The Role and Significance of Different Types of Scenarios in the Safety Case for Surface Disposal of Low Level Waste at Dessel, Belgium – 14092

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ABSTRACT

ONDRAF/NIRAS, the Belgian Agency for Radioactive Waste and Enriched Fissile Materials, and its partners have developed a safety case in support of a construction and operation license application for a surface repository for low level radioactive waste (category A waste in Belgium) at Dessel, Belgium. On 31 January 2013, the application has been submitted to the Federal Agency for Nuclear Control (FANC), the Belgian regulatory body for nuclear matter, who are currently reviewing it. The paper aims to set out the reasoning behind the selection of different types of scenarios in the long-term radiological safety assessment performed in the framework of this safety case. Indeed it was found that different scenarios are needed so as to (1) substantiate the foundations of long-term safety, (2) meet the different purposes of the assessment over different timeframes and (3) quantify and illustrate the features of the safety concept. The role and significance for the safety case of the various scenarios selected on this basis is clarified by means of key safety arguments gathered.

INTRODUCTION

ONDRAF/NIRAS, the Belgian Agency for Radioactive Waste and Enriched Fissile Materials, is entrusted by law with developing a coherent policy for the safe management of all Belgian radioactive waste and implementing that policy consistent with royal decrees, government decisions and decisions by the regulatory body.

The program leading to the development of a surface repository for low level waste – termed ‘category A waste’ in Belgium – is divided into a series of phases (program steps), each culminating in a decision that allows the subsequent program step to proceed. Adopting surface disposal at Dessel as the reference solution for the management of the Belgian low level waste constituted the subject of a policy decision by the Belgian government in 2006. The envisaged disposal site is located in the north-eastern part of Belgium at approximately 150 km from the Belgian coastline. It is characterized by a flat topography and a geology based on semi-horizontal layers of quaternary permeable sands with a groundwater table a few meters below the surface.

Siting at Dessel hence constituted a boundary condition to further design development. Taking account of the site’s characteristics and building on the preliminary design developed in partnership by ONDRAF/NIRAS and the Dessel municipality, a highly-engineered, vault-type facility is considered. The waste is placed and immobilized in disposal packages termed *monoliths*, which are emplaced in structurally independent concrete vaults termed *modules* on top of a sand-cement embankment. At a later stage, a multi-layer cover will be implemented on top of the filled and sealed modules (see Fig. 1).

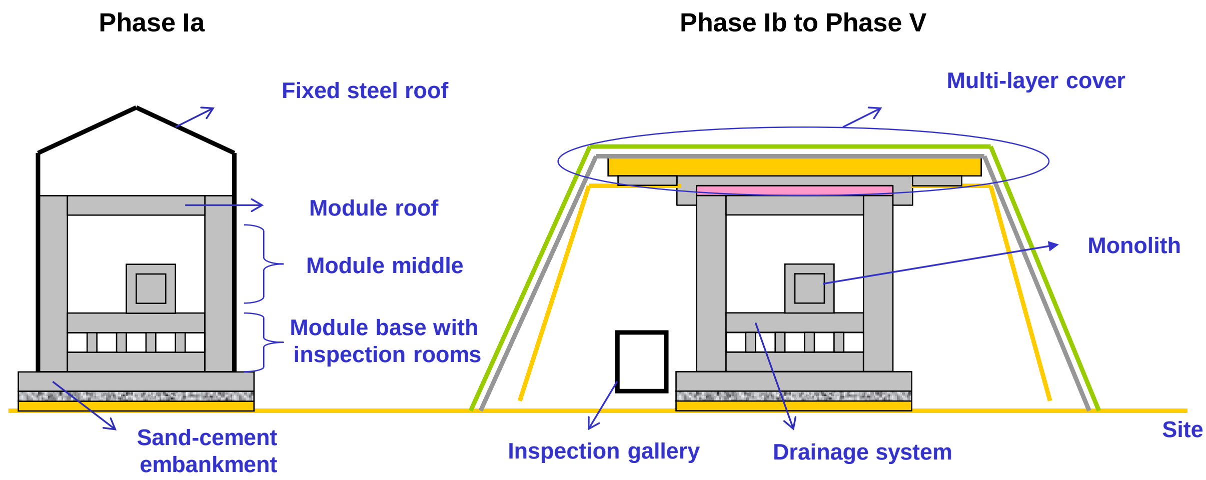

Fig. 1. Systems, structures and components (SSCs) considered in the safety concept [1]. Phases in the repository lifetime are described in Fig. 3.

On 31 January 2013, the further development of the preliminary disposal project since 2006 has culminated in the submission of an application for a construction and operating license for a surface repository at Dessel to the Federal Agency for Nuclear Control (FANC), the Belgian regulatory body for nuclear matter. This license application builds on the modern concept of a *safety case*, which is a formal compilation of evidence, analyses and arguments that quantify and substantiate a claim that the repository will be safe [2, 3].

