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Scenario Analysis for the Safety Assessment of Nuclear Waste Repositories: A Critical Review

Edoardo Tosoni,[1,2,*] Ahti Salo,[1] and Enrico Zio[2,3]

A major challenge in scenario analysis for the safety assessment of nuclear waste repositories pertains to the comprehensiveness of the set of scenarios selected for assessing the safety of the repository. Motivated by this challenge, we discuss the aspects of scenario analysis relevant to comprehensiveness. Specifically, we note that (1) it is necessary to make it clear why scenarios usually focus on a restricted set of features, events, and processes; (2) there is not yet consensus on the interpretation of comprehensiveness for guiding the generation of scenarios; and (3) there is a need for sound approaches to the treatment of epistemic uncertainties.

KEY WORDS: Nuclear waste repositories; safety assessment; scenario analysis

1. INTRODUCTION

Nuclear power plants produce highly radioactive waste that must be disposed of safely. The preferred disposal technology is to bury this waste in geological repositories hundreds of meters deep in the ground, protected by a system of redundant barriers. The nuclear waste repository and its surrounding environment form the disposal system.

For a repository to be licensed, its safety must be assessed over several millennia.[(1)] High-level waste contains radionuclides with half-lives of hundreds of thousands of years; however, a sizeable portion of the inventory has a half-life of 1,000 years or less. Initially, the short-lived portion of the inventory poses a significant hazard that becomes vanishingly less hazardous after 10,000 years. For spent fuel, 90% of the initial inventory decays after 100 years, and 99.9% decays after 10,000 years; however, the long-term hazard prevails well beyond 10,000 years, and analyses may need to extend up to 1 million years.

A key concern in the safety assessment of a nuclear waste repository is aleatory uncertainty, which refers to the unpredictable variability of a system that behaves stochastically.[(2)] Nuclear waste repositories are such systems,[(3)] and apart from models (e.g., computer codes of corrosion, radionuclide transport) for representing the evolution of some parts of the disposal system in a nearly deterministic manner, the evolution of many parts of the disposal system involves uncertainties that call for a stochastic representation.

Among alternative methods,[(4)] the generation and analysis of scenarios (or, more succinctly, scenario analysis) is the most widely used method for spanning the evolutions of the system, thus addressing aleatory uncertainty. One of the earliest, and currently broadly accepted,[(5)] definitions of *scenario* is "a hypothetical sequence of events."[(6)]

Over the last few decades, extensive studies have been produced to assess the safety of the proposed repositories. Still, some stakeholders continue to express distrust in the safety of geologic disposal. Apart from the possible political or economic

[1]Department of Mathematics and Systems Analysis, Aalto University, Espoo, Finland.
[2]Energy Department, Politecnico di Milano, Milan, Italy.
[3]Chair System Science and the Energy Challenge, Fondation Electricité de France, Centrale Supélec, Université Paris Saclay, Chatenay-Malabry, France.
*Address correspondence to Edoardo Tosoni, Systems Analysis Laboratory, Aalto University, Otakaari 1, 02150 Espoo, Finland; edoardo.tosoni@aalto.fi.

reasons, this distrust suggests that the safety assessments may need to be more transparent and understandable to support an informed dialogue among stakeholders. For example, as remarked by STUK (Säteilyturvakeskus, the Finnish Radiation and Nuclear Safety Authority) regarding the proposed repository at Olkiluoto, Finland,[7–13] current scenario approaches may be partly lacking in "comprehensiveness."[14] In other words, they do not necessarily address all the ways in which the factors that influence the disposal system significantly (i.e., the so-called features, events, and processes [FEPs]) can evolve and interact with each other.

Nevertheless, there is not only aleatory uncertainty. In scenario analysis, analysts use tools such as diagrams to represent the conceptual structure of the disposal system, and models to represent the evolution of some of its parts. No matter how accurate, these diagrams and models can capture reality only to some extent. The imprecision resulting from such a knowledge gap is what defines the epistemic uncertainty of the analysis.[2] Thus, while *aleatory uncertainty* refers to the stochasticity of the actual evolution of the system, *epistemic uncertainty* refers to the inability to eliminate the uncertainties.

Against this backdrop, we discuss challenges in conducting scenario analysis for nuclear waste repositories. Specifically, we provide a review of the literature, with the aim of identifying and partly resolving methodological challenges that can impede the attainment of comprehensiveness. We identify challenges in making it clear why scenarios usually focus on a restricted set of FEPs, providing a definitive interpretation of comprehensiveness, and characterizing the epistemic uncertainties affecting the analysis.

We set the stage by discussing the structure of the scenario analysis process. We then introduce the concept of comprehensiveness, present a taxonomy of uncertainties in scenario analysis, and distinguish between the pluralistic and the probabilistic approaches to the generation of scenarios. In the pluralistic approach, there are relatively few scenarios that represent different assumptions by experts. In the probabilistic approach, scenarios are generated as subsets from a large random sample of futures.

