Scenario Development for Safety Assessment in Deep Geologic Disposal of High-Level Radioactive Waste and Spent Nuclear Fuel: A Review

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Abstract:
Radiation and radioactive substances result in the production of radioactive wastes which require safe management and disposal to avoid risks to human health and the environment. To ensure permanent safe disposal the performance of a deep geological repository for radioactive waste is assessed against internationally agreed risk-based standards. Assessing post-closure safety of the future system's evolution includes screening of Features, Events, and Processes (FEPs) relevant to the situation, their subsequent development into scenarios, and finally the development and execution of safety assessment (SA) models. Global FEP catalogs describe important natural and man-made repository system features and identify events and processes that may affect these features into the future. By combining FEPs, many of which are uncertain, different possible future system evolution scenarios are derived. Repository licensing should consider both the reference or "base" evolution as well as alternative futures that may lead to radiation release, pollution, or exposures. Scenarios are used to derive and consider both base and alternative evolutions, often through production of scenario-specific SA models and the recombination of their results into an assessment of the risk of harm. While the FEP-based scenario development process outlined here has evolved somewhat since its development in the 1980s, the fundamental ideas remain unchanged. A spectrum of common approaches is given here (e.g., bottom-up vs. top-down scenario development, probabilistic vs. bounding handling of uncertainty), related to how individual numerical models for possible futures are converted into a determination as to whether the system is safe (i.e., how aleatoric uncertainty and scenarios are integrated through bounding or Monte Carlo approaches).

200-Character Summary: We review development of scenarios from features, events and processes as part of a radioactive waste disposal safety case, illustrating there is a spectrum of modern approaches, and we present their origins from fault-tree analysis.

Keywords: Scenario development; Safety Case; Radioactive Waste; Features Events and Processes; international comparison

1.0 INTRODUCTION

Radiation and radioactive substances have many beneficial applications, including power generation, medical or industrial uses. Many such applications result in the production of radioactive wastes which require safe management and disposal to avoid risks to human health and the environment. For the permanent disposal of high-level radioactive waste and spent nuclear fuel, the preferred strategy is to contain it within engineered barriers and isolate it in a deep geological repository, away from the accessible biosphere (IAEA, 2011a). Deep geological repositories provide long-term stability, and the geosphere can provide robust isolation. For high-level radioactive waste (HLW) and spent nuclear fuel, deep geological disposal is therefore seen scientifically as the preferred solution (Hamilton & Scowcroft, 2012). To assess long-term safety the expected performance of a deep geological repository is compared against a regulated standard (e.g., mean dose of radioactivity to future inhabitants or minimization of pollution to natural resources; NRC, 1995; NEA, 2012).

There is significant uncertainty in the prognosis of the future over timescales during which the long-term safety of a HLW repository must be assessed, typically up to 10^6 years. The licensing of a repository needs to show the facility is safe despite this uncertainty. There are two types of uncertainty: epistemic and aleatoric (Helton et al., 2000a; 2000b). Epistemic (i.e., subjective) uncertainty is due to our limited ability to characterize a complex system, and results in uncertain material properties and model parameters. Aleatoric (i.e., stochastic) uncertainty represents a lack of knowledge about which future will happen and is considered irreducible. Scenario development is largely concerned with handling aleatoric uncertainty, although there will also be epistemic uncertainties in the consideration and assessment of scenarios. Non-quantifiable uncertainties often form the basis for scenario definition.

Commonly, the base scenario (also nominal or reference) includes the expected behavior of the repository and surrounding geosphere, while variant scenarios are made up of possible deviations from the base scenario (i.e., alternative scenarios) considering possible types of failures leading to releases. A scenario is a hypothetical future evolution of the system. Scenarios typically require numerical models to assess their impacts. Scenario classes are groupings of similar behaviors, allowing use of fewer assessment simulations to assess a wide range of possible future behaviors. The existence of one possible future (scenario) built from a set of FEPs implies existence of alternative futures considering both uncertainty in the initial state of features (epistemic) and different outcomes of future events and processes (aleatory).

Scenarios are a key part of the overall safety assessment to formalize, plan, and assess a complex decision process considering significant uncertainty. Scenarios have a key role in the development of a post-closure safety case for geologic repositories for the permanent disposal of radioactive waste (Cranwell et al., 1982; Andersson, 1989; Billington & Bailey, 1998; Galson et al., 2000; NEA, 2001; Hansen et al., 2014; Tosoni et al., 2018), strategic businesses planning (Schoemaker, 1993; Bradfield et al., 2005; Wright & Goodwin, 2009), extreme flood and drought preparation (Reilly & Willenbockel, 2010), CO_2 sequestration (Paulley et al. 2011; Yamaguchi et al., 2013), environmental remediation (Meyer et al., 2007), flood risk assessment (Jonkman et al., 2008), hydraulic fracturing (Tatomir et al., 2018), geothermal development (Lowry, 2021), climate model prediction (IPCC, 2000; Hawkins & Sutton, 2009), and climate intervention analyses (Wheeler et al., 2023).

In a post-closure safety case for geologic repositories, the aim is not to predict the future, or even to identify everything that the future could hold, but rather to provide confidence that all credible futures will be safe. This requires a focus much more on what *matters* in terms of safety, rather than what *happens*. Whilst the approach of course needs to be mathematically robust, an equal, if not higher aim, is to build confidence in the understanding and acceptance of the safety of a GDF despite remaining uncertainties, particularly aleatoric uncertainties over the future. This affects the analysis approach and leads to the scenario methodology described in this paper.

The development of a robust safety case includes consideration of the complex site investigation process (e.g., Keeney, 1987; Markhofer & Keeney, 1987) and the development of national guidelines and regulations which will govern the process (e.g., Morton et al., 2008). The public perception and acceptance of risk is also a key component of the overall repository development and licensing process (Flynn et al., 1992; Hine et al., 1997; Sjöberg, 2004; Chung et al., 2008).

The use of scenarios derived from features, events, and processes (FEPs) for radioactive waste disposal, as outlined here, originated in the 1970s after site selection for the Waste Isolation Pilot Plant (WIPP) (DOE, 1980; Cranwell & Helton, 1980; Cranwell et al., 1982; Marietta et al., 1989; Rechard, 2000). This approach uses the systematic development of scenarios directly from an exhaustive list of system FEPs, rather than extracting scenarios from the results of a fault- or event-tree approach, as used in reactor safety (NRC, 1975; Haasl et al., 1981; Milstein, 2001). This alternative FEPs-based scenario approach was developed for three primary reasons (Cranwell & Helton, 1980; Rechard, 1999). First, in waste disposal, "processes" represent slow continuous changes (not discrete events, as event-trees are built around), second, "processes" and "events" in a repository don't necessarily occur in a particular sequence (which event trees require), and third, fault-tree analysis cannot easily include feedback loops (which natural systems may require). A key distinction between the fault-tree approach and the FEP/scenario approach is the abstraction of time and sequencing from the scenario approach. Scenarios are a simplification, making analysis of the system more tractable.

Scenarios have been used in a wide range of applications, with varying complexity, uncertainty, and consequences. Even among international geological repository programs for radioactive waste disposal there is significant diversity in radioactive material inventories, geological disposal media, and societal tolerance for risk from radioactive waste. Scenario development is an integral part of repository design and its iterative optimization, but there is no simple definition or recipe appropriate in all situations. This manuscript presents both the origins and motivation for the scenario development process, as well as the commonalities of approaches used for post-closure assessments in radioactive waste disposal programs around the world. The scenario process is contrasted to fault-tree analysis, from which it arose. Summaries of the different scenario approaches being used in programs around the world exist (e.g., Tosoni et al., 2018), but this manuscript fills a gap, by providing a readable high-level summary of the process, its origins, and including the motivations for the steps taken.

In radioactive waste disposal, the safety case is the integration of arguments and evidence that describe, quantify, and substantiate the safety, and the level of confidence in the safety, for a deep geological repository (IAEA, 2012). **Fig. 1** shows how scenario development (Steps 3-5) sits at a crucial point in the overall safety case development process. Scenario development is a key part of the safety strategy that bridges the gap between the early idea generation phase (Steps 1-2) and the later numerical model evaluation phase (Steps 6-8). Both the resulting scenarios, and the list of FEPs they are derived from, are required to be comprehensive—to the extent possible—to ensure no significant source of contamination or risk is left unconsidered. Although **Fig. 1** shows a linear progression of steps, the overall process is quite iterative (later steps in early iterations can influence earlier steps in later iterations).

For comparison, a naive implementation of the fault-tree approach with stochastic sampling of all permutations of processes and events (occurring continuously over a long time horizon) for the relevant set of system features (both man-made and natural) at each step in time over millions of years, would result in too large a population of fault trees that would then be difficult or impossible to group uniquely or summarize into scenarios (i.e., from Step 2 to 5). The scenarios approach allows the consideration of possible characteristic evolutions of the system in an abstracted sense, without the fault-tree analysis step. Causality and time are then re-introduced to the process later when going from scenarios to assessment modeling (i.e., from Step 5 to 6).