A central feature hereof is the *safety strategy*, i.e. the high-level approach adopted for achieving safe disposal, which encompasses:

1. The *safety objective*, i.e. to protect people and the environment now and in the future from harmful effects of ionizing radiation [4, 5];
2. The *(safety) principles* that should be adhered to in order to fulfill the safety objective (i.e. radiation protection principles, isolation and containment, robustness, defense-in-depth…); and
3. The *choices, input and processes* contributing to the fulfillment of the safety objective and the control over its implementation, i.e. (1) the management strategy, (2) the design strategy and (3) the assessment strategy.

The safety strategy is framed within an *iterative* safety approach [5], i.e. an overall management approach firmly focused on safety, ensuring a permanent awareness of safety and iteratively applied during each further program step.

Safety functions, constituting a practicable interpretation of the safety principles for surface disposal, are used as a means to summarize key safety-related choices in a *safety concept*, i.e. the integrated description of the major safety functions provided by the system and of the systems, structures and components (SSCs) ensuring that each of the safety functions will be fulfilled over the assigned timeframes at the least. The assignment of safety functions to different SSCs reflects state-of-the-art scientific knowledge and understanding on the behavior and evolution of the repository. A schematic view of the repository, indicating its main SSCs, is shown in Fig. 1.

In one respect, the safety concept constitutes a design input aimed at obtaining a robust system performance with adequate defense-in-depth, yet it also denotes the safety features to be relied upon in the safety assessment. Hence, the developed design already takes full account of fundamental requirements to assure safety, so that safety assessment, composed of formal safety and performance analyses [6], is aimed at confirming the safety of the design (Fig. 2).

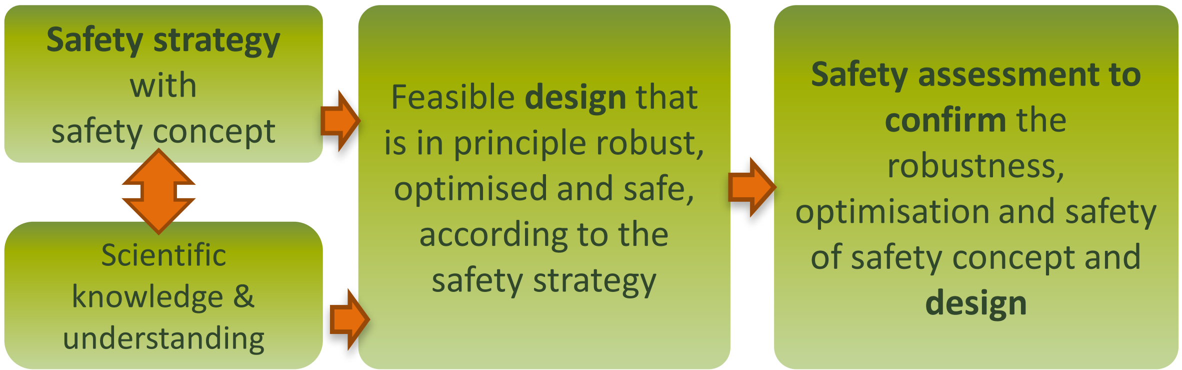

Fig. 2. The role of safety assessment as the safety strategy is being implemented in the framework of a safety approach iteration.

DRIVERS FOR SCENARIO SELECTION

Different types of scenarios are used in the long-term safety and performance analyses, with a view to

1. substantiating the foundations of long-term safety,
2. meeting the different purposes of the assessment over different timeframes; and
3. quantifying and illustrating the features of the safety concept.

The implications of each of these inputs to scenario selection and development are discussed below.

The foundations of long-term safety

Surface disposal of radioactive waste implies radioactive waste emplacement in a repository situated in the accessible biosphere. Long-term safety, or post-closure safety, therefore rests on four essential foundations:

1. Repository characteristics ensuring passive *containment* and *isolation* of the waste, i.e. the safety functions assigned to the SSCs in the safety concept
2. Site characteristics ensuring a stable environment such that the containment and isolation performance of the repository is not affected or impaired, and mitigating[1] the radiological impact
3. Restrictions to the admissible radiological source term (mainly the activity level of long-lived radionuclides), in line with the isolation and containment provided by the surface repository

[1] Mitigation of impacts through the site characteristics is of secondary importance as compared to the repository's containment performance.

4. Monitoring and surveillance of the repository and its close surroundings during the first few centuries, so as to prevent inadvertent human intrusion during this timeframe as well as to confirm the adequacy of the repository's performance (stakeholder confidence in safety).

Implications for scenario selection are that:

- Two types of scenarios should be considered, i.e. *gradual leaching* scenarios, with water as the main dispersion vector, addressing the containment performance, and *human intrusion scenarios* addressing the consequences of an impaired isolation performance following the abolition of site surveillance.
- The scenario description should build on the *safety functions* in the safety concept, and potential deviations in the provision of these safety functions.
- Scenarios should allow for a sufficiently cautious, though not overly restrictive, determination of *disposal limits*[2] for the Dessel near surface repository, i.e. concentration limits per disposal package as well as an overall radiological capacity for the repository.