Our review covers the literature on several nuclear waste repository projects worldwide (hereafter referred to as *sample assessments*; Table I) and research papers and technical reports on nuclear waste disposal in the broader context. We have sought to build a representative collection of state-of-the-art approaches by covering several decades and countries, including a variety of methodologies and analyzing safety assessments at an advanced level of methodological maturity. Building on this review, we offer critical reflections on scenario analysis, identify methodological challenges, and provide suggestions for future research. Throughout the review, we refer to the sketch of a disposal system in Fig. 1 when making specific observations. The general properties of scenario analysis are discussed in Section 2. The pluralistic and probabilistic approaches to scenario generation are examined in Section 3. Section 4 discusses challenges in scenario analysis and provides suggestions for future research. Section 5 offers a conclusion.

2. GENERAL PROPERTIES OF SCENARIO ANALYSIS

2.1. Scenario Analysis Process

Following Campbell and Cranwell,[58] the structure of the scenario analysis process consists of scenario development and consequence analysis (Fig. 2). The phase of scenario development forms a set of scenarios whose radiologic consequences (e.g., radionuclide release, dose to humans) are calculated in the phase of consequence analysis. We focus on scenario development because many of the challenges discussed later pertain to this phase. In addition, we describe the following steps in scenario development: (1) the identification of FEPs, (2) the development of a system model (SM) of the disposal system, and (3) the generation of scenarios.

2.1.1. Identification of Features, Events, and Processes

Well established in the safety assessments of nuclear waste repositories,[59,60] the FEPs are the factors that are relevant for describing the current state of a disposal system and its future evolution. As an example, Table II lists some FEPs that can significantly influence the disposal system in Fig. 1.

The identification of the FEPs is typically based on the elicitation of expert judgments. This elicitation often takes place in workshops, as exemplified by Anderson *et al.*[61] Identification is done in stages that extend from the compilation of the initial FEP list to the screening, categorization, and verification of FEPs, whereby the last three stages are not necessarily conducted in any strict order.

Table I. List of Sample Assessments

Assessment	Location	Most Recent Publication[a]	References
Dry Run 3	United Kingdom	1993	Sumerling and Thompson,[15] Thompson and Sagar[16]
Kristallin-I	Switzerland	1994	Sumerling *et al.*,[17] NAGRA (National Genossenschaft für die Lagerung radioaktiver Abfälle)[18]
SITE-94	Sweden	1996	Stenhouse *et al.*,[19] Chapman *et al.*,[20] SKI (Statenskarnkraftinspektion)[21]
Waste Isolation Pilot Plant (WIPP)	United States	1996[a]	Howard *et al.*,[22] Galson *et al.*,[23] Helton *et al.*,[24–26,29] Berglund *et al.*,[27] Stoelzel *et al.*[28]
Canadian Nuclear Fuel Waste Management Program (CNFWMP)	Canada	1998	Goodwin *et al.*,[30,31] Andres and Goodwin[32]
TILA-99	Finland	1999	Vieno and Nordman[33]
H12	Japan	2000	JNC (Japan Nuclear Cycle Development Institute)[34]
Drigg	United Kingdom	2002[a]	Paper 6 in OECD-NEA (Organisation for Economic Cooperation and Development—Nuclear Energy Agency),[35] Environment Agency[36]
ANDRA	France	2005	ANDRA (Agence Nationale pour la Gestion des Déchets Radioactifs)[37]
Yucca Mountain	United States	2008[a]	U.S. Department of Energy,[38] Helton and Sallaberry,[39,40] Rechard *et al.*,[41] Helton *et al.*,[42,44,46,50,51,53] Hansen *et al.*,[43,45,47,52] Sallaberry *et al.*[48,49]
Korean Reference Disposal Concept (KRDC)	South Korea	2009	Hwang *et al.*,[54] Lee and Hwang[55]
Deep Geological Repository (DGR)	Canada	2011	NWMO (Nuclear Waste Management Organization)[56]
SR-SITE	Sweden	2011	SKB (Svensk Kärnbränslehantering AB)[57]
Olkiluoto	Finland	2012[a]	Nykyri *et al.*,[7] Posiva[8–13]

[a]Official year of the assessment, although later publications exist.

2.1.2. System Model of the Disposal System

An SM is a representation of the set of factors that are relevant for describing a system and of the interactions between these factors. In the case of a disposal system, these factors are the FEPs. The FEPs define the scope of the disposal system, whereas the system structure is defined by the interactions.

Relatively few authors have stressed the importance of building an SM;[17,20] however, the SM is central in scenario development because it establishes the requisite[54] link between the identification of FEPs and the generation of scenarios. Specifically, this link helps to make analysts more aware of all FEPs and interactions between these FEPs when generating scenarios.