The fault-tree approach is more frequently used to characterize consequences associated with operational safety (i.e., pre-closure) for deep geologic repositories. The scenario approach lends itself more to complex (i.e., multiple ongoing nonlinear processes) and uncertain processes, where consequences from an earlier step (i.e., damage to a canister during waste emplacement) must be propagated to later steps to determine their contribution to the overall response (i.e., dose or contamination at the receptor over the regulatory time horizon). Fault-tree analysis is more applicable during operational phases when workers are in proximity of the waste, and any dose can be computed directly and doesn’t need to be propagated through many other processes to a distant receptor throughout the regulatory time horizon to determine its effects.

National nuclear regulations include requirements for siting, licensing, construction, operation, and closure of repositories as well as for their long-term safety assessment (including safety demonstration methodology). They often consider recommendations of the International Atomic Energy Agency (IAEA, 2011b) and Nuclear Energy Agency (NEA, 2004), but also include special national strategies. The regulations may define the general framework for the methodological approach of safety assessment.

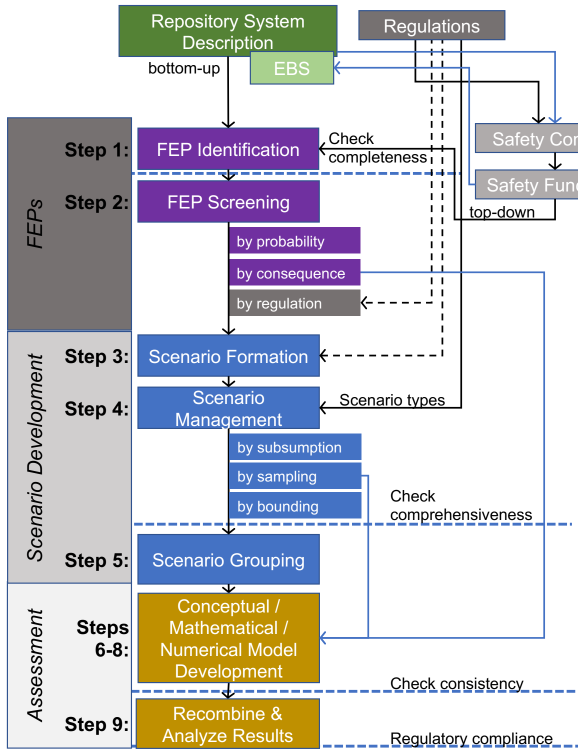

Fig. 1. Safety case development, showing FEPs, scenarios, and assessment steps for a geological radioactive waste repository.

Risk can be conceptualized as the product of two measures: a probability of occurrence for some detrimental situation and a measure of the consequence associated with its occurrence (Helton, 1993). Kaplan & Garrick (1981) present a risk triplet, analogous to the process outlined in **Fig. 1**. First, brainstorm what can happen or go wrong (i.e., FEPs), developing scenarios of interest. Second, evaluate how likely it is to happen, assigning probability to scenarios (this is where scenario approaches presented here mainly differ). Third, evaluate the hazard if it happens, estimating the consequences of the scenario.

A Bayesian distinction is taken here between probability and likelihood (also called frequency). Probabilities are associated with possible outcomes and are constrained to sum to one across all possible alternatives (Gallistel, 2015). Likelihoods are instead associated with hypotheses and are not constrained to sum to one (Edwards, 1972). Hypotheses may overlap, and the set of hypotheses may not cover every possible result.

We contend scenario development is hypothesis creation. If the goal is to assemble probabilistic scenarios from hypotheses, then effort must be made to ensure scenarios cover all possible cases, and any overlap between scenarios is reflected in their probabilities, which must sum to one. For example, two scenarios that consider the evolution of the repository system but differ only in how a waste package evolves exhibit significant overlap. The mechanisms governing migration of radionuclides to the far-field is likely quite similar (with different timing), therefore the two scenarios are not independent, and their probabilities cannot be directly summed without careful consideration.

In business and planning fields, scenario generation begins with a brainstorming phase, which allows the consideration of multiple futures in situations that might otherwise be solely deterministic (i.e., facilitating better decision making by improving the use of available information). Schoemaker (1993) considered hypothesis testing with scenarios a compromise between rigorous completeness of fault-tree analysis and lax simplicity of not considering uncertainty at all. In radioactive waste disposal, fault-tree analysis would not be practicable for the complex systems and long time-horizons considered.

In climate modeling, scenarios specify possible future human greenhouse gas emissions or intervention strategies, which can drive the resulting climate response (Hawkins & Sutton, 2009). Scenario uncertainty typically surpasses other sources of uncertainty derived from numerical model implementations and natural atmospheric fluctuations. The governing physics is different, but the importance of carefully considered scenarios is common to climate and repository systems (IPCC, 2000). To address this scenario uncertainty, the regulator defines scenario types that are of regulatory interest.

Not all scenarios reflect expected evolutions of the system (i.e., base system behavior); scenarios can also be used to define less likely, unlikely, or even impossible futures. Another type of case (sometimes called a scenario) may arise by asking "what if" questions required by regulations or to test system robustness. Developed scenarios are implemented in safety assessment models (conceptual, mathematical, and numerical – **Fig. 1**, Steps 6-8), which are used to measure the consequences associated with a given a set of assumptions about the behavior of the system. Two end members of scenario development are presented: a probabilistic approach, and a bounding approach. The aleatoric uncertainty is accounted for in either the parameter distribution (i.e., the probabilistic approach) or it exists between the scenarios (i.e., the bounding approach).

The final recombination and comparison step of the safety assessment (**Fig. 1**, Step 9) depends on the approach taken during scenario construction and includes explicit weighting of a complete set of probabilistic scenarios, or it can be done in a simpler bounding sense (e.g., if all scenarios are individually consistent with required performance metrics). Here the term "probabilistic" is used to refer to a SA system where probabilities of all considered futures sum to one (i.e., nothing left out, nothing counted twice). The probabilistic approach places additional constraints on scenario development and relies on stochastic sampling and parameter distributions to quantify both epistemic and aleatoric uncertainty, but then results in a straightforward mechanical recombination step (Meyer et al., 2007; Helton & Sallaberry, 2009). In contrast, the scenario hypothesis approach is more akin to likelihood. This bounding (called "pluralistic" by Tosoni et al. (2018)) approach quantifies the aleatoric uncertainty in the system between a smaller number of expert-chosen scenarios (i.e., the uncertainty in the overall problem is bounded by judiciously chosen scenarios). They are then either checked independently against regulatory thresholds (without necessarily recombining the results) or they are weighted and recombined in a way specified by regulations, rather than derived from probability theory. The bounding case may be simpler to explain and present to the public than the probabilistic one, while the probabilistic approach may be more systematic and exhaustive. A purely bounding case requires additional exploration of epistemic parameter uncertainty to quantify uncertainty in the prediction.

The remainder of the manuscript follows the development steps for a repository safety assessment, as laid out graphically in **Fig. 1**. The identification and screening of FEPs (Section 2) is the brainstorming phase, where all possible components and effects are included. This is followed by the development and management of scenarios (Section 3), where the overall behavior of the system is first assembled into a set of possible futures. The assessment steps (Section 4) are where the scenarios are quantified and re-combined into a total long-term repository performance measure. Finally, we reflect on differences in the ways countries implement these steps, and how they might be applied in other fields (Section 5). The processes, laid out linearly in **Fig. 1**, is iterative. Some countries may include iteration or even optimization of the process as part of their regulations. Even when optimization of the result is not enforced, the process will require multiple attempts, and things learned or found in a later step of one iteration often impact earlier steps in a subsequent iteration.

2.0 FEPS

The brainstorming process in radioactive waste disposal now starts from an existing comprehensive list of safety relevant FEPs, rather than developing a FEP list anew. FEP screening then identifies which FEPs may be relevant to the repository's safety, and which are not relevant under any scenario. This identification and screening process can be regarded as the tailoring of relevant FEPs to a waste stream, host rock, location, and disposal concept, with transitions to more specificity made as a national disposal program matures.

2.1 Step 1: FEP Identification

Radioactive wase disposal programs no longer need to develop FEP catalogs for radioactive waste disposal from scratch, as robust FEP catalogs have been developed through prolonged international effort with regular review by international actors, although additional FEPs are added if needed (e.g., to add site-specific detail to generic lists). Using the FEP and scenario approach for an application besides radioactive waste disposal may require development of new FEP lists or adaptation of existing ones. The development of FEP lists is considered elsewhere, as there already exist generic international lists (NEA, 2000; 2019), host-rock specific lists (Mazurek et al., 2003; Lommerzheim et al., 2018; Freeze et al., 2020), and country- or program-specific lists (Locke & Bailey, 1998; Galson et al., 2000; Freeze, 2002; NEA, 2013b). The Nuclear Energy Agency (NEA) has developed a generic international FEP database for radioactive waste disposal, which compiles the international experience of repository projects with different waste inventories and different host rocks (NEA, 2000; 2019). This NEA FEP database can be a starting point for FEP catalog compilation and can be used to check comprehensiveness and safety relevance of any other FEP catalog, with a mapping between project specific FEPs and international FEPs, a common undertaking by safety case authors.

The general objectives of the FEP catalog include:

- Comprehensive description of all safety-relevant features (physical and logical components) of the repository system, the biosphere, and receptors and their relevant properties that characterize the initial state of the repository system after repository closure. Examples: host rock, access shaft/ramp
- Identification of processes (ongoing) or events (discrete in time) that may influence the future system evolution. Examples: erosion, earthquakes
- Evolution (processes) of natural site characteristics through interaction with engineered components of the waste disposal system. Examples: heat flow, mine convergence
- A compilation and documentation of information relevant to the subsequent steps of scenario development and SA modeling. Examples: intensity of event occurrences, characteristics, and properties of important system components, how they contribute to the safety concept
- Enhancement of transparency and traceability of the information necessary for the safety assessment and to identify open questions, ensuring nothing important is left out.

