for the exemplary safety statement is the effective dose rate. In the case of the effective dose rate, the national legal limit could be used as reference value.

At this stage the safety indicator is theoretically defined and fixed. There is no further interaction between the PA model and a safety indicator. The outcome of the PA model or the progress of the safety case has no influence on existing safety indicators. It is of course possible and useful to define further safety indicators.

In order to use a safety indicator in a safety case, it is necessary to calculate the outcome of the considered numerical measure (e.g., the effective dose rate) by means of a PA model for the corresponding repository system. The PA model allows the calculation of the migration of radionuclides in the repository system based on a reference design and a description of the geological site. By comparing the results of the PA model with the reference value of the safety indicator, the determination of the safety indicator is complete and can be added to the safety case.

In contrast to safety indicators there can be a close interaction between the PA model and the definition and calculation of performance indicators, especially between the compartment structure and the repository design. For every performance indicator a compartment structure has to be defined. As stated in chapter 4.1 the chosen compartment structure depends on several conditions, e.g. the host rock or the type of quantity (concentration, flux) that is calculated. If several performance indicators are used within one study, the compartment structures should be identical, or at least as similar as possible, in order to allow a comparison of the results.

Since performance indicators are not based on a safety statement their use is more flexible. In figure 3 performance indicators are illustrated as a part of the PA model. They are very important for the understanding of the modelled processes and they can be used for the optimisation of the repository system. At the end not every applied performance indicator is added to the safety case, but most of them give valuable arguments for increasing the confidence in the safety of a repository system.

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6. Annex: The concept of risk

In some countries the regulations require an assessment of risk, which should not exceed a limit of typically 10^{-6}/yr. What is meant by this, however, is either not defined at all or a more or less simplified calculation procedure is provided. In Spain, for example, the risk of 10^{-6}/yr is directly associated to a dose rate of 10^{-4} Sv/yr, so that the risk calculation is actually a dose calculation.

The actual risk originating from a repository is hard to determine. Firstly, it has to be defined, what risk means. In general, risk (R) is a combination of the probability of the occurrence of an adverse event for a defined time frame and a measure of the consequences of this event. Thus every quantitative description of risk must involve a triple of information: A set of conditions (the scenario S), a probability of the scenario p and the consequences of the scenario C. The consequence must be a calculable measure, which can itself serve as a safety indicator. Any of the indicators mentioned in the previous chapter could be used, but it seems most sensible to consider the safety aspect "human health" and to calculate the risk on the basis of doses.

The dose risk R_D resulting from a number of possible scenarios S_i with the probabilities p_i can be calculated as

$$R_D = \sum_{S_i} p_i C_i \ ,$$

where C_i is the dose rate resulting from scenario i. It is the expected value of the dose rate. Consequently, the dose risk is measured in Sv/yr.

In order to compare the calculated dose risk with other accepted risks it must be transformed to a more illustrative value that allows assessing the personal risk. A risk indicator (RI) compares the probability of an event and its consequences (e.g. the risk of a certain effective dose RD) with a risk limit accepted by regulators and/or the society. To compare the consequences with such a measure a quantitative evaluation of the incidence of an adverse effect that is expected in a population as a result of an exposure to these consequences is necessary. For a simple linear dose-response-function without a threshold value this can be done by defining a risk coefficient r:

$$R = rR_D$$

The risk of suffering health damage can be much higher than the risk of dying. One could try to quantify the detriment of different adverse health effects, but then one would have to decide how much worse it is to die than to get ill. The probably best way to avoid this problem is to define risk as the risk of getting cancer due to the releases from the repository. This can be coupled with the effective dose. Assuming a linear relationship, risk-per-dose coefficients r between about 4 and 7 percent per Sievert have been found, depending on the considered group of people and whether only fatal or all kinds of cancer are considered. In [6] a value of r = 5 percent per Sievert is recommended.

In comparison with risks from other natural or technical sources the calculated risk can be used as a special safety indicator. This requires, of course, a clear definition of the scenarios considered relevant and their probabilities, which must add up to 1. The maximum risk that can result from a set of possible scenarios, regardless of their real probabilities, can be calculated by assuming a probability of 1 for the most adverse scenario. Provided that this scenario still holds the dose criterion of 0.3 mSv/yr (the German regulatory value), the risk is $1.5 \cdot 10^{-5}$/yr, which is about a fourth of the probability of dying in a traffic accident in Germany.

A risk indicator may be helpful especially where scenarios of very different probabilities play a role, for example, when comparing clay and salt concepts. While in clay there will always be a certain release of radionuclides, in salt the expected evolution yields a zero output, but specific scenarios of very low probability can lead to relatively high doses. One can expect that the calculated risk originating from a salt repository is much lower than that from a clay repository. On the other hand, risk indicators can be misleading, due to the high uncertainty of scenario probabilities. In most cases, these probabilities can only be guessed or roughly estimated, while the resulting risk value may suggest an exact calculation.

7. Literature

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