Over the last few decades, several techniques have been developed to identify interactions when building an SM of the disposal system. Influence diagrams[18,20,21,34,55,62] portray the system as a set of nodes (i.e., FEPs) and directed arcs (interactions). Interaction matrices[9,34,56,63–65] are matrices in which the element a_{ij} indicates the influence of FEP_i on FEP_j, $i \neq j$. Influence tables[9,57] are similar to interaction matrices, but they do not admit feedback loops between the FEPs.

For illustrative purposes, the disposal system of Fig. 1 is shown in Fig. 3 as an influence diagram whose nodes represent the FEPs of Table II and whose directed arcs represent the interactions between these FEPs. The diagram of all these interactions reveals the complexity of the system. In particular, complexity is caused by feedback loops—known as *thermal*, *hydraulic*, *mechanical*, *and chemical couplings*[60]—due to which it is not possible to represent the system as a directed acyclic graph. The couplings in Fig. 3 include the two-way interactions of *Groundwater Flow* with both *Buffer Temperature* (convection, thermal buoyancy) and *Buffer Density* (washing away, formation of cavities).

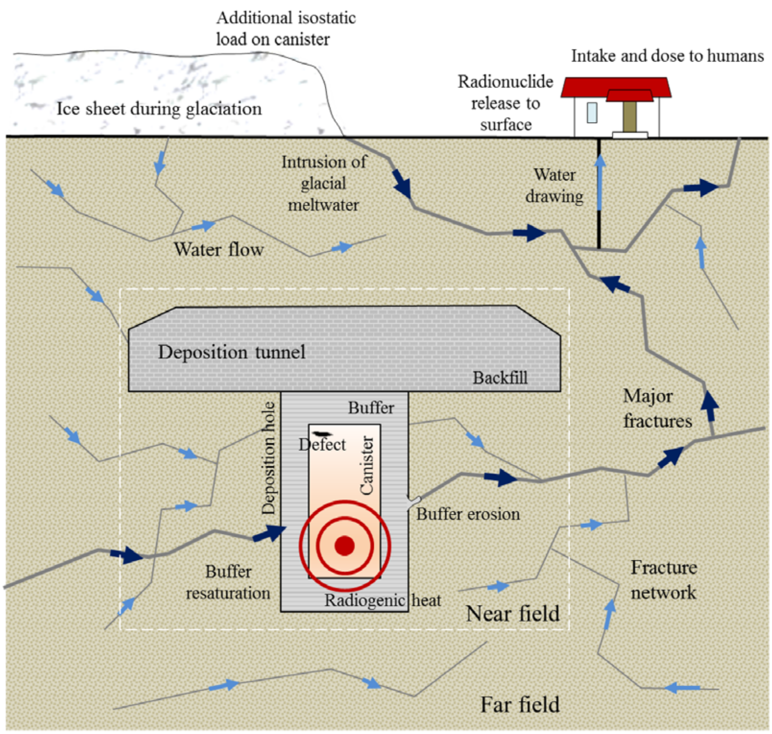

Fig. 1. Sketch of a disposal system: nuclear waste repository and surrounding environment (not to scale).

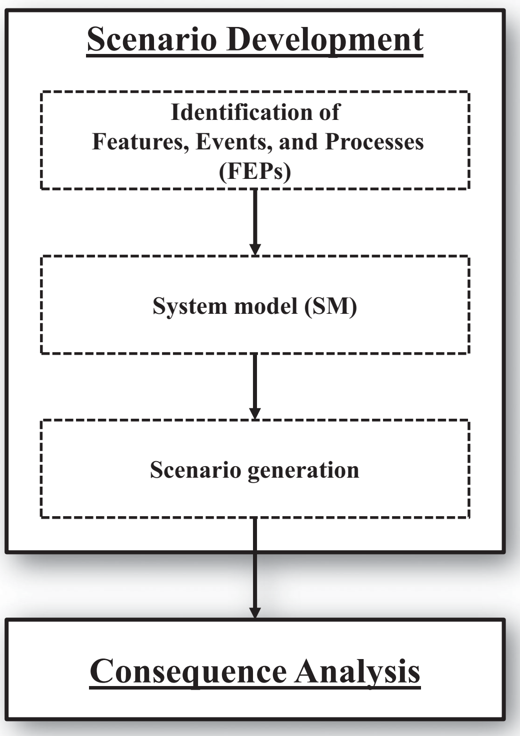

Fig. 2. Scenario analysis as the sequence of scenario development (subdivided in steps) and consequence analysis.

Table II. Features, Events, and Processes List for the Disposal System Sketched in Fig. 1

Climate type
Groundwater composition
Groundwater flow
Buffer water content
Buffer density
Buffer hydraulic conductivity
Swelling pressure
Buffer temperature
Canister thermal power
Isostatic load on canister
Canister state
Radionuclide release to surface

There is also a loop that starts from *Groundwater Flow* and returns to this node after having traversed *Buffer Water Content, Swelling Pressure*, and *Buffer Hydraulic Conductivity*.