Fig. 2 shows scenario development from FEPs, considering the system evolution over the entire regulatory horizon (0 to N). This figure focuses on steps 1-5 in **Fig. 1** (i.e., before SA). The left panel of **Fig. 2** Illustrates the relation between features (circles) and events or processes (squares). Features only connect to other features through processes or events, and processes and events only connect to other processes or events through features. The grid illustrates the relationship in two dimensions (i.e., four neighbors), but real systems are not constrained in the number of connections, or only to have connections between immediate neighbors. Arrows above and below the middle panel represent the iterative nature of the process. Outcome from a later step (e.g., scenario grouping) may impact an earlier step (e.g., FEP screening) during a later iteration through the process.

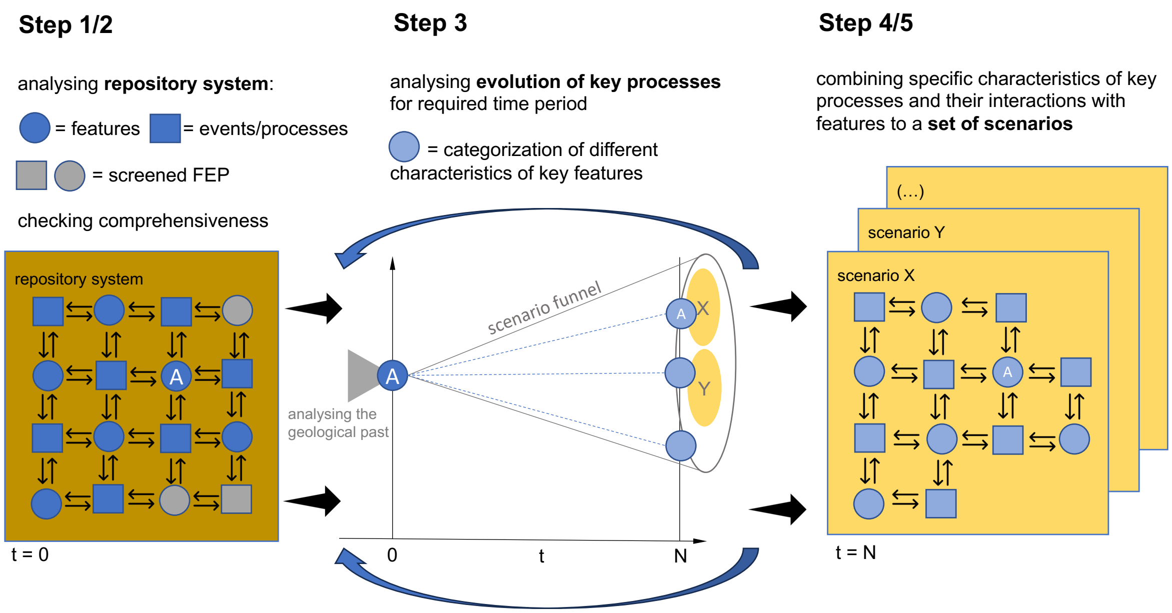

Fig. 2. Development of scenarios using FEP approach (t is time to regulatory horizon, N). Iteration (backwards arrows) may be specified by regulations (i.e., optimization) or may be a by-product of the development process.

Repository systems are complex, requiring an understanding of technical (Engineered Barrier Systems (EBS) – Matteo et al., 2021) and natural features (geological barriers) over long periods of time, yet with limited possibilities for observation and monitoring. In the middle panel of **Fig. 2**, the set of possible future evolutions is reduced or managed and only identified key processes and events (and their associated influence) relevant to that scenario are carried forward (i.e., key process "A" in **Fig. 2**). The scenario funnel in **Fig. 2** represents the safety envelope, and scenarios X and Y as shown in the middle panel do not overlap. Typically, the base scenario overlaps significantly with variant scenarios, which may only differ in one or two key safety functions. For key geological processes this is often based on the analysis of the past (e.g., tectonic processes, magmatism, and glaciation). In the right panel of **Fig. 2**, the possible evolutions of processes and events for the various factors are selected and subsequently condensed into scenarios and scenario classes which, together, address the uncertainty in the system and span the possible evolutions of the system.

An important purpose for FEP identification, FEP screening, and scenario development is a geoscientific long-term prognosis which considers the evolution of geosphere and biosphere in the past and gives a prognosis of several possible future site evolutions (i.e., understanding the past is key to identifying future possibilities – the actualism principle). The geosphere's properties (as analyzed by results of site exploration) are part of the design even though they are uncertain (i.e., epistemic uncertainty), since rock properties vary spatially, with scale, and can never be fully characterized (e.g., Clauser, 1992). The repository concept on the other hand is man-made and adaptable within engineering constraints; it can be modified to match the site-specific requirements (considering needs for both operational and long-term safety).

Apart from the compilation of relevant system properties, the FEP catalog reflects the interrelation between the site- and rock-type specific geological conditions and the man-made modifications resulting from the disposal of radioactive waste (e.g., excavation damage, thermal perturbation, and gas generation). Completeness of the starting FEP catalog is important, to ensure the reliability and completeness of the overall safety assessment.

2.2 FEPs and Safety Functions

The safety case describes the general strategy to comply with relevant legal requirements. The safe containment and isolation of radionuclides should (IAEA, 2011a; 2011b) be ensured by a multi-barrier concept, with safety functions assigned to different barriers and components in line with the safety concept. For salt and argillaceous host rocks, the host rock and geosphere are the typically most relevant, long-term stable barrier. In crystalline rock repositories, more emphasis is placed on the engineered barriers (i.e., waste packages, buffer, backfill). Man-made perforations of the geological barrier during repository construction will be restored by geotechnical barriers (i.e., seals and plugs). These barriers may have a limited functional lifetime, while the long-term sealing of the mine openings will be ensured by a host rock specific backfill and possible natural closure processes. The impairment of the safety functions of the barriers by possible future processes and events may be starting points for scenario development.

<u>Safety functions</u> describe elements of the safety concept that contribute positively to future system evolution (Hedin, 2008); they are the ‘functions’ that collectively need to be performed by the system to ensure safety (e.g., isolation, containment) and are often linked to design requirements, for example a particular thickness of container to ensure sufficient container lifetime. They are useful to understand the requirements of barriers (both in terms of an acceptable initial state and evolution of a system) in relation to the safety concept. They can help target the overall analysis to safety-relevant scenarios by focusing on which FEPs may provide or impact one or more safety functions, and hence lead to releases through alternative evolutions, and thus help establish an objective and formalized methodology. Individual FEPs may be positive, negative, or neutral in their impact on each safety function and hence contribution to overall risk.

2.3 Step 2: FEP Screening

The compiled comprehensive FEP list must then be screened to the relevant host rock, site, and disposal concept. It is possible to screen without a chosen host rock, site, or project, but fewer FEPs will be screened out. Screening reduces the number of open FEPs to consider, and therefore reduces the number of scenarios to assess. FEPs are retained by default *unless* a justification is provided to screen them out to ensure the robustness of the process.

Screening typically involves the exclusion of a FEP from further consideration for one of the following reasons (e.g., Marietta et al., 1989; Freeze et al., 2020), presented in decreasing order of preference (i.e. robustness) for the safety case:

- **Significance of non-nuclear consequence:** some large-consequence events may still be excluded due to the much wider effect on society that would overwhelm those from the geologic disposal facility. Example: meteor impact
- **Low consequence**: when an event will not have any significant impact on the overall assessment results (this may require assessment to quantify). Example: osmosis is not a significant process compared to advection in a repository context
- **Positive safety function**: beneficial FEPs that have only positive impact on the overall assessment results may be left out to simplify the analysis (i.e., conservative assumptions), but this should be avoided when the aim is design optimization rather than SA. Example: chemical precipitation may plug fractures and reduce permeability, but conservatively it is not included
- **Regulatory:** explicit direction from the regulator may exclude the consideration of some FEPs. Example: deliberate future human sabotage or intentional human intrusion
- **Future behaviors assumed like current and past:** to screen out remotely possible but highly speculative future developments to reduce undue speculation. Example: evolution of new microbe that destroys engineered components
- **Low likelihood:** because an event or process is very unlikely (usually with some quantified threshold of annual occurrence specified by a regulator). Example: large earthquakes in a seismically quiet area

Screening based on consequence, rather than likelihood, is preferred as it is generally much easier to be confident about a consequence assessment than a likelihood elicitation. It is also more reassuring for stakeholders to understand that if a scenario materialized its consequences would be acceptable (perhaps through mitigation measures), than to ask them to have faith that a detrimental scenario is very unlikely to happen.

Most screened-in FEPs are included within the base scenario, while other FEPs are the basis for alternative scenarios. All screened-in FEPs must be included in at least one of the final scenarios (i.e., completeness). For alternative scenarios, an event's existence (e.g., earthquake occurs), likelihood of occurrence, properties (features) or intensity (processes) makes the difference in how it is included in a scenario (e.g., low corrosion rate in a base scenario, high corrosion rate in an alternative scenarios). The failure or exclusion of an inherently positive FEP (a lost or reduced safety function) may be the basis of a scenario.