Safety assessment purposes and timeframes

In the current safety case for license application, safety assessment aims at

1. cautiously determining *radiological disposal limits* to restrict the activity of long-lived radionuclides.

Because the majority of the waste eligible for disposal at Dessel has yet to be produced (including low-activity decommissioning waste from nuclear power plants), an *estimated* source term, based on existing waste and forecasts of future waste production, in compliance with these limits is then used to show

2. that the *radiological impacts* and associated risks comply with the regulatory criteria; and
3. that the *performance* of the disposal system is robust and offers an adequate level of defense-in-depth.

The key issue here is to structure the assessment so that it is defensible on the basis of the available knowledge of the long-term performance and evolution of a facility, which implies establishing an appropriate balance between "realism" (i.e. as good an estimate as possible of the disposal system behavior and evolution) and "conservatism" (i.e. whereby the ability of the disposal system to provide protection is deliberately underestimated). The balance depends, among other things, on the nature and purpose of the assessment. For example, a gradual leaching scenario used to determine disposal limits should be on the conservative side, while still accounting for the repository characteristics assuring containment, as described in the safety concept.

As illustrated in Fig. 3, four timeframes are considered in the post-closure period:

- the nuclear regulatory control phase, during which access controls are in place to prevent inadvertent human intrusion and remediation measures can be taken should any anomalies in repository performance be observed during monitoring/surveillance;

[2] Disposal limits are translated and used in operational criteria ensuring compliance with the safety criteria. The ONDRAF/NIRAS waste acceptance system ensures an adequate waste characterization, as well as procedures and criteria for accepting waste for disposal.

- the isolation phase, during which containment is ensured both by physical (limitation of flow and transport) and chemical (sorption) characteristics and processes;
- the chemical containment phase, during which containment is assumed to rest only on chemical (sorption) characteristics and processes; and
- the post-containment phase, addressing longer timeframes and during which, in the light of uncertainties gradual leaching scenarios and human intrusion scenarios are used in a more illustrative manner. In addition, the FANC's requirements include the consideration of so-called *penalizing scenarios* involving a minimum level of isolation and containment and constituting an envelope to a large range of exposure situations in terms of impacts.

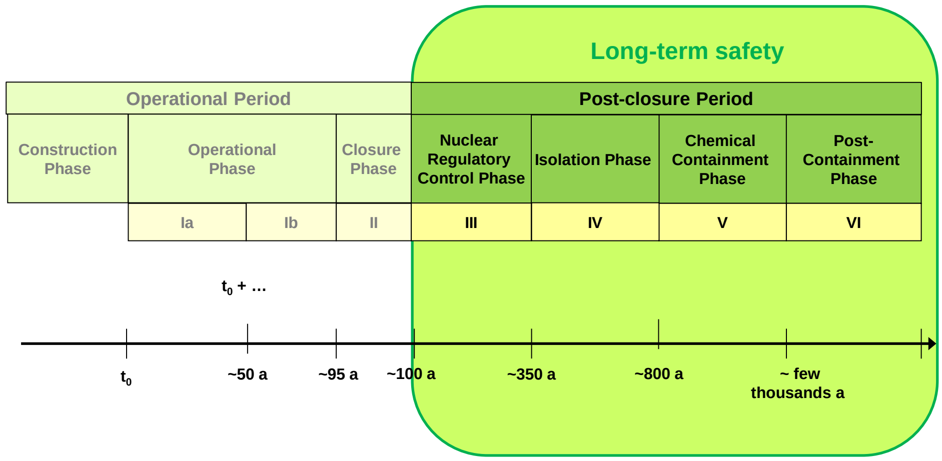

Fig. 3. Timeframes for long-term safety assessment.

Scenarios linked to the safety concept

The safety functions to be fulfilled by the repository SSCs, and the timeframes over which they should be fulfilled, are schematically shown in Fig. 4[3].

Going into detail, the roles of the various SSCs are categorized to indicate the relative importance of the safety functions that a given SSC fulfills (Fig. 5) [1, 5]. The categories are "Main" (i.e. it must be demonstrated and verified that the SSC, under normal circumstances, will fulfill the required long-term safety function) or "Contribute" to the fulfillment of a long-term safety function.

Scenarios for long-term safety assessment primarily build on the "Main" safety functions considered in the safety concept, so as to quantify and illustrate the features of the safety concept. The exact conceptualization of any "Main" safety function role depends on the level of conservatism / realism for the scenario at hand. Further, possible threats to the fulfillment of any safety function are also identified and constitute the basis for further scenario descriptions.