The significance of the interactions in an SM is to be characterized by eliciting estimates about their magnitudes. For example, for representing the dependence of FEP_j on FEP_i (referred to as the *predecessor* of FEP_j), one option is to use conditional probabilities. Operatively, analysts can elicit the probability that FEP_i assumes any given state, conditioned on the state of its predecessors. Here, the magnitude of the interaction is given by how much

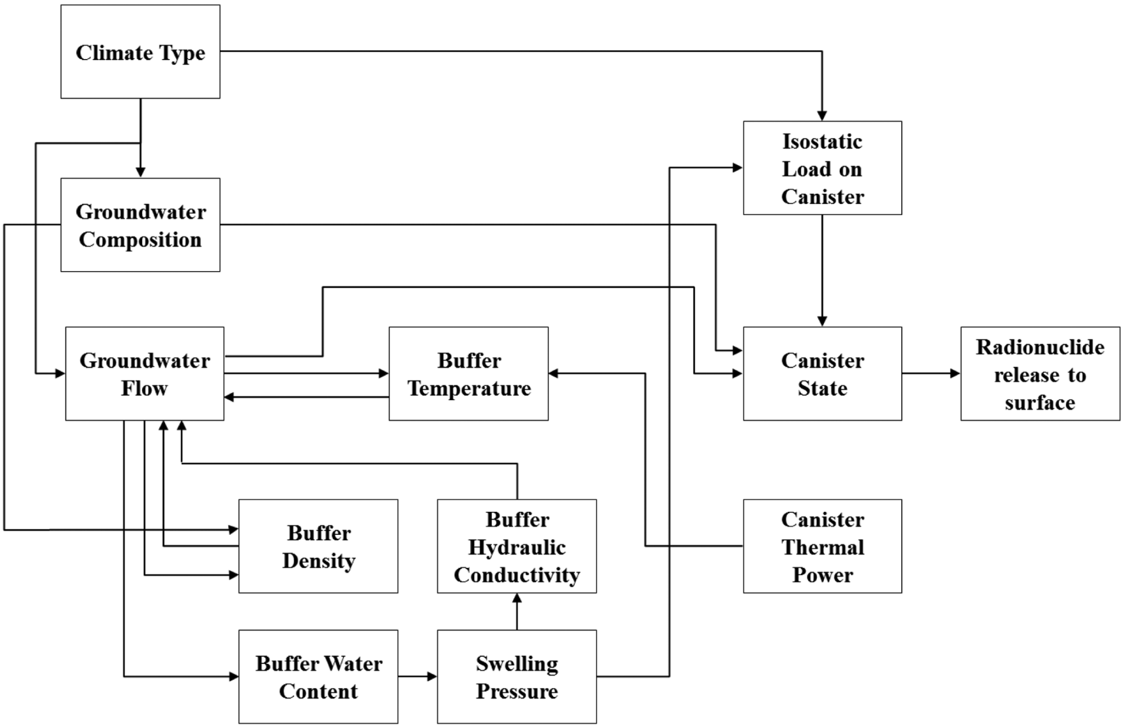

Fig. 3. System model of the disposal system as an influence diagram identifying the interactions among the features, events, and processes of Table II.

the conditional probabilities vary in response to the predecessors' states.

As an alternative to probabilities, analysts can use deterministic models of the physical and chemical phenomena in these interactions (e.g., computer codes of corrosion, radionuclide transport). For instance, FEP_j and FEP_i can be related by an equation such as $FEP_j = g(FEP_i, \boldsymbol{\theta})$, where $\boldsymbol{\theta}$ is a vector of physical and chemical parameters in the function g. Here, the magnitude of the interaction is determined by the shape of the function g and the values of $\boldsymbol{\theta}$. Equations can also include more than two FEPs. For instance, the relationship among *Groundwater Flow* ($\vec{\nu}$), *Buffer Temperature* (T), and *Canister Thermal Power* (λ_T) in Fig. 3 can be described by the heat equation $\alpha\nabla^2 T = \dot{T} + \vec{\nu}\nabla T - \lambda_T$, where α is the thermal conductivity.

2.1.3. Scenario Generation

From the system perspective, the FEPs are all those variables that are needed to describe the disposal system. In consequence, the future evolution of the disposal system, or the system evolution, is determined by the joint evolution of the FEPs.[23]

As discussed in Section 1, and as we shall elaborate in Section 2.3.3, there is aleatory uncertainty about system evolution. This uncertainty can be characterized by generating different scenarios. Thus, in keeping with Sumerling *et al.*,[17] a scenario can be viewed as a specific evolution of FEPs.

Scenarios can be generated either bottom up or top down. In the bottom-up approach, the FEPs have initial-state values from which alternative evolutions unfold because of FEPs interactions. The goal is to assess whether any evolution leads to unacceptable radiologic consequences (*Radionuclide release to surface* in Fig. 3).