There are likely too many FEPs (hundreds) to consider each separately in detail with safety assessment numerical models. The fault-tree approach would lead to an even larger number of cases to consider. FEPs are grouped by similar processes, events, or features (e.g., one FEP to describe all characteristics of the host rock). The screening process reduces the number of FEPs, and the scenario process groups these FEPs together into scenario classes to allow consideration of a small number of unique scenarios, which are then addressed and possibly built into SA model assessments.

3.0 SCENARIOS

Starting from the screened-in FEPs, scenarios are developed, but how FEPs are turned into scenarios depends on the type of scenario. **Fig. 3** graphically illustrates the bounding approach (left panel) and the probabilistic approach (right panel). In the bounding approach, the per-scenario standards would be set by a regulatory authority, possibly derived through their own analysis, which essentially maps an expected set of per-scenario results onto the overall expected result for the entire repository system.

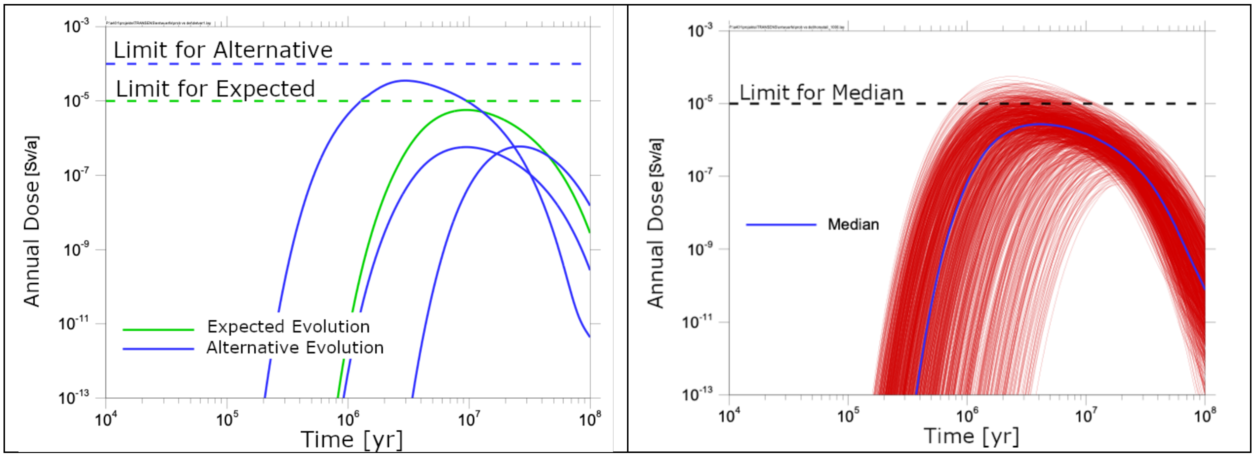

Fig. 3. Classification of scenario methodologies and comparison to a standard. Left illustrates "bounding" approach with per-scenario standards, while right illustrates "probabilistic" approach with the standard compared to the weighted median (modified from Becker et al., 2024).

Uncertainty in the analysis of scenarios arises from two major sources (Cranwell & Helton, 1980): first, the inexactness with which the *occurrence* of scenarios can be predicted (aleatory), and secondly, the inexactness with which the *consequences* of individual scenarios can be predicted (epistemic). An example of the first source of uncertainty is the inclusion of a variant scenario; does it happen or not? The way to include aleatoric uncertainty is the main difference between the bounding and probabilistic approaches. The bounding approach spans aleatoric uncertainty between scenarios, while the probabilistic approach samples the aleatoric uncertainty directly. The second source of uncertainty comes from epistemic uncertainty associated with the parameters in each simulation and can be handled similarly in either the bounding or probabilistic approaches.

In either of these two approaches, scenarios can be broadly categorized as:

- **Base** (i.e., reference case or nominal/expected evolution): repository system and safety concept are designed and optimized around this scenario. The base scenario needs to be realistic but as broad-based as credible.
- **Plausible alternative** (variant scenarios): deviations from base scenario with a lower likelihood of occurrence. Included explicitly with probability distributions in probabilistic scenarios or through weighting or per-scenario regulatory limits in bounding approaches

    - **Future human action**: only inadvertent intrusion into the repository is considered (IAEA, 2012). Deep disposal minimizes the impacts to a small group of unintentional future intruders compared to surface storage. These are often stylized scenarios (or even "what if" cases) dictated by regulations, but they also can be included in the base scenario (e.g., WIPP)
    - **Rare high-consequence events (volcanos; meteor impact)**: associated with rare geological events (often excluded by site-selection or regulatory processes)
    - **Failure of a geotechnical barrier:** early failure of a key barrier may be considered plausible (simultaneous failure of multiple barriers is typically relegated to "what if" cases)
- **"What if"** cases do not impact compliance: these may not be developed from the FEP catalog and are regulated differently (i.e., the whole repository doesn't fail if a "what if" case leads to failure). They demonstrate *defense in depth*, by illustrating how the system responds when one or more components completely fails or is left out. Due to their significant differences from plausible alternative scenarios, they are here referred to as "cases" rather than scenarios. Any action or design change aimed at mitigating a potential "what if" case should not be detrimental to the consequences from the base scenario.
    - **Specified implausible "what if" cases**: often a regulator-specified case that must be investigated (e.g., early simultaneous failure of all waste canisters)
    - **Failure of multiple/many simultaneous barriers**: several or all engineered barriers fail simultaneously
    - **Future human action**: depending on regulations, human intrusion may be considered here, rather than as a variant scenario

The base evolution of the system usually assumes the geosphere remains in the future as has been observed in the recent past (e.g., last hundred thousand years). The influence the repository has on the geology (i.e., heat, damage, and gas production) is one of the key processes that cannot be extrapolated from the geologic record (although some natural analogues may help, e.g., volcanic intrusions into similar rocks). The EBS is designed using tested current technology, which can be expected to perform as desired. Disturbances to the EBS are mainly handled in the alternative or variant scenarios for the bounding approach, with catastrophic (e.g., two failing at once) disturbances more likely considered "what if" cases, rather than base or alternative scenarios. For the probabilistic approach (e.g., Yucca Mountain – Helton & Salaberry, 2009), EBS disturbances may be included in the base scenario weighted by the appropriate aleatoric probability distributions for their occurrence (e.g., probability of a seismic or volcanic event at Yucca Mountain or probability of a human intrusion at WIPP). The expected evolution is not identical with the most likely scenario, but this is possible. For example, an off-normal event (e.g., human intrusion or seismic) may be quite likely to occur at some point over long geologic timeframes (~10^6 years), but the case without this disruptive event may still be considered the base scenario, since the timing of the event is still uncertain. Human intrusion is a special type of case or scenario where there are consequences to the perpetrators of the scenario (the intruders) as well as the consequences to the system being breached. There is a potential for a regulatory authority to prescribe a stylized human intrusion scenario to enhance confidence in a safety case evaluation.

3.1 Step 3: Scenario Development

In radioactive waste disposal the base scenario is typically central in the design and itself eventually (Step 4) has a wide range of scenarios subsumed within it. Possible variant scenarios include consideration of the credible loss of safety function related to key man-made and geologic components. What-if cases are to test certain barriers in isolation or under extreme circumstances. What-if cases are analogous to scenarios, but they serve a different purpose and therefore are not considered in scenario development for the safety assessment even though they may be an important part of the safety case (i.e., boosting understanding and confidence building).

Scenarios are grouped into classes, based on the types of FEPs in the scenarios, their probability or likelihood, and their associated consequences (**Fig. 4**), as determined by regulatory guidance. In **Fig. 4**, the base scenario has highest likelihood with the smallest consequence. The variant scenarios (A, B, and C) have much lower weight or likelihood (logarithmic scale), but they also have much higher consequence (also logarithmic scale).

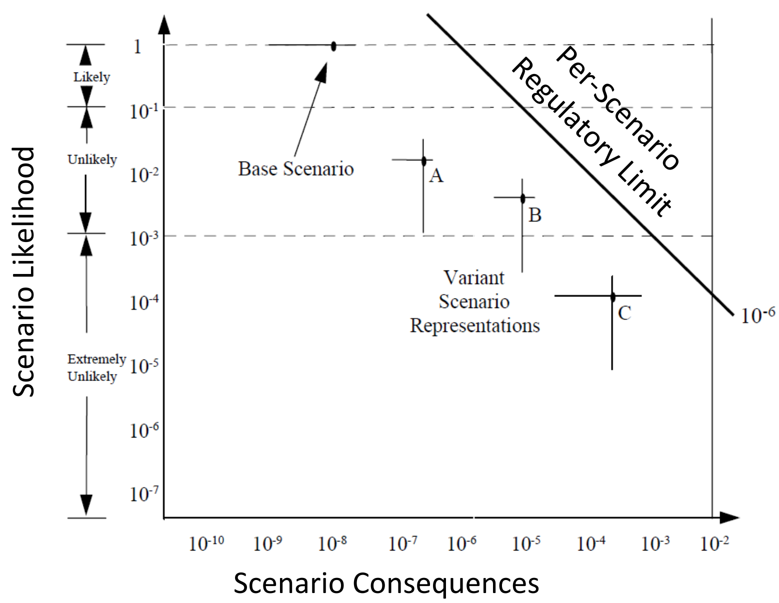

Fig. 4. Classification of scenario types and comparison of scenarios to a per-scenario standard (modified from Bailey & Billington, 1998).