[3] *Note that safety function I1 is considered effective until the end of the isolation phase in the safety concept (Fig. 4) – nevertheless, human intrusion is considered to occur during the isolation phase. This apparent discrepancy can be explained by the fact that human intrusion scenarios are stylized and represent, by definition, an engineered barrier bypass [7]. In reality, however, heavily engineered barriers will not be easily bypassed as long as they present some physical integrity.*

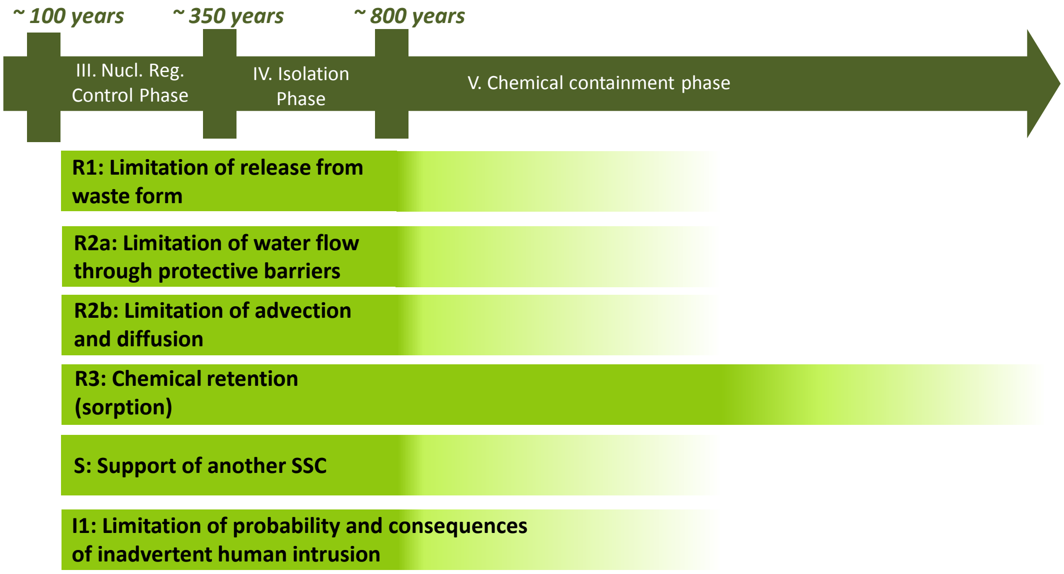

Fig. 4. Schematic representation of the safety concept and its safety functions. Safety functions R1, R2a, R2b and R3 (and S) are related to the containment performance; safety function I1 is related to the isolation performance.

	Long-Term Safety Function 1			Long-Term Safety Function 2			...
	Phase III	Phase IV	Phase V	Phase III	Phase IV	Phase V	
SSC 1	M	M	C	M	M	C	
SSC 2	M			M			
...							

Fig. 5. Principles for structuring the safety concept (M = "Main", C = "Contribute").

GRADUAL LEACHING SCENARIOS

In the Dessel repository assessment, screening calculations have identified *water* as the major dispersion vector [8]. Hence, gradual leaching scenarios consider natural and facility-related phenomena causing a progressive and slow leaching of radionuclides from the repository into the underlying aquifer and subsequent use of water extracted from the aquifer for drinking, field irrigation, cattle watering, etc.

With the safety concept being firmly focused on the SSCs (cf. foundations of long-term safety), the focus for scenario selection and development is on repository behavior and evolution. We distinguish between the expected evolution of containment performance and disturbances of the containment performance, both of which are discussed below.

Expected evolution of containment performance

The starting point for scenarios addressing the expected evolution of containment performance lies in the scientific and technical knowledge and understanding in support of the containment performance. Three broad scenarios are considered for conceptualizing this expected evolution, with a different degree of realism/conservatism depending on the purpose of the scenario, as schematically represented in Fig. 6.

