Scenario Development in Safety Assessment

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INTRODUCTION

Radiation and radioactive substances have beneficial applications, including power generation and medical or industrial uses. Many such applications result in the production of radioactive waste which requires safe management and disposal to avoid risks to human health and the environment. For permanent disposal of radioactive waste, deep geological disposal is internationally considered the best scientific solution as it contains and isolates radioactive waste from the accessible environment. To test long-term safety, the expected performance of a deep geological repository is compared against a standard or constraint (e.g., mean dose of radioactivity to future humans or minimization of pollution to natural resources) [1,2] usually prescribed by national regulations.

Over the timescales during which radioactive waste remains harmful, typically hundreds of thousands of years for long-lived radioactive waste, there is significant uncertainty in both the initial state and in the future, and the designer of a repository needs to show that the repository system is safe despite this uncertainty. One approach is to consider both the repository base-case evolution and any plausible futures associated with early failure of one or more safety-related features. Through numerical models, these repository futures are evaluated to determine severity of any releases and subsequent radiation exposures or pollution. Scenarios are used to derive and consider both these types of cases: the base scenario (also called the nominal scenario, normal evolution) includes the designed behavior of the repository, and other scenarios (alternative or disturbed scenarios) are made up of possible deviations from the base scenario that might lead to releases or might need to be considered to quantify uncertainty.

Scenarios are an option for formalizing, planning, and assessing a complex decision process in a transparent manner that must be made when considering significant uncertainty. Scenarios have been a key component in the planning of geologic repositories for the permanent disposal of radioactive waste [3,4] and climate model prediction [5,6], among other fields (e.g., carbon sequestration [7] and business planning [8]). The development of scenarios for radioactive waste disposal, as outlined here, arose in the 1980s during the development of the Waste Isolation Pilot Plant (WIPP) in the United States, and has since been used for many other facilities around the world. The systematic development of scenarios from an exhaustive list of system features, events, and processes (FEPs) was considered, as an alternative to the event tree and fault tree approaches used since the 1960s in reactor safety [9], because of the increased uncertainty regarding the initial state of a geologic system and future evolution of a repository over very long time periods (and associated increase in possible futures) [3]. Scenarios have been used in a wide range of applications, with varying complexity, uncertainty, and risk. Geological repository programs for radioactive waste in different countries may also span a range of radioactive material inventories, geological media, and societal tolerance for the risk from the waste. Scenario planning is an integral part of repository design, but there is no simple definition or methodology complying with all requirements.

In radioactive waste disposal [10], scenario development is based on a formalized approach including delineation of system FEPs. Features of both the engineered system (e.g., waste form, waste package, buffer, backfill, and seals) and natural system (e.g., host rock) interact through events (discrete in time) and processes (may be ongoing). Uncertainty comes from both the unknown initial state of the system (both natural and man-made components) and the processes and events which may act on the system through time. Using an external FEP list helps ensure comprehensiveness that all possible significant failure mechanisms are being considered. The identification process often starts from an existing comprehensive list of FEPs and a related discussion of which FEPs may be relevant to the repository's safety and which are not relevant under any scenario (i.e., the FEP screening process). FEP lists include generic international ones [10], host-rock specific lists [11,12,13], and country or program-specific ones [14,15,16,17]. This evolution may be regarded as the tailoring of relevant FEPs to a host rock and then location and concept of interest, with the transition made as a national program develops.

In climate modeling for example, scenarios dictate the impact of possible future human greenhouse gas emissions on climate response. Man-made emissions are key forcing terms in climate models [6], where uncertainty in future emissions scenarios tends to dominate the total uncertainty in the model predictions. Earth's surface and atmospheric processes are governed by different physics than fractured or porous media flow and radionuclide transport from a deep geological repository, but the importance of carefully considered scenarios is common to both climate and repository systems [5].