Alternative scenarios have significant overlap with the base scenario. These scenarios change only a few significant things to include plausible scenarios with associated consequences that cannot be excluded. Alternative scenarios can also be used to test a hypothesis through numerical modeling regarding the importance of a safety function. This is a type of sensitivity analysis, to isolate the impacts of a safety function, by comparing it to the base case with as few ancillary differences as possible. More formal sensitivity analyses may guide which scenarios are worth exploring numerically, or whether some could be bounded and therefore not need to be calculated explicitly. There may be a tradeoff between uncertainty, sensitivity analysis, and calibration for many models, due to the computational effort associated with performing these activities.

Although general international scenario lists (analogous to FEP lists) have not been created or maintained (aside from some IAEA effort to create generalized lists of human intrusion scenarios), general guiding principles for scenario development can be presented and repositories for similar wastes in similar rock types would likely need to assess similar scenarios. The starting point (FEP lists) is common, but the scenario development process is sufficiently distinct between countries and programs that the formal development of an international scenario list would be less useful. A scenario considers all aspects of the disposal system and its environment, therefore generic scenarios are less helpful than the generic FEPs that combine to form a specific scenario. The exception is generic stylized scenarios for human intrusion where there is merit in following an internationally agreed generic stylized approach.

Any sufficient set of scenarios should:

- Be developed systematically and transparently.
- Be used to choose or justify what is included explicitly or left out of subsequent SA simulations.
- Be physically realistic or intentionally bounding based on today's state of the repository system (except for some bounding "what if" or human intrusion cases).
- Contain the entire relevant physical system from the source to the receptor (*extent in physical space*). This comes from the need to include all screened-in FEPs and enforces comprehensiveness.
- Encompass the entire lifecycle of the repository (*extent in time*) to be assessed. Additionally, evolution of the repository system from the past to its current state is a useful technique to demonstrate understanding of the site and hence to bolster the understanding of future evolution. Some regulations dictate the time horizon over which safety must be demonstrated.
- Comprehensively include all possible failure mechanisms or relevant off-normal behaviors. All screened-in FEPs are retained and included in at least one scenario (*extent in scenario space*).

Scenarios are developed differently, based on how SA results will be recombined in the end to make the final comparison against the regulatory standard.

In a probabilistic approach, scenario classes are implemented numerically and probability distributions for key aleatoric parameters are sampled. Each aleatoric parameter sample represents a different future (Tosoni et al., 2018 referred to them as different scenarios), but the futures are all derived from one or a small number of scenario classes. The weighted results of SA are then summed (all possibly sequences of events are considered, with no overlap). In this case, the risk is the sum of the probability multiplied by the consequences for each scenario. The probabilistic approach is most similar to the fault-tree approach, which is widely used in operational safety, but the scenarios approach is better suited to systems in which there are many interacting processes over time. In a post-closure safety case for a geological repository, it is highly challenging to weight all potential future scenarios in a way that the weights sum to unity (i.e. assigning probabilities to all future scenarios). Fortunately, it is not necessary to do this to demonstrate that the future will be safe.

The alternative approach (Bailey & Billington, 1998) assigns a weight of unity to the base scenario and then subsumes all scenarios of lower consequence into the base scenario. This makes the safety assessment tractable and means that the focus becomes on significant FEPs that could lead to higher consequences than the base scenario – these are the variant scenarios (generally identified by considering FEPs that are detrimental to one of more of the system safety functions). Such variant scenarios can be identified systematically and comprehensively by consideration of the FEP list and system safety functions. Each scenario is considered individually in relation to the base scenario and screened in or out of the safety case as discussed in Step 2 (FEP Screening) above. These variant scenarios often also lead to system design requirements to mitigate consequences and increase post-closure safety.

In the bounding approach each scenario can either be compared to a standard directly (e.g., **Fig. 4**) or they could be weighted and recombined in a manner not derived from probability theory (e.g., specified by regulations). The bounding approach doesn't necessarily convert the model-derived consequences (i.e., dose or pollution) to a risk, but it could. The bounding approach doesn't require the individual scenarios to be independent or non-overlapping. The numerical regulatory limits used in the probabilistic and bounding approaches would be different, due to their different meaning. The specification of a standard based on a model performance measure (e.g., total radionuclide flux to a boundary, or migration of radionuclides beyond a containment region) implies the connection between the model prediction and risk has been made by the regulator.

3.2 Aside: Bottom-up vs. Top-down Scenario Development

The "bottom-up" inductive scenario development approach starts with individual FEPs and builds up a comprehensive description of the future evolution of the repository system into a scenario. Thus, safety relevant consequences and the interaction of FEPs can be analyzed for the whole system in a transparent, inductive manner. A bottom-up based scenario development results in a system with many detailed descriptions which may be difficult to model numerically, with numerous processes and length- or time-scales needing to be modelled.

The "top down" deductive approach is centered around a deviation from nominal (e.g., failure of the shaft seal), and analyzes the consequences on repository system evolution (Andersson, 1989). Therefore, the corresponding scenarios are more consequence driven; rather than considering everything that could happen (including many inconsequential things), they focus on things that could be important. This approach is commonly used for development of variant scenarios (for example by pre-supposing an early container failure without explicitly modelling any of the mechanisms, such as corrosion or mechanical crushing, which may cause 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, which may not be complete or realistic, in mind). The top-down approach can also incorporate results from more detailed process models (e.g., low-level process or component models) through abstraction to give a top-down model which only includes processes shown to be important to the system. This is beneficial because its often difficult to make low-level process models probabilistic, due to their geometrical and physical process complexity.

In practice bottom-up and top-down approaches are being used together and in parallel. Bottom-up approaches are used to develop the base scenario but are built with knowledge of the safety functions that will be considered to create variant scenarios using a top-down approach.

3.3 Step 4: Scenario Management

During the scenario development process for a bounding case, a decision must also be made to assess a scenario independently or subsume it into a scenario with more significant consequences in terms of the metric of interest (e.g., risk or contamination), as well as how to assess it (e.g., numerically or via reasoned argument). Subsuming a less-consequential scenario into another worse scenario is an important point in the scenario management process that makes the assessment process more tractable, while maintaining process integrity. Merging scenarios into a scenario class with similar consequence or failure mechanisms is a useful way to reduce complexity without reducing completeness, if it may be shown that such a 'bounding' consideration is sufficient. In a probabilistic system, the management of scenarios is handled through probabilities assigned to aleatoric model input parameters.

At both the FEP screening and scenario grouping stages, the process needs to be explicit about exactly why and how things are included or excluded before proceeding on to the next stage (horizontal dashed lines on **Fig. 1**). Multiple reasons may exist for excluding items at each stage, depending on the setting. There is an expectation of comprehensiveness at each stage (NEA, 2012), but comprehensiveness has different meanings at each level. The FEPs list has been constructed to be exhaustive or comprehensive in terms of current understanding for any geological disposal system. The scenarios are constructed to include all screened-in FEPs. To bound risk, the resulting managed scenarios should include the expected (i.e., highest likelihood) evolution of the system on one hand, while bounding every screened-in evolution of the repository that leads to system failure or release (i.e., all significant consequences) on the other hand.

Combining or grouping scenarios implicitly assumes a mostly linear system, where two small less-consequential effects don't combine to make a large more-consequential effect or that two scenarios are mutually exclusive. This assumption is utilized broadly in SA modeling, where problems are broken down into simpler components, processes, or unit responses, then recombined and scaled.

The specific criteria used for subsuming or bounding scenarios together requires care to ensure a reasonable and consistent application (analogous to the requirements on the FEP screening stage). Generally, a scenario can be subsumed into one of higher consequence and equal or higher weight. As a result, any scenario that does not have a higher consequence than the base scenario can be subsumed into the base scenario. This is a highly important aspect to limit the (large) number of scenarios which need explicit assessment and thereby make the post-closure safety assessment for a geological repository tractable.

A pointer may also be saved into the original FEP database, indicating the use of each FEP in any given scenarios. This allows for the creation 'FEP crosswalks' to demonstrate that each FEP is considered, as well as how.

An important point during scenario management is how to deal with the general increase in uncertainty through time (i.e., distant future is very uncertain and simulations to 10^6 years are beyond the ability of many conceptual models to extrapolate credibly – e.g., Kessler et al., 2023). A possible approach uses detailed SA simulations out to the time when uncertainty has not grown exceedingly large (i.e., possibly 10^4 years, or the next glaciation event), then only continues to the repository licensing horizon (e.g., 10^6 years) with simpler deterministic scenarios. How exactly to combine the two approaches would need careful consideration and may depend on national regulations (e.g., in the US), or could be left to the implementor (e.g., in the UK).

Scenarios are often not designed with the aim of illustrating a likely evolution of the disposal system and its surroundings, but rather to illustrate the properties or safety function of one or more of the natural or engineered barriers, like a more integrated and exhaustive form of FEP analysis. For that purpose, it can be instructive to assign parameter values or other properties to the remaining parts of the barrier system such that the barrier under consideration is influenced in an exaggerated or bounding way (a less-drastic type of "what-if" case). The aim is then to show conclusively that such exaggerated conditions do not hold true or that they can be avoided by design. By assuming such extreme conditions, the robustness of the various natural and engineered barriers can be more clearly exhibited.