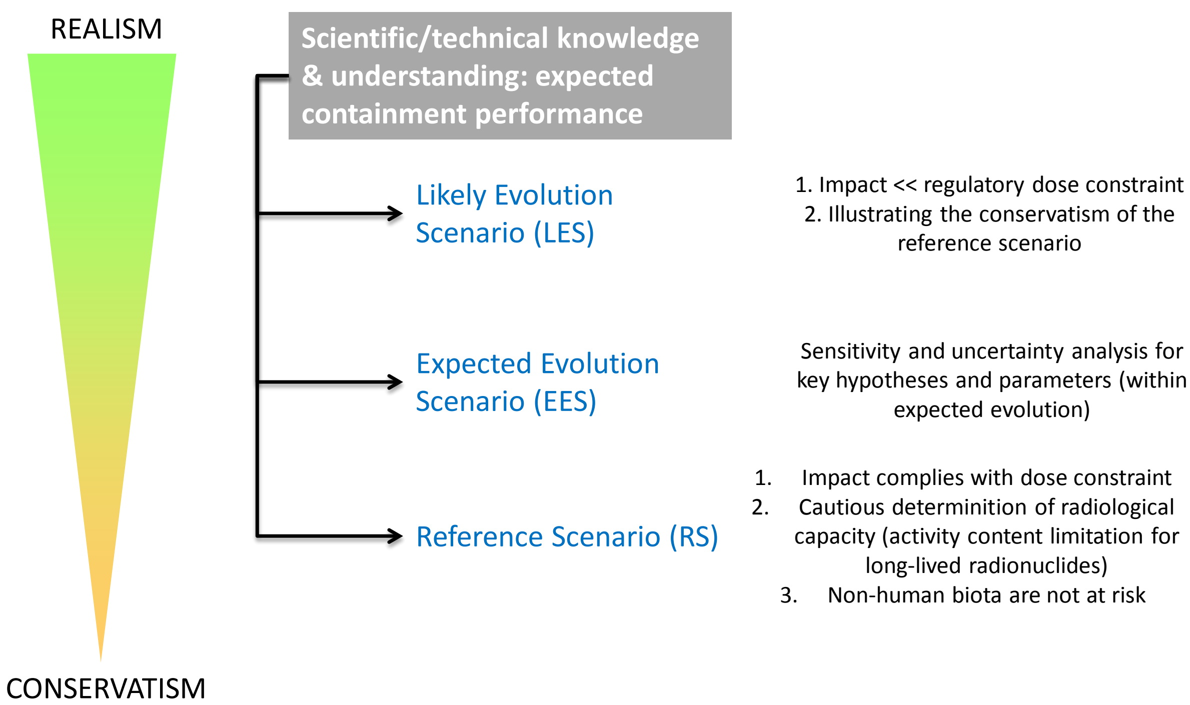

Fig. 6. Scenarios in which the expected evolution of the containment performance is conceptualized by considering a varying level of realism / conservatism and how they are used in developing safety arguments.

The reference scenario (RS), used for setting the radiological capacity, is the most conservative, such that the source term will in practice be duly restricted. The impact of the (estimated) source term under the RS must comply with a 0.1 mSv/year dose constraint.

The likely evolution scenario (LES) at the other side of the spectrum still has elements of conservatism, resulting from a cautious interpretation of the scientific understanding, yet incorporates more realism, which is desirable for three purposes [9, 10]:

- communication of the expected order of magnitude of impacts to a broad public;
- providing a comprehensive picture of uncertainties, rather than merely accumulating those uncertainties that could impair the containment performance;
- providing a tool for ‘demonstrating’ that the scenarios/models used for formal compliance demonstration, in particular the reference scenario, are indeed conservative.

The expected evolution scenario (EES) has an intermediate level of conservatism, as needed to meaningfully explore model sensitivities, which is not always possible when the level of conservatism is too high.

An overview of key assumptions of LES, EES and RS is given in Table I.

TABLE I. Key assumptions for different features in scenarios addressing the expected evolution of containment performance: reference scenario (RS), expected evolution scenario (EES) and likely evolution scenario (LES).

<table>
<tr><th></th><th>LES</th><th>EES</th><th>RS</th></tr>
<tr><td colspan="4">CONTAINMENT PERFORMANCE</td></tr>
<tr><td>Waste form</td><td>Instantaneous release (R1 not accounted for)</td><td>Contribution of R1 for different waste forms in sensitivity study</td><td>Instantaneous release (R1 not accounted for)</td></tr>
<tr><td rowspan="2">Module</td><td colspan="3">R2a/R2b considering a fast increase in effective hydraulic conductivity between 350 and ~ 500 years</td></tr>
<tr><td colspan="3">Through-going cracks in module base from isolation phase onwards (preferential pathway)</td></tr>
<tr><td>Monoliths</td><td colspan="2">R2a/R2b considering a fast increase in effective hydraulic conductivity between 350 and ~ 800 years</td><td>R2a/R2b considering a fast increase in effective hydraulic conductivity between 350 and ~ 500 years</td></tr>
<tr><td>Multi-layer cover</td><td>R2a of multi-layer cover effectively reduces the infiltration rate to ~ 10^{-9} m/s up to the end of the chemical containment phase (~ 2000 years)</td><td colspan="2">Clay infiltration barrier ineffective from the start of the isolation phase onwards, with a fast increase in infiltration to ~ 10^{-8} m/s during the isolation phase</td></tr>
<tr><td>Physical & transport properties</td><td>Parameters evolving from initial to final values as R2a/R2b degrade (diffusion coefficient, dispersivity) or as cement phases leach out (porosity, bulk density)</td><td>Parameter values evolving from initial to final values as R2a/R2b degrade</td><td>Parameter values representative of degraded concrete at all times</td></tr>
<tr><td rowspan="2">Chemical retention</td><td colspan="3">Sorption values based on data review, selection and scientific argumentation by an International Expert Panel [11, 12]</td></tr>
<tr><td colspan="3">Evolution of sorption performance (R3) as cement phases leach out (in line with results from geochemical modeling)</td></tr>
<tr><td colspan="4">EXPOSURE GROUP</td></tr>
<tr><td>Well location</td><td>Average concentration in contamination plume in the aquifer</td><td colspan="2">Maximum concentration at the foot of the disposal tumuli (70m away from the modules)</td></tr>
<tr><td>Degree of self-sustainability</td><td>50%</td><td colspan="2">100%</td></tr>
</table>

Disturbances to the containment performance

The scenarios in which disturbances to the containment performance are addressed, have been developed by means of a top-down methodology [7] considering the expected evolution and a list of *initiating FEPs (Features, Events and Processes)*, i.e. potential events or processes that affect the performance of the disposal facility in a detrimental manner by causing a change in the state of the disposal facility and the pathway(s) of radionuclide release from the facility.