The top-down approach considers an event, such as the failure of a barrier, and then generates scenarios that could plausibly lead to that event. For instance, one scenario may depict the mechanisms that, in Fig. 3, cause *Buffer Density* to drop. Top-down scenario generation can also be applied in risk-management analyses;[57] for example, repository designers can decide to modify the buffer material or to implement other risk-reduction measures.

To guide the top-down generation of scenarios, the safety functions of the barriers[8,37,57] are usually defined. Safety functions are fulfilled if the

Table III. Performance Indicators and Performance Targets for the Disposal System of Fig. 3

Performance Indicators	Performance Targets
Buffer density (ρ)	$1{,}800\ kg/m^3 \leq \rho \leq 2{,}050\ kg/m^3$ (11,57)
Buffer hydraulic conductivity (K_H)	$K_H \leq 10^{-12}$ m/s (57)
Swelling pressure (P_{SW})	0.2 MPa $\leq P_{SW} \leq 15$ MPa (57)
Buffer temperature (T)	-4 °C ≤ T ≤ 100 °C (11,57)
Isostatic load on canister (σ)	$\sigma \leq 45$ MPa (11,57)

performance indicators lie within their respective targets,(8,57) meaning that there is no threat in scenarios in which no performance target is violated.(8,57) Table III shows the FEPs that, in Fig. 3, can be used as performance indicators, along with their respective performance targets.

2.2. Comprehensiveness in Scenario Analysis

Idealistically, scenario analysis should account for everything that matters. The word *everything* suggests that all the FEPs and their possible evolutions should be covered. This is usually referred to as *completeness*; however, it is widely held that completeness is difficult to attain. This difficulty motivates the more pragmatic concept of *comprehensiveness* through the following reasoning: If it is not possible to analyze everything (completeness), which "portion of the everything" needs to be analyzed to assess the safety of the repository conclusively (comprehensiveness)? The relationship between completeness and comprehensiveness can be illustrated in the light of two concerns in two steps of scenario development.

The first concern pertains to the identification of the FEPs. Here, completeness requires that all the FEPs relevant to the description of the disposal system be identified. Completeness in FEP identification is an extremely ambitious goal, even unachievable according to some.(20,35) More modestly, comprehensiveness requires that all the FEPs that significantly influence the disposal system are identified.(22,38) Nonetheless, this coverage is not easy to ensure.(20) One possible method is to iterate the process of FEP identification to allow previously identified FEPs to be examined further and new FEPs to be included, as the experts may expand their thinking and more experts from diverse disciplines may be involved over the iterations. Still, this process might not be effective in extending the FEP list, because many idea-elicitation methods in workshops tend to favor consensus over diversity.(66) In addition, some significant FEPs can remain "unknown unknowns"(2) and are hence highly unlikely to enter the list at any stage. In consequence, it is difficult to make improvements in the comprehensiveness of the FEP list through methodological advancements. In practice, the accumulated experience of researchers and practitioners must be relied upon for obtaining as comprehensive FEP lists as possible.

The second concern pertains to the generation of scenarios. Here, completeness would make it necessary to analyze all scenarios that represent all possible combinations of FEP states over the time horizon of the assessment. In this regard, there can be tension if the analysis of each scenario is burdensome because of, for instance, the computational times of the models of the underlying physical and chemical phenomena. Completeness is still achievable if the available computational resources are sufficient.[4] Otherwise, if only a limited number of scenarios can be analyzed because of constraints of schedule or budget, the restricted set of scenarios has to be comprehensive. However, generating a comprehensive scenario set is challenging in that there is no exhaustive or widely accepted interpretation of comprehensiveness in scenario generation. Only nontechnical characterizations have been provided, such as the statement that all the relevant scenarios must be examined.(12,35,57,67,68) But how, exactly, does relevance pertain to probabilities, consequences, or other aspects of the analysis? This question has been addressed through varying interpretations of relevance and, hence, of comprehensiveness. As we discuss in Section 3, these interpretations have been shaped by the methodological assumptions and the practical implementation of the pluralistic or the probabilistic approaches. Arguably, a less methodologically bound interpretation of comprehensiveness would help analysts and regulators to build confidence when developing and reviewing safety assessments. For example (as elaborated in Section 4), comprehensiveness can be interpreted as the ability to cover all scenarios in which there are violations of the performance targets, because these are the scenarios that contain all risks.

[4]If FEPs are modeled as continuous variables, the infinitely many resulting scenarios may be covered by analytical (if possible) or numerical integration, as discussed in Section 3.3.