3.4 Step 5: Development of Final Scenario Set

During the transition from scenario development to assessment modeling the timing and sequencing of events is added back in. Scenarios do not need to explicitly include time evolution or ordering of events, but to evaluate them numerically (i.e., with causality) typically does. An uncertain event can then be timed at the point of greatest impact.

The nature of the final scenario set depends on the approach taken. In a probabilistic approach, scenarios include most of the uncertainty in the distributions associated with aleatoric parameters (e.g., the probability an event or failure occurs). In a bounding approach, scenarios are chosen to span the aleatoric uncertainty between a group of expert-selected scenarios that characterize the key risks of the system and are more like the scenario groups developed from the probabilistic approach.

4.0 MODELING AND ASSESSMENT

The SA is the part of the long-term post-closure safety case dealing with the site suitability and long-term assessment of risk and consequence related to the repository after its closure. The safety assessment evaluates a set of scenarios that cover both the nominal evolution of the system and all "significant" deviations from the base case regarding the safety of the repository.

4.1 Steps 6-8: Development of Conceptual and Mathematical Models

The conceptual model is a concrete realization of the more abstract scenario through the processes of delimitation, reduction, composition, aggregation, and abstraction borrowed from database theory (Brodie, 1984). The construction of numerical models from data and relationships can further be formalized using constructs from category theory, which is a generalization of database theory (Spivak & Kent, 2012). Once developed, the conceptual model is converted to a mathematical model and finally a numerical model, which requires specification of physical parameters, initial conditions, and boundary conditions.

When documenting the movement from FEPs to scenarios and from scenarios to assessments, the use of conservatisms and simplifications should be documented. Conservatisms are usually made to save the implementor computational effort, though they also often exchange complexity for safety margin. This itself can have consequences, for example, if the operator of the facility wished to modify the waste inventory in the future, or if the repository were required to add improvements. Conservatisms must be made cautiously since what is conservative for one process or event may be anti-conservative for another event or process.

From the conceptual model a mathematical model is developed using governing differential or integral equations that describe the time evolution of the system, given the required initial and boundary conditions, which themselves may be uncertain. Initial and boundary conditions of assessment models are often derived from or influenced by operational processes. Numerical models are an implementation of the mathematical models, often as implementations of a numerical scheme (e.g., finite difference, finite element, or finite volume). These models require discretization in space and time to solve them, but they also allow physically realistic geometries, configurations, heterogeneities, and non-linearities, unlike analytical solutions (where available) to mathematical models.

The implementation of uncertainty quantification in numerical models depends on the scenario development approach, but epistemic uncertainty can be handled similarly in both approaches. The bounding approach largely brackets the aleatoric uncertainty between the realizations, while each realization may include some quantification of epistemic uncertainty. For the probabilistic approach, uncertainty is explicitly covered via aleatoric parameter distributions, and it is discretized through sampling. The inefficiency of sampling the long tails of stochastic processes may make it hard to adequately cover rare events, and could underestimate or dilute the overall risk, unless a very large sample size or importance/stratified sampling (e.g., Latin hypercube – Helton et al., 2014) is used, which must be accounted for during interpretation. Importance sampling can naturally focus on risks associated with rare events therefore sampling must be performed with care.

4.2 Step 9: Final Recombination Step

The final step in the numerical assessment is the recombination of results from the individual scenarios into an overall result. The probabilistic approach uses a formal weighted integral or sum of risk, comprised of products of probabilities (which must be constrained so all the possible cases add up to one) and simulated consequences. This type of approach was taken for WIPP (Helton, 1993) and Yucca Mountain (Helton & Salaberry, 2009; Helton et al., 2014) and was called "probabilistic" by Tosoni et al. (2018). Another approach uses a bound for each scenario or group of scenarios. The boundary approach either compares individual SA predictions against a standard or uses a method of recombining the results of scenarios derived from other means than probability theory.

These two cases are endmembers in a spectrum of possible behaviors. **Fig. 5** shows a purely probabilistic approach on the left, with an approach that uses stochastic sampling of aleatoric parameters (i.e., determining if scenario will occur). The model construction and aleatoric parameter distributions are chosen by expert judgement, with complexity more directly in the models themselves. In contrast, a purely bounding approach is on the right, where scenarios are chosen by experts to capture the aleatoric uncertainty of the system, with the complexity more in justifying the choices made. The purely probabilistic approach may be too complex to implement, justifying the addition of simplifying aspects from the bounding approach. Since epistemic uncertainty is usually addressed through sampling, this bounding approach either requires additional sampling, or some other means to quantify epistemic uncertainty. Both implementations can sample on epistemic uncertainty, to characterize uncertain parameters. Implementations may also fall somewhere between these two extremes.

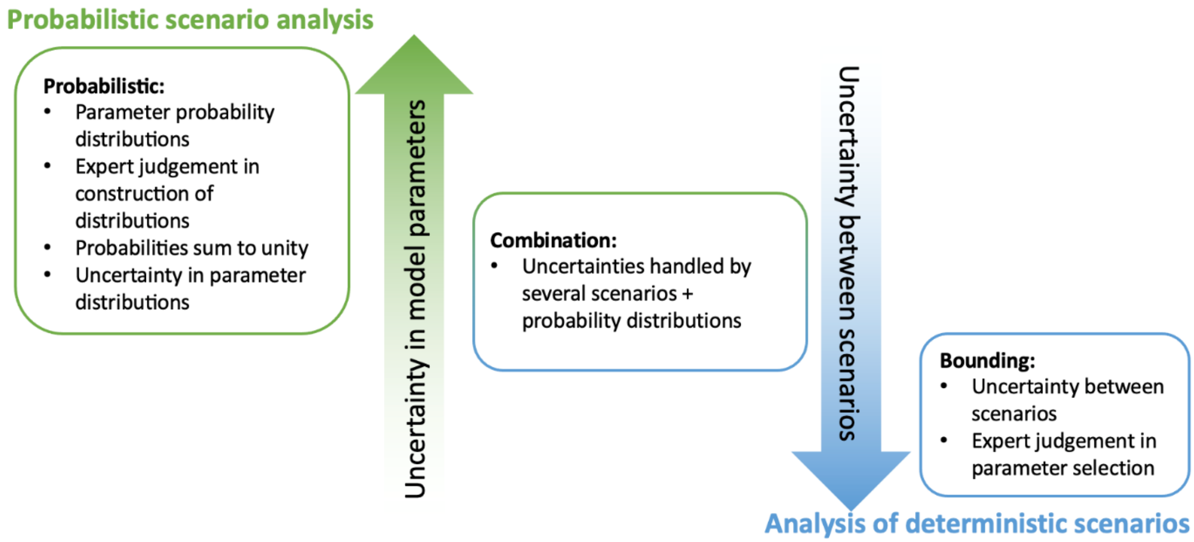

Fig. 5. Continuum of scenario development approaches (adapted from Swift, 2017).

5.0 SUMMARY DISCUSSION

This manuscript reviews and summarizes both the origins and current state of scenario analysis for the long-term safety case development of deep geological repositories for radioactive waste. While there are implementation differences in the regulations that govern the process in individual countries, this manuscript focuses on the commonalities and themes common between approaches.

This manuscript highlights the use of scenarios to assess a large, complex system with highly uncertain inputs (i.e., radioactive waste disposal). Other Earth-science applications (e.g., carbon sequestration, hydraulic fracturing, geothermal development, and climate intervention modeling) have already adopted some aspects of this process—most notably FEPs—but the approach could be useful to still wider applications. The main barriers to wider adaptation of the approach are effort required to develop a FEP database for a new problem and the iteration needed to arrive at the final scenarios. The continuum of approaches just discussed show that a range of implementations are possible, and knowledge of this flexibility may make their application more palatable in other applications.

Scenarios sit at a key point in safety case development for the disposal of radioactive waste in a deep geological repository. Preceding scenario development is the brainstorming stage, involving cataloging and exploration of all possible system components and behaviors, through the use exhaustive international FEP catalogs. The FEP approach was developed for radioactive waste disposal in the late 1970s as an abstraction of the fault-tree analysis method and international FEP catalogs were developed in the 1990s and continue to be refined. This process is done to demonstrate completeness to regulators and the public. FEPs are screened in or out based on their applicability using several criteria. Scenario development then takes the collection of as many as several hundred screened-in FEPs, forms scenarios, and then groups them to create a much smaller set of scenarios classes. The approach usually utilizes a bottom-up developed base scenario and several top-down developed variant scenarios and associated safety functions (developed in 2000s). Unlike fault-tree analysis, scenarios are abstractions that do not explicitly need to involve time or sequencing of events.

Critically, a range of approaches can be chosen when developing scenarios and the subsequent numerical assessment models. Probabilistic approaches have a system of numerical models that explicitly includes all screened-in FEPs using expert-derived parameter distributions for sampling aleatoric uncertainty (epistemic uncertainty would still need to be handled separately). Sampling is then used to explore the aleatoric uncertainty. A purely deterministic approach involves a base scenario and a handful of expert-derived deterministic scenarios that capture the aleatoric uncertainty in repository behavior, and are more like scenario classes, by construction. The standard to which the results are compared is different, depending on national regulations and the approach taken. These two extremes are not the only options, with a spectrum of possible intermediate behaviors existing between the endmembers. Often, scenarios are taken beyond the realm of possible to explore “what if” cases, where questions are asked about the consequences of impossible events to test the robustness of the repository system.