Potential initiating FEPs were derived from the category A FEP list [13], which in turn is based on a compilation of internationally established FEP lists tuned towards the Dessel repository. Further steps in the development of alternative evolution scenarios (AESs) can then be summarised as

- describe the effects of initiating FEPs on the EES in terms of SSCs and safety functions affected;
- adding detail to the initiating FEPs (timing and extent of safety function degradation, other safety functions affected);
- consolidating the thus obtained AESs to remove redundancy; and
- identifying assessment cases for each AES as a part of the treatment of uncertainties as well as to allow for an assessment of the robustness of the containment performance. This process is again followed by a consolidation step so as to remove redundant assessment cases.

The set of AESs allows for a broad “what-if” analysis including combinations of degradations with a very low likelihood, and thus aids in arguing the adequacy of the level of defense-in-depth in view of the radiological source term in the repository.

Those alternative evolutions that are not covered by the conservative assumptions of the reference scenario, but are nonetheless deemed to have some plausibility, are further developed into alternative reference scenarios (ARSs) for which the radiological risk is formally assessed. The ARSs deal mainly with what one could call ‘contextual uncertainty’ which increases with time:

1. poor construction of protective SSCs, particularly poor implementation of the multi-layer cover at the start of phase Ib (see Fig. 3) after ~ 50 years of operation, yielding a reduced R2a effectiveness during phases III and IV. In combination with a module base and walls fulfilling their R2b role, this could lead to the so-called *bathtubbing* effect which could in turn result in part of the radionuclide flux bypassing the physical and chemical retention capability (R2b& R3) of the module base and the embankment;
2. poor closure, i.e. fault in backfilling of inspection rooms & sealing of drainage system after ~ 100 years (see Fig. 3) – whereby the improper backfilling affects the R3 function of the module base, whereas the sealing error causes a bypass of the physical and chemical retention capability (R2b & R3) of the module base as leachate is diverted towards the inspection gallery;
3. occurrence of a major earthquake against which the disposal facility is not designed to be resistant after ~ 350 years – yielding a fast loss of R2a of the multi-layer cover and module roof and R2b of the other parts of the module early in phase IV.

A schematic overview of the development of alternative leaching scenarios and how they are used in the safety argumentation is given in Fig. 7.

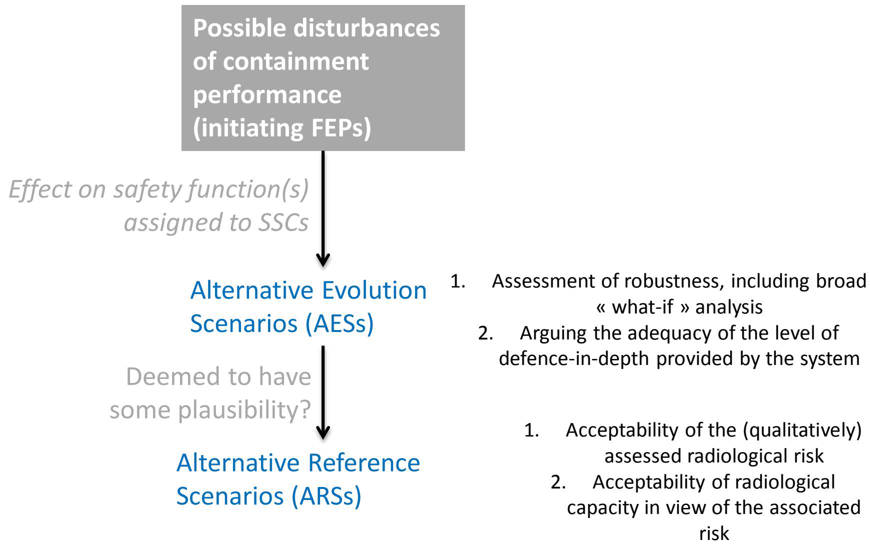

Fig. 7. Alternative leaching scenarios in which disturbances to the containment performance are conceptualised and how they are used in developing safety arguments.

HUMAN INTRUSION SCENARIOS (HISs)

By definition, human intrusion scenarios (HISs) deal with disturbances to the isolation performance of the repository. It is assumed that the intrusion is *inadvertent*, i.e. its initiator is unaware of the potential radiological consequences. Consequently, intrusion is assumed to be prevented as long as access controls are in place (nuclear regulatory control phase). There may either be a 'direct' impact to the initiator of the intrusion or a 'deferred' impact to members of the neighboring population as contaminated material (including waste remnants) is spread near the disposal site.

Since future human actions are inherently impossible to predict, *stylized* scenarios are considered, in which it is assumed that

- barriers are easily penetrated[4] at any intrusion time;
- prior to the time of intrusion, no leaching has occurred.