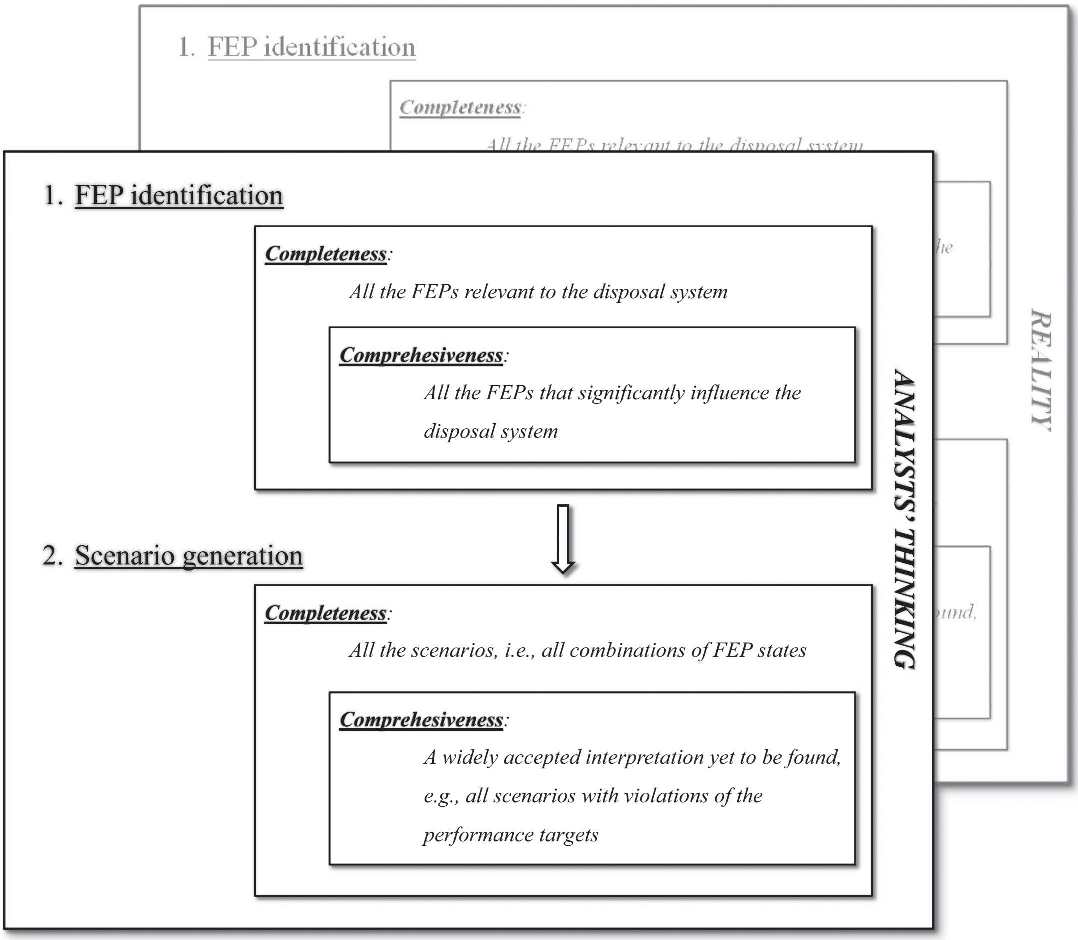

Fig. 4. Relationship between completeness and comprehensiveness in feature, event, and process (FEP) identification and scenario generation. If it is not possible to identify all the FEPs relevant to the disposal system (completeness), then comprehensiveness requires the identification of all FEPs that significantly influence the disposal system. If it is not possible to analyze all scenarios (completeness), then a restricted set of scenarios can be generated on the basis of a widely accepted interpretation of comprehensiveness, which has not been found yet (e.g., all scenarios with violations of the performance targets). Analysts can only deal with what they can think of (foreground scheme), while it is not possible to ascertain completeness or comprehensiveness with respect to absolute reality (blurred background scheme).

The relationship between completeness and comprehensiveness in FEP identification and scenario generation is illustrated further in Fig. 4. The figure shows that analysts can handle only the FEPs and scenarios they can conceive, whereas it is not possible to ascertain completeness or comprehensiveness with respect to absolute reality.[20]

This review does not cover the comprehensiveness in FEP identification, except for a discussion of the related uncertainty in Section 2.3.1; rather, it focuses on comprehensiveness in scenario generation, for which methodological advancements can be foreseen more readily. Thus, in the remainder of this review, the term *comprehensiveness* refers to scenario generation, unless specified otherwise.

2.3. Uncertainty in Scenario Analysis

There are many uncertainties in scenario analysis. In theory, analysts need to identify and characterize all conceivable uncertainties by appropriate techniques, usually through those of mathematical quantification.[41] In practice, uncertainty in a geological system is primarily concerned with the uncertainties that can cause sufficiently significant changes in system behavior (e.g., failure of a large number of waste packages over a short period, large changes in the groundwater flow), so that the range of uncertainties can be partly curtailed.