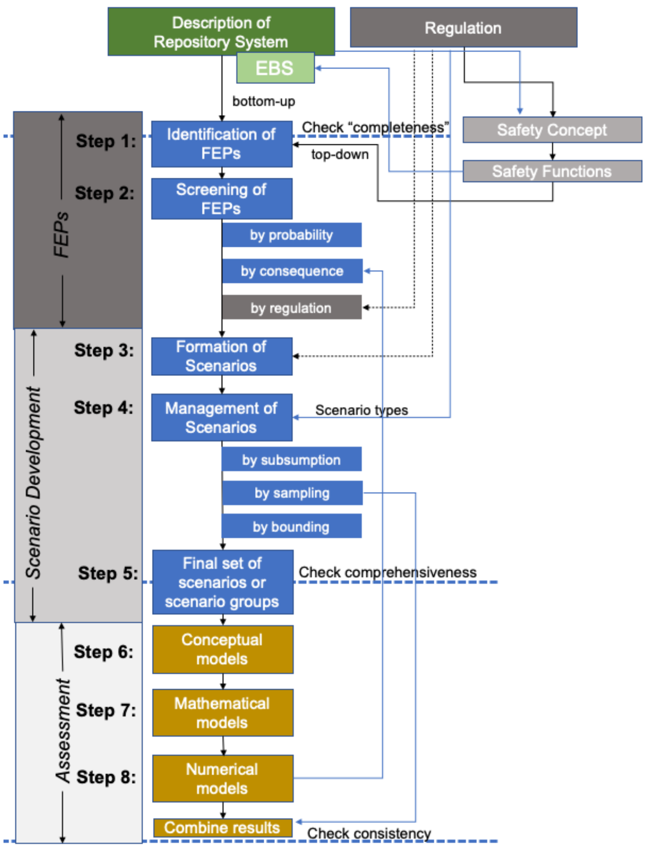

Fig 1. FEPs, scenarios, and assessment in safety case development for deep geological disposal of radioactive waste.

The post-closure safety assessment (also referred to as a performance assessment; PA) is the part of the safety case dealing with the site suitability and long-term assessment of risk and consequence related to the repository after its closure. The post-closure safety assessment is built from a set of scenarios that cover both the evolution of as-designed system and all "significant" deviations from the base case regarding the safety of the repository (i.e., all scenarios that could result in a release or dose to the accessible environment, including the base scenario).

While it is possible to include many scenarios associated with all possible evolutions of the system, scenario analysis tends to focus attention and resources onto the consideration of possible evolutions which may increase the risk (or other performance metrics). In many possible scenarios the system performs as expected and any slow migration of radionuclides does not compromise its safety. This is the result of repository system optimization and robustness through iteration between PA and repository design. PA is the embodiment of the scenarios as conceptual, mathematical, and numerical models. The development of scenarios and PA iteratively quantifies risk.

Risk is often conceptualized as a product of two measures: a probability of occurrence and a measure of the consequence [18]. PA models are used to quantify the consequences, while scenarios are used to manage the probability or likelihood associated with the consequences. Contamination-based standards are often directly associated with a PA model prediction like maximum change in dissolved radionuclide concentration.

The remainder of this paper discusses the flow of steps in a post-closure safety assessment, as laid out vertically along the left edge of Figure 1.

FEPS AND THEIR SCREENING

For radioactive waste disposal programs, FEPs are typically identified by starting from an exhaustive list of FEPs from existing international lists (e.g., the IFEP list prepared by the NEA [10]). Before proceeding on to the next step, the FEP list must be screened to the relevant host rock, site, and disposal concept, but preliminary FEP screening can occur before the site or disposal concept are finalized, usually resulting in a larger number of screened-in (i.e., the default) FEPs.

FEPs can be simply screened out based on either low probability or low consequence, as these two components make up the definition of risk. Additionally, there may be regulatory reasons for screening in or out FEPs (e.g., applicable regulations defining the investigation scope), and the problem can be simplified by screening out processes that are complex to consider, but ultimately only beneficial to safety (i.e., conservatisms). The future system is also often assumed to look like the current system (e.g., not considering evolution of microbes that will selectively destroy engineered systems).

A primary reason for using an international FEP database is to ensure completeness (top horizontal dashed line in Figure 1). The process should not ignore or miss a potentially important process or event that may impact one of features of the disposal system.

The list of initial FEPs (hundreds) are narrowed down through the screening process. Sometimes modeling is performed to assess the likelihood or consequence of individual FEPs as part of the screening process. To consider the entire set of screened-in FEPs in numerical models, they must be assembled into scenarios, which are then translated into conceptual, mathematical, and numerical models.

SCENARIO DEVELOPMENT

The main scenarios are the "base" scenario and a group of plausible alternative scenarios. The base scenario is what the engineered system is designed around, and the plausible alternatives are typically associated with the degradation or unexpected evolution of one or more key components of the system which contribute to the overall system safety (i.e., safety function). For example, alternative scenarios might consider early failure of a single geotechnical barrier (e.g., buffer or shaft seal), inadvertent human intrusion, or impacts on the future system state associated with alternative climate change futures.

Some scenarios may be created that are very unlikely or even impossible to happen, but they are often considered for hypothesis testing, or to bound and constrain the performance of the overall system. These "what if" scenarios are different from the base and plausible alternative scenarios since they typically do not contribute to the scenario recombination step at the end of the performance assessment. An example of a what-if scenario would be simultaneous early failure of multiple geotechnical barriers. The repository doesn't necessarily fail to comply with the applicable regulatory standards if one of the what-if scenarios leads to an exceedance of the dose constraint, but they instill confidence when they illustrate the system is robust to extreme circumstances.

Scenarios: Top Down vs. Bottom Up

The "bottom up" scenario development approach starts with individual FEPs and builds up a comprehensive description of the future evolution of the repository system through the development of scenarios for possible evolutions. Thus, safety-relevant consequences and their complex interaction can be analyzed for the whole system and in a transparent, inductive manner. A purely bottom-up scenario development process results in a system with many detailed descriptions.