The final set of abstract scenarios are made into concrete conceptual models (including the sequencing of events), which is implemented as a numerical SA model. All the screened-in FEPs must make it into one or more scenarios (comprehensiveness), and all the scenarios must be evaluated in a consistent way, but how exactly depends on the approach taken. Purely probabilistic approaches use probabilities (constrained to sum to one) to weight the consequences estimated from SA models. Probabilistic models are more complex to implement, but in the end, they result in a straightforward mechanical summation of results. A simpler purely deterministic approach can either develop weights or likelihoods to recombine results, or it may directly compare each scenario’s consequence to a standard individually, depending on national regulations.

The purely probabilistic approach places all the complexity and uncertainty into the numerical models and relies on sample size or importance sampling to ensure rare (but possibly consequential) events are adequately captured in the results. A purely bounding approach instead focuses the effort on the rare events as individual variant scenarios, using expert judgement to ensure any consequences are adequately captured and represented in the results. More realistically, approaches will combine aspects of both endmembers to accurately and efficiently evaluate whether a radioactive waste disposal facility is safe.

The United States has used an approach close to the probabilistic end of the spectrum for Yucca Mountain and WIPP. Other countries (Sweden, Finland, France; Tosoni et al., 2018) have proposed something closer to the bounding end of the spectrum. In the UK, the approach is to adopt a broad base scenario, assigned a weight of unity, and then consider as variant scenarios those less likely situations that, if they occurred, could have consequences greater than that of the base scenario (effectively all lower consequence scenarios are subsumed into the base scenario). Whichever approach is taken, it is specified by national regulations, which are developed within the existing nuclear regulatory framework that exists internationally and for that country. Clearly there are different approaches that can be taken, but if the goals of the approach are to transparently illustrate minimization of risk and/or pollution, an approach anywhere on the spectrum can produce the desired results.

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6.0 REFERENCES

Andersson, J. [Ed] (1989). *The Joint SKI/SKB Scenario Development Project*, SKB 89-35. Svensk Kärnbränslehantering AB, Stockholm, Sweden.

Bailey, L.E.F. & D.E. Billington (1998). *Overview of the FEP Analysis Approach to Model Development*, (88 p.) S/98/009. UK NIREX Ltd., Harwell, United Kingdom.

Billington, D.E. & L.E.F. Bailey (1998). *Development and Application of a Methodology for Identifying and Characterising Scenarios*, S/98/013. UK NIREX Ltd., Harwell, United Kingdom.

Bradfield, R., G. Wright, G. Burt, G. Cairns & K. Van Der Heijden (2005). The origins and evolution of scenario techniques in long range business planning. *Futures*, *37*(8):795-812.

Brodie, M.L., “On the development of data models” in [Eds] Brodie, M.L., J. Mylopoulos & J.W. Schmidt, *On Conceptual Modeling* (p. 19-47). Springer, (1984).

Chung, J.B., H.K. Kim & S.K. Rho (2008). Analysis of local acceptance of a radioactive waste disposal facility. *Risk Analysis, 28*(4):1021-1032.

Clauser, C. (1992). Permeability of crystalline rocks. *EOS Transactions American Geophysical Union, 73*(21):233-236.

Cranwell, R.M. & J.C. Helton (1980). “Uncertainty analysis associated with radioactive waste disposal: a discussion paper” in *DOE Statistical Symposium, Berkeley CA 29 Oct 1980*. SAND80-2017C.

Cranwell, R.M., J.E. Campbell, J.C. Helton, R.L. Iman, D.E. Longsine, N.R. Ortiz, G.E. Runkle, M.J. Shortencarier (1987). *Risk Methodology for Geologic Disposal of Radioactive Waste: Final Report*, (103 p.) NUREG/CR-2452, SAND81-2573. Sandia National Laboratories, Albuquerque, NM.

Cranwell, R.M., R.W. Guzowski, J.E. Campbell & N.R. Ortiz (1982). *Risk Methodology for Geologic Disposal of Radioactive Waste: Scenario Selection Procedure*, (110 p.) NUREG/CR-1667, SAND80-1429. Sandia National Laboratories, Albuquerque, NM. doi: 10.2172/7178896

DOE (1980). *Final Environmental Impact Statement – Waste Isolation Pilot Plant. Volumes 1 and 2*, (1590 p.) DOE/EIS-0026 UC-70. US Department of Energy, Albuquerque, NM.

Becker D., U. Noseck, R. Seidl & J. Wolf (2024). "Bedeutung von deterministischen und probabilistischen Methoden zur Behandlung und Kommunikation von Ungewissheiten hinsichtlich der Sicherheitsaussagen in einem Safety Case" in Eckhardt A., F. Becker, V. Mintzlaff, D. Scheer, R. Seidl (Eds.) *Entscheidungen in die weite Zukunft. Ungewissheiten bei der Entsorgung hochradioaktiver Abfälle*. Springer VS Wiesbaden ISBN 978-3-658-42698-9.

Edwards, A.W.F (1972). *Likelihood*, Cambridge Press.

Flynn, J., W. Burns, C.K. Mertz, & P. Slovic (1992). Trust as a determinant of opposition to a high-level radioactive waste repository: Analysis of a structural model. *Risk analysis, 12*(3):417-429.

Freeze, G (2002). *The Enhanced Plan for Features, Events and Processes (FEPS) at Yucca Mountain*, (57 p.) TDR-WIS-PA-00005, Rev. 00. US Department of Energy, Las Vegas, NV. doi: 10.2172/893832

Freeze, G., S.D. Sevougian, K. Kuhlman, M. Gross, J. Wolf, D. Buhmann, J. Bartol, C. Leigh & J. Mönig (2020). *Generic FEPs Catalogue and Salt Knowledge Archive*, (151 p.) SAND2020-13186. Sandia National Laboratories, Albuquerque, NM. doi : 10.2172/1815346

Gallistel, C.R. (2015). Bayes for beginners: probability and likelihood. *Association for Psychological Science Observer, 28*.

Galson, D.A., P.N. Swift, D.R. Anderson, D.G. Bennett, M.B. Crawford, T.W. Hicks, R.D. Wilmot & G. Basabilvazo (2000). Scenario development for the Waste Isolation Pilot Plant compliance certification application. *Reliability Engineering & System Safety*, *69*(1-3):129-149.

Hamilton, L.H & B. Scowcroft (2012). *Report to the Secretary of Energy*, Blue Ribbon Commission on America's Nuclear Future. https://www.energy.gov/ne/articles/blue-ribbon-commission-americas-nuclear-future-report-secretary-energy

Haasl, D.F., N.H. Roberts, W.E. Vesely & F.F. Goldberg (1981). *Fault Tree Handbook*, NUREG-0492.

Hansen, C.W., G.A. Behie, A. Bier, K.M. Brooks, Y. Chen, J.C. Helton, S.P. Hommel, K.P. Lee, B. Lester, P.D. Mattie & S. Mehta (2014). Uncertainty and sensitivity analysis for the nominal scenario class in the 2008 performance assessment for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada. *Reliability Engineering & System Safety*, *122*: 272-296.

Hawkins, E., & R. Sutton (2009). The potential to narrow uncertainty in regional climate predictions. *Bulletin of the American Meteorological Society*, *90*(8):1095-1108.

Hedin, A. (2008). "Safety Functions and Safety Function Indicators – Key Elements in SKB's Methodology for Assessing Long-Term Safety of a KBS-3 Repository" in *Safety Cases for Deep Geological Disposal of Radioactive Waste: Where Do We Stand?* Symposium Proceedings (pp. 221-230) NEA No. 6319, Nuclear Energy Agency, Paris, France.

Helton, J.C. (1993). Risk, uncertainty in risk, and the EPA release limits for radioactive waste disposal. *Nuclear Technology, 101*(1):18-39.

Helton, J.C., F.J. Davis & J.D. Johnson (2000a). Characterization of stochastic uncertainty in the 1996 performance assessment for the Waste Isolation Pilot Plant. *Reliability Engineering & System Safety, 69*:167-189.

Helton, J.C., M.-A. Martell & M.S. Tierney (2000b). Characterization of subjective uncertainty in the 1996 performance assessment for the Waste Isolation Pilot Plant. *Reliability Engineering & System Safety, 69*:191-204.

Helton, J.C. & C.J. Sallaberry (2009). Conceptual basis for the definition and calculation of expected dose in performance assessments for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada. *Reliability Engineering & System Safety, 94*:677-698.

Helton, J.C., C.W. Hansen & C.J. Sallaberry (2014). Expected dose and associated uncertainty and sensitivity analysis results for all scenario classes in the 2008 performance assessment for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada. *Reliability Engineering & System Safety*, *122*:421-435.

Hine D.W., C. Summers, M. Prystupa & A. McKenzie-Richer (1997). Public opposition to a proposed nuclear waste repository in Canada: An investigation of cultural and economic effects. *Risk Analysis, 17*(3):293-302.

IAEA (2011a). Disposal of Radioactive Waste. Specific Safety Requirements No. 5, STI/PUB/1449, International Atomic Energy Agency, Vienna, Austria.

IAEA (2011b). *Geological Disposal Facilities for Radioactive Waste*. Safety Standards No. SSG-14, STI/PUB/1483, International Atomic Energy Agency, Vienna, Austria.