To support the decision about which uncertainties to consider, Fig. 5 provides an indicative

Epistemic					Aleatory
System scope and structure		*Models*			*System evolution*
FEPs	Interactions	Correctness of assumptions	Choice among models	Values of parameters	

Fig. 5. Taxonomy of the uncertainty in scenario analysis for nuclear waste repositories.

taxonomy of uncertainty in scenario analysis. Building this taxonomy is not straightforward,[20,69] but we distinguish the scope and structure of the SM, the validity of the models, and the system evolution. As Fig. 5 shows, system scope and structure and models involve various kinds of uncertainties. In keeping with the literature, the identified uncertainties are categorized as either aleatory or epistemic.[24,42] Specifically, system evolution is aleatory because it refers to the stochastic behavior of the disposal system, whereas system scope and structure and models are epistemic because they refer to how the system is represented.

The concepts of aleatory and epistemic uncertainty can be clarified with an example. Consider the FEPs in Fig. 3. There are epistemic uncertainties about what the possible states of these FEPs can be. Often, these states are defined by expert judgment, whereby the remaining aleatory uncertainty about which state will occur can be characterized through probability distributions. In addition, the models used for simulating climate and groundwater evolution also involve epistemic uncertainties regarding the validity of the underlying modeling assumptions, including relevant model parameters and their values. Besides, epistemic uncertainty makes it difficult to ascertain which FEPs are needed to bound the system scope, and which interactions between these FEPs best define the system structure.

For characterizing both aleatory and epistemic uncertainties, the suitability of parameterization needs to be discussed. Unless other approaches, such as fuzzy sets,[70] are used, parameterization consists of defining a probability space to describe the uncertain outcomes. Following Helton and Sallaberry,[39] a probability space is $(\mathscr{S}, \boldsymbol{\mathcal{S}}, p_S)$, where $\mathscr{S}$ is the sample space of possible outcomes, $\boldsymbol{\mathcal{S}}$ is a suitably restricted set of subsets of $\mathscr{S}$, and p_S is a probability measure over the elements of $\boldsymbol{\mathcal{S}}$. Parameterization is illustrated by the assessments of the Waste Isolation Pilot Plant (WIPP)[24] and the Yucca Mountain[39] repositories. The conceptual structure of these assessments is based on the following mathematical entities: (1) a probability space $(\mathscr{A}, \boldsymbol{\mathcal{A}}, p_A)$,[39] which characterizes aleatory uncertainty; (2) a large suite of models of physical and chemical phenomena for simulating the system evolution and calculating the radiologic consequences for a given realization of aleatory uncertainty; and (3) a probability space $(\mathscr{E}, \boldsymbol{\mathcal{E}}, p_E)$,[39] which characterizes epistemic uncertainty.

From a purely technical perspective, analysts can parameterize uncertainty by defining probability distributions over the outcomes of random variables. Here, the methodological challenge is that of adapting parameterization to each form of uncertainty, whereby the following two concerns must be addressed.

One concern is the reliability of the information on which the assessment of probabilities is based. There can be some historical or laboratory data available for variables such as earthquake occurrence or soil compressibility. For other variables, similar statistical data might not be available, in which case analysts often use expert elicitation procedures.[71–77] However, parameterization becomes difficult if experts are not confident about providing probability judgments, such as in assessments of the probability that a given model assumption is correct.[78]

The other, even more fundamental concern pertains to the ability or inability to define all the outcomes over which the probabilities are to be elicited in the first place. For example, models can be incorrect for many different reasons, but *ex ante* it may be impossible to enumerate all the collectively exhaustive reasons for which the models can be incorrect. As a result, there are no straightforward approaches for eliciting probability distributions for characterizing for what reason the model is possibly incorrect.

In summary, the characterization of uncertainties may involve nontrivial decisions in designing the appropriate elicitation approach. In the following sections, we examine the uncertainties in Fig. 5 and discuss their characterization with special attention to parameterization.

2.3.1. System Scope and Structure

The uncertainties about the scope and the structure of the system are classified as epistemic because they relate to the representation of the system. Specifically, the uncertainty about the scope concerns the comprehensiveness of the FEP list.[57] At the FEP level, comprehensiveness requires the identification of the FEPs that can significantly influence the disposal system. In Fig. 3, the uncertainty is whether these FEPs adequately represent the disposal system of Fig. 1: Shall different FEPs be added to describe rock movements along fractures, or the migration of radionuclides from canister to surface?

Among the reasons why significant FEPs may be missing, there can be biases in the expert-based FEPs elicitation process.[79] An expert may limit the search to the FEPs with which he or she is most familiar; misjudge the importance of and thus omit significant FEPs; exclude FEPs for oversimplifying the problem. Biases can also arise from group dynamics.[80] During idea generation, one participant may discard some FEPs to comply with the viewpoints of others.