The "top down" or deductive approach is centered around an initiating deviation from nominal (e.g., failure of the shaft seal), and analyzes its consequences on repository system evolution. Therefore, the corresponding scenarios are event-specific and not intended to cover a broad spectrum of possible evolutions. This approach is commonly used for development of alternative scenarios (for example by pre-supposing an early container failure without specifying or explicitly modeling any of the mechanisms, such as corrosion, which may trigger it). Logically, one must be careful not to prejudice the answer sought, by following a purely top-down approach (i.e., starting with a pre-defined set of intuitively expected failures in mind, which may not be complete or realistic). But even when working with a bottom up FEP approach, the base scenario is the basis for design.

There is no conflict between the bottom-up and top-down approaches [4,12]; they are especially effective when used in combination. Almost all national radioactive waste programs use a combination of bottom-up and top-down approaches. Starting with a bottom-up approach for the definition of the base scenario, it can be ensured that a comprehensive description of repository system is given, and a plausible spectrum of possible future repository system evolutions is covered. The impact of the perturbing FEPs, either individually or in combination, is then considered when defining scenarios for the evolution of the repository, which are assigned to various categories.

Alternative scenarios will significantly overlap with the base scenario and differ only in a few safety-function relevant characteristics. Practically, top-down evolutions can be directly linked with the base scenario and then realized as an evaluation of the differences and alternative consequences in comparison to the likely system evolutions.

Management of Scenarios

Analogous to how FEPs must be screened to localize the international FEP database to the site, host rock, and disposal concept, the group of scenarios developed must be managed before moving on to the assessment phase.

Unlike FEP screening, the management of scenarios is not associated with a comprehensive list of all possible scenarios, but a consideration of how to evaluate each non-base scenario. Some scenarios are a small perturbation on the base scenario (e.g., failure, degradation, or evolution of some system safety function). It may be possible to bound, lump, or subsume similar alternative scenarios to simplify the overall analysis. If several similar alternative scenarios are all less severe than a single bounding scenario, the individual assessment of each of the less severe scenarios might not be required or might be treated in a less explicit manner.

Once a final set of comprehensive scenarios is developed (middle dashed horizontal line in Figure 1), they are used to assemble the final assessment. For scenarios, comprehensiveness is the consideration of all system outcomes that contribute to the overall risk. Not all scenarios must be considered in the same manner.

ASSESSMENT

The scenarios are methodologically translated into conceptual, mathematical, and numerical models. These models describe how the consequences are evaluated to either compute a risk-based standard (i.e., risk = consequence × probability) or a pollution-based standard (e.g., the repository must not increase radiation levels above background at some compliance distance).

The base scenario is converted into a conceptual model through the process of delimitation, reduction, composition, aggregation, and abstraction [19]. The conceptual model is then converted to a mathematical model and finally a numerical model, which requires specification of physical parameters, initial conditions, and boundary conditions. Uncertainties associated with the properties, conditions, and conceptualizations must be carefully considered. During the mapping of the base scenario onto the conceptual, mathematical, and numerical models, there may be multiple alternative models to consider or evaluate.

At the end, the final aggregate performance of all assessed scenarios of the repository system is compared against either risk- and/or pollution-based standards by combining the scenarios. During the combination of results from the assessment, consistency with the standards and between different approaches should be confirmed (bottom dashed line in Figure 1).

The final scenario recombination process can be probabilistic [4,20], requiring all quantified possible alternative futures be incorporated (and ensuring their probabilities add up to unity), or the combination may be done in a bounding sense by ensuring the consequences associated with any single scenario does not exceed some lower threshold.

PROCESS ITERATION

The steps of the process are laid out here sequentially, but the process is often iterative. Sometimes earlier steps require evaluation or consideration of things from later in the process. Going through the process the first time may reveal the need to reconsider earlier steps.

For example, the development of scenarios or numerical assessment models may reveal the lack of consequence for some previously screened-in FEPs, which may change some screening decisions. Some scenarios may end up being assessed to be very similar and they may then be treated by lumping or bounding them with another more consequential scenario. The results of FEP screening, scenario management, or assessment may trigger a repository design optimization, which would require reconsidering the entire process.

SUMMARY

This paper summarizes the development of post-closure safety assessment for radioactive waste disposal from the point of view of scenarios, which occupy the key point in the process between FEPs and assessment using conceptual, mathematical, and numerical models. Scenarios are used in other fields for similar purposes, but they have a central role in safety assessment for radioactive waste disposal, given the large uncertainties in natural and engineered systems over long time periods.

Repository design and assessments are built around a base scenario, which is usually built up from FEPs in a deductive bottom-up fashion. The alternative scenarios are often a perturbation of the base scenario, constructed in a top-down fashion around individual safety functions of key repository features.

Despite differences between nations in how they implement scenarios, largely from regulatory differences, the concept of scenarios is beneficial and is used universally in development of deep geological repositories. The methodology has also seen some use outside the field radioactive waste disposal, but its wider adoption might be warranted.

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