Combined with a cautious choice of exposure groups, HISs thus allow for a determination of the residual risk associated with the waste from a few hundred years following disposal onwards. Table II summarizes the HISs considered in the assessment.

[4] In order to assess the possible contribution of safety function I1 during the isolation phase (see Fig. 4), three additional HISs have been defined, in which the multi-layer cover, the module roof and the monoliths act as intrusion barriers. These are: house construction on top of a tumulus, residence post-house construction and an excavation scenario in which intact monoliths are discovered.

TABLE II. Human Intrusion Scenarios (HISs) considered in the Dessel repository assessment.

Type of scenario (regulatory requirement)	Scenario conceptualization	Scenario use
Drilling and core analysis	Core analysis	Determining admissible activity concentration per waste package*
	Borehole drilling	Radiological impact
Large-scale construction site	Excavation	Determining radiological capacity Radiological impact
Exposure of self-sufficient family	Residence post-excavation	Determining radiological capacity Radiological impact
	Residence post-drilling	Radiological impact

* Meeting the criteria per waste package is a necessary, though not a sufficient, condition for waste to be eligible for disposal at the Dessel repository.

KEY ARGUMENTS FOR SAFETY FROM ASSESSING DIFFERENT SCENARIOS

In what follows, two aspects are further highlighted: the radiological impact, also in view of uncertainties, and the assessment of robustness.

Fig. 8 clearly illustrates that the expected impact to the neighboring population of the Dessel site will be negligible, i.e. in the order of 1 µSv/year, or three orders of magnitude below the natural background. This shows that the repository provides adequate containment and that the activity content of long-lived radionuclides has been duly restricted.

The impact of the estimated source term under the conservative reference scenario, aimed at not underestimating the possible impact is below the 0.1 mSv/year constraint, which further substantiates the radiological system optimization.

The sensitivity of results in the light of uncertainties, including scenario-initiating FEPs, has been explored in the expected and alternative evolution scenarios. In terms of impacts, this is schematically illustrated in Fig. 9. The impact ranges indicate that the repository is rather insensitive, hence robust, with respect to a range of possible threats.

Those cases for which a high impact is found (i.e. a few mSv/year at most) consider early (i.e. during the nuclear regulatory control phase) and simultaneous failure of multiple barriers, including the protective barriers (multi-layer cover and module roof), the plausibility of which is extremely low. The impacts and risks can be deemed acceptable in view of the *unforeseen* nature of the resulting exposure situations [14].

For comparison, the alternative reference scenario ‘major earthquake’, leading to degradation of the modules and the cover, at the start of the isolation phase gives cause to a maximum impact of 0.46 mSv per year, corresponding to a risk below 10^{-6} per year.

Fig. 9 further shows the impacts of human intrusion, which are at most a few tens of mSv per year (for the residence post-excavation scenario). The impact will thus not or scarcely be noticeable with respect to the natural background radiation amounting to a few mSv per year.

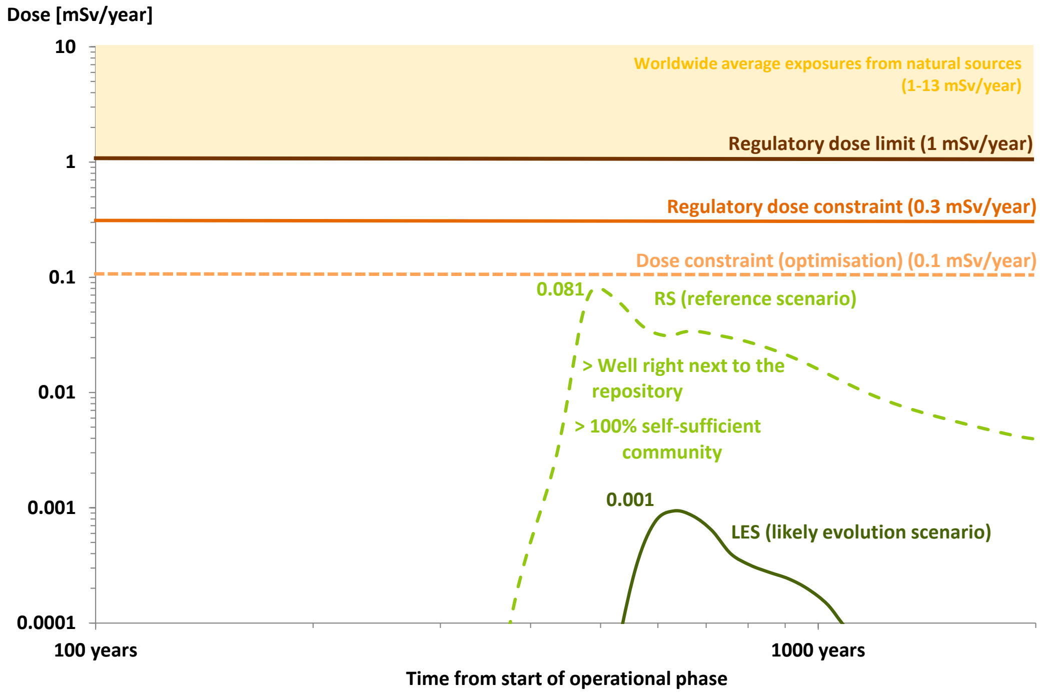

Fig. 8. Impact of the 'conservative' reference scenario, which complies with the dose constraint of 0.1 mSv/year vs. that of the more 'realistic' likely evolution scenario, which is trivial.