IAEA (2012). *The Safety Case and Safety Assessment for the Disposal of Radioactive Waste*. Specific Safety Guide No. SSG-23, STI/PUB/1553, International Atomic Energy Agency, Vienna, Austria.

IPCC (2000). *Special Report on Emissions Scenarios, Summary for Policymakers*, Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Jonkman, S.N., M. Kok, J.K. Vrijling (2008). Flood Risk Assessment in the Netherlands: A Case Study for Dike Ring South Holland. *Risk Analysis, 28*(5):1357-1374.

Kaplan, S. & B.J. Garrick (1981). On the quantitative definition of risk. *Risk Analysis, 1*(1):11-27.

Keeney, R.L. (1987). An analysis of the portfolio of sites to characterize for selecting a nuclear repository. *Risk Analysis, 7*(2):195-218.

Kessler, J., P. Swift, M. Apted, L. Barrett & S. Nesbit (2023). *Recommendations on Postclosure Aspects of Generic Standards for the Permanent Disposal of Spent Nuclear Fuel and High-Level and Transuranic Radioactive Wastes in the United States*, (76 p.) American Nuclear Society. https://www.ans.org/file/12339/ANS+Disposal+Standards+Report+final+booklet-online.pdf

Locke, J. & L.E.F. Bailey (1998). *Overview Description of the Base Scenario Derived from FEP Analysis*. (50 p.) S/98/011, UK NIREX Ltd., Harwell, United Kingdom.

Lommerzheim, A., M. Jobmann, A. Meleshyn, S. Mrugalla, A. Rübel L. & Stark (2018). "Safety concept, FEP catalogue and scenario development as fundamentals of a long-term safety demonstration for high-level waste repositories in German clay formations" In Norris, S., Neeft, E.A.C. & van Geet, M. (eds) *Multiple Roles of Clays in Radioactive Waste Confinement*. Geological Society, London, Special Publications, 482.

Lowry, T.S. (2021). "Understanding Uncertainty in Geothermal Energy Development Using a Formalized Performance Assessment Approach" in *GRC Transactions*, 45.

Marietta, M.G., S.G. Bertram-Howery, D.R. Anderson, K.F. Brinster, R.V. Guzowski, H. Iuzzolino & R.P. Rechard (1989). *Performance Assessment Methodology Demonstration: Methodology Development for Evaluating Compliance with EPA 40 CFR 191, Subpart B, for the Waste Isolation Pilot Plant*, (252 p.) SAND89-2027, Albuquerque, NM: Sandia National Laboratories. https://doi.org/10.2172/5083309

Matteo, E., E. Simo, P. Herold, A. Lommerzheim, A. Keller, T. Hadgu, R. Jayne, M. Mills & K. Kuhlman (2021). "Methodology for Design and Performance assessment of Engineered Barrier System in a Salt Repository for HLW/SNF - 21132" in *WM2021 Conference, March 7-11, 2021, Phoenix, Arizona, USA.*

Mazurek, M., F.J. Pearson, G. Volckaert & H. Bock (2003). *Features, Events and Processes Evaluation Catalogue for Argillaceous Media*, (379 p.) NEA No. 4437, Nuclear Energy Agency, Paris, France.

Merkhofer, M.W. & R.L. Keeney (1987). A multiattribute utility analysis of alternative sites for the disposal of nuclear waste. *Risk Analysis, 7*(2)*:*173-194.

Meyer, P.D., M. Ye, M.L. Rockhold, S.P. Neuman & K.J. Cantrell (2007). *Combined Estimation of Hydrogeologic Conceptual Model, Parameter, and Scenario Uncertainty with Application to Uranium Transport at the Hanford Site 300 Area*, (125 p.) PNNL-16396, Pacific Northwest National Laboratory, Richland WA.

Morton, A., M. Airoldi & L.D. Phillips (2009). Nuclear risk management on stage: A decision analysis perspective on the UK's Committee on Radioactive Waste Management. *Risk Analysis, 29*(5):764-779.

Milstein, R.I. (2001). *Integrated Safety Analysis Guidance Document*, (73 p.) NUREG-1513. Nuclear Regulatory Commission, Washington DC.

NEA (2000). Features, Events and Processes (FEPs) for Geologic Disposal of Radioactive Waste: An International Database, (92 p.) Nuclear Energy Agency, Paris, France. doi:10.1787/9789264187511-en

NEA (2001). *Scenario Development Methods and Practice: An Evaluation Based on the NEA Workshop on Scenario Development Madrid Spain, May 1999*, (242 p.) Nuclear Energy Agency, Paris, France. doi:10.1787/9789264193536-en

NEA (2004). *Post-Closure Safety Case for Geological Repositories: Nature and Purpose*. (56 p.) NEA No. 3679. Nuclear Energy Agency, Paris, France. https://www.oecd-nea.org/jcms/pl_13678/

NEA (2012). *Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste: Outcomes of the NEA MeSA Initiative*. (242 p.) NEA No. 6923. Nuclear Energy Agency, Paris, France. doi:10.1787/9789264991903-en

NEA (2013a). *Natural Analogues for Safety Cases of Repositories in Rock Salt: Salt Club Workshop Proceedings.* (269 p.) NEA/RWM/R(2013)10. Nuclear Energy Agency, Paris, France. https://www.oecd-nea.org/jcms/pl_19454

NEA (2013b). *Updating the NEA International FEP List – An IGSC Technical Note – TN1: Identification and Review of Recent Project-Specific FEP Lists*. (122 p.) NEA/RWM/R(2013)7. Nuclear Energy Agency, Paris, France. https://www.oecd-nea.org/jcms/pl_19387

NEA (2019). International Features, Events and Processes (IFEP) List for the Deep Geological Disposal of Radioactive Waste, Version 3.0, (166 p.) NEA/RWM/R(2019)1. Nuclear Energy Agency, Paris, France. https://www.oecd-nea.org/jcms/pl_19906

NRC (1975). *Reactor Safety Study: An Assessment of Accident Risks in US Commercial Nuclear Power Plants*, (228 p.) WASH-1400 (NUREG-75/014). US Nuclear Regulatory Commission.

NRC (1995). *Technical Bases for Yucca Mountain Standards*, The National Academies Press, Washington, DC. doi: 10.17226/4943Paulley, A., R. Metcalfe & L. Limer (2011). Systematic FEP and scenario analysis to provide a framework for assessing long-term performance of the Krechba CO_2 storage system at In Salah. *Energy Procedia*, *4*:4185-4192.

Rechard, R.P., (1996). *An Introduction to the Mechanics of Performance Assessment Using Examples of Calculations Done for the Waste Isolation Pilot Plant Between 1990 and 1992*, (327 p.) SAND93-1378 Revised. Sandia National Laboratories, Albuquerque, NM. doi : 10.2172/366492

Rechard, R.P., (1999). Historical relationship between performance assessment for radioactive waste disposal and other types of risk assessment. *Risk Analysis, 19*(5):763-807.

Rechard, R.P., (2000). Historical background on performance assessment for the Waste Isolation Pilot Plant. *Reliability Engineering & System Safety, 69*(1-3), 5-46.

Reilly, M., & D. Willenbockel (2010). Managing uncertainty: a review of food system scenario analysis and modelling. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1554):3049-3063.

Schoemaker, P.J. (1993). Multiple scenario development: Its conceptual and behavioral foundation. *Strategic Management Journal*, *14*(3):193-213.

Sjöberg, L. (2004). Local acceptance of a high-level nuclear waste repository. *Risk Analysis, 24*(3):737-749.

Spivak, D.I. & R.E. Kent (2012). Ologs: A categorical framework for knowledge representation. *PLoS ONE, 7*(1):e24274.

Swift, P.N. (2017). “Safety assessment for deep geological disposal of high-level radioactive waste” in M.J. Apted & J. Ahn [Eds.] *Geological Repository Systems for Safe Disposal of Spent Nuclear Fuels and Radioactive Waste* (pp. 451-473), second edition, Woodhead Publishing.

Tatomir, A., C. McDermott, J. Bensabat, H. Class, K. Edlmann, R. Taherdangkoo & M. Sauter (2018). Conceptual model development using generic Features, Events, and Processes (FEP) database for assessing the potential impact of hydraulic fracturing on groundwater aquifers. *Advances in Geosciences, 45*:185-192.

Tosoni, E., A. Salo & E. Zio (2018). Scenario analysis for the safety assessment of nuclear waste repositories: A critical review. *Risk Analysis*, *38*(4):755-776.

Wheeler, L., T. Zeitler, S. Brunell, J. Lien, L. Shand, B. Wagman, E. Roesler, C. Martinez & K. Potter (2023). Performance assessment for climate intervention (PACI): preliminary application to a stratospheric aerosol injection strategy evaluation. *Frontiers in Environmental Science, 11*:1205515.

Wright, G., & P. Goodwin (2009). Decision making and planning under low levels of predictability: Enhancing the scenario method. *International Journal of Forecasting*, *25*(4): 813-825.

Yamaguchi, K., K. Takizawa, O. Shiragaki, Z. Xue, H. Komaki, R. Metcalfe, M. Yamaguchi, H. Kato & S. Ueta (2013). Features events and processes (FEPs) and scenario analysis in the field of CO_2 storage. *Energy Procedia*, *37*:4833-4842.