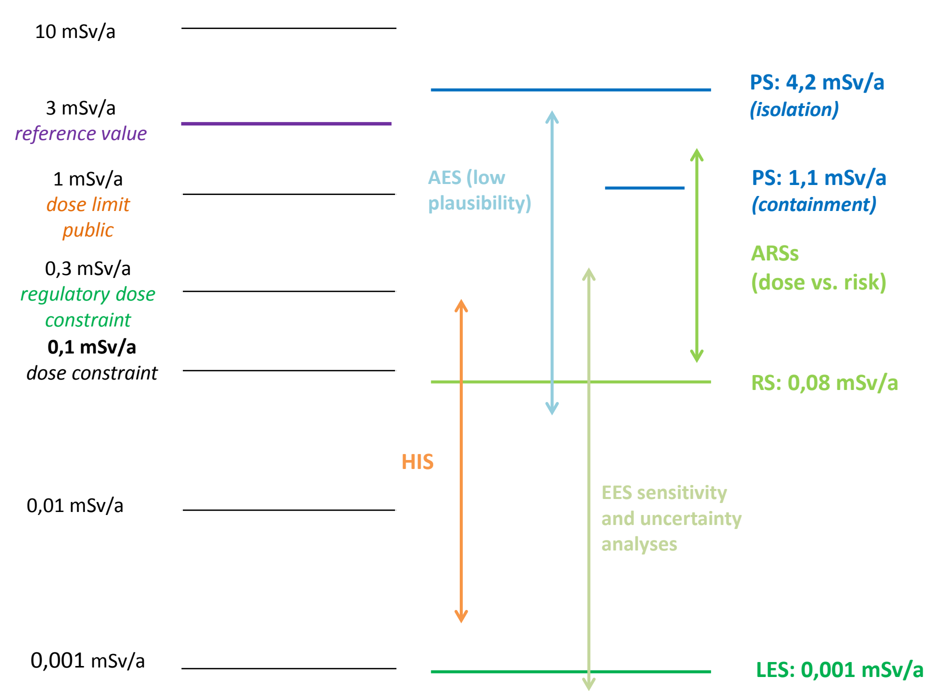

Fig. 9. Schematic overview of impacts calculated for different scenarios in the Dessel repository safety assessment.

CONCLUSIONS

The application for a construction and operating license for the Dessel near surface repository is substantiated by an extensive safety assessment, making use of different types of scenarios which serve different purposes. Table III presents an overview of the role and significance of the different scenarios.

TABLE III. Overview of different scenarios used for different assessment purposes.

Role	Significance of different scenarios
Cautious determination of disposal limits	Determination of limits on the basis of reference scenario and human intrusion scenarios
	Acceptability of the limits is further argued on the basis of alternative reference scenarios (and penalizing scenarios)
Confirmation that radiological impact/risk of estimated source term is acceptably low	Reference scenario and alternative reference scenarios comply with dose/risk constraint
	Sensitivity and uncertainty analysis for the expected evolution scenario confirms the adequacy of the assumptions adopted in the reference scenario
	Likely evolution scenario confirms the conservatisms adopted in the reference scenario
	The impacts of human intrusion scenarios (and penalizing scenarios) do not exceed a few mSv per year
Assessment of robustness	Alternative evolution scenarios in comparison to the expected evolution scenario
	Alternative reference scenarios in comparison to the reference scenario

On the basis hereof, key safety arguments are established, i.e.:

- disposal limits for long-lived radionuclides have been determined in a cautious manner, and have been translated into operational criteria so that the consideration of long-term safety takes a central position throughout the operational life of the repository;
- the radiological impact of the “realistic” likely evolution scenario is trivial, i.e. below 0.001 mSv/year while the impact of a conservative reference scenario is also below the 0.1 mSv/year constraint set as a target constraint (below the maximum regulatory dose constraint of 0.3 mSv/year);
- the disposal system is robust to a variety of uncertainties and threats, especially as long as the protective barrier system, preventing water infiltration, is functioning;
- a *what-if* analysis considering the non-functioning of SSCs from a few hundred years onwards gives rise to calculated radiological impacts of the order of a few mSv/year at most, thus confirming both the adequacy of the level of defense-in-depth provided by the repository, with respect to the estimated source term for disposal.

As such, the benefits of considering, in the context of a safety case development, a wide range of scenarios with varying degrees of realism/conservatism are highlighted.

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Prior to the finalization of the safety case for license application, key aspects including the safety strategy and the long-term safety assessment methodology, have been the subject of an international peer review under the auspices of the NEA [9].