Thus, determining whether significant FEPs are absent can be difficult, if not impossible. When developing ways to characterize uncertainty in FEP identification (e.g., use parameterization by assigning probabilities to the FEPs based on the share of experts, elicit a FEP's importance similarly to Könnölä *et al.*[66]), it is advisable to use debiasing techniques.[79,80]

Once the scope has been characterized, there are uncertainties regarding the structure of the system—that is, the interactions between the FEPs. By stating that "FEPs may be improperly linked to other FEPs, or the importance of a linking may be misjudged," Chapman *et al.*[20] draw attention to the uncertainty about the magnitude of the interactions. This uncertainty reflects on the tools used to represent the interactions as follows.

When interactions are represented through conditional probabilities, the uncertainty concerns the values of these probabilities. Here, characterization can take place by aggregating, for each probability, different values from different sources of information (e.g., experts) or by using interval-valued probabilities.[81]

When interactions are represented by models such as $FEP_j = g(FEP_i, \boldsymbol{\theta})$, there are uncertainties regarding (1) the validity of the assumptions concerning the structure and the parameters of the function g, (2) the choice of g among other plausible functions, and (3) the values of the model parameters $\boldsymbol{\theta}$.

2.3.2. Models

Model uncertainty deserves attention, as Linkov and Burmistrov[82] note. Specifically, models introduce three kinds of uncertainty. These uncertainties are epistemic, as they undermine the ability of models to capture reality.

First, there is uncertainty regarding the validity of model assumptions.[16,20,37] In hydrogeology, for example, the appropriateness of modeling the fractured rock as an equivalent continuous porous medium (ECPM)[8] might not be taken for granted. As a result, the primary task is to ascertain whether the results of the model are consistent with the physics of the modeled phenomenon; this is called *model verification.*[83,84] Subsequently, model validation[20,60] is a common way to assess the predictive performance of models. Yet, the system evolution cannot be observed at the safety assessment stage;[85] therefore, analysts can use data only from different case studies. Hence, alternative ideas for characterization may have to be found. For instance, model estimates can be adjusted through a stochastic factor that represents the uncertain distance from reality.[86]

Second, there can be many available models.[16,60] In the previous example, the discrete fracture network[8] is another plausible model besides the ECPM one. In such a situation, it can be difficult to choose between the available models because there is uncertainty regarding which model better serves the analysts' goal[18,34] (in this example, the accurate representation of a physical phenomenon). However, no approach to the characterization of model uncertainty is conclusive. For example, the U.S. Department of Energy, in its performance assessment for Yucca Mountain, has evaluated a range of alternative models. These evaluations help to ensure that plausible changes in the modeling assumptions do not cause large changes in the results.[38] Sophisticated techniques have also been proposed. Among these, the *alternate hypotheses* approach defines the confidence in the correctness of each model.[86] Specifically, confidence values can be assigned to the models based on nonprobabilistic approaches[78,87,88] or, alternatively, on parameterization, which defines a probability mass function over the various models. Nevertheless, Savage[60] advises not to parameterize the choice between alternative models, mostly because the available models might not include all models that could exist (i.e., the probabilities over the available models might not sum up to 1).

Third, there is uncertainty regarding the value of model parameters.[18,20,24,34,37,39,57,69] In the heat equation in Section 2.1.2, assigning a value to the thermal conductivity α might not be trivial. In this case, parameterization is a well-established practice.[26,40] The distributions of uncertain parameters can be derived from historical information or expert judgment,[58] such as in DeWispelare *et al.*[89] and Neri *et al.*[90] Once obtained, these distributions can be processed through uncertainty analysis and sensitivity analysis.[45,47,49,52,53] Uncertainty analysis evaluates how uncertain the model results are due to uncertainties in the model parameters. Sensitivity analysis identifies which parameters most influence the model results, so that efforts to reduce the remaining uncertainty can be focused on these parameters. There are many methods of uncertainty analysis and sensitivity analysis.[91–93] The choice of which methods are most appropriate depends on the specific case, on the objectives of the analysis, and on the availability of computational resources, as both uncertainty analysis and sensitivity analysis may require many runs of the model.

2.3.3. System Evolution

System evolution uncertainty is the uncertainty regarding the evolution of the FEPs. Referring to Fig. 3, it is not known ahead of time whether the *Climate Type* will be temperate, boreal, tundra, or glacial.[15,16] As a result, interactions propagate the uncertainty from one FEP to another, so that it is difficult to know the *Groundwater Composition*, the *Buffer Temperature*, and similarly until *Radionuclide Release To Surface* on the right of Fig. 3. As it relates to the stochastic behavior of the system, this system evolution uncertainty is classified as aleatory.

Other expressions resembling system evolution uncertainty have been discussed in the literature. Dormuth[94] talks of uncertainty regarding the evolution of the disposal system. Thompson and Sagar[16] use the expression “future state uncertainty,” which revisits the concept of state-of-nature uncertainty, represented by chance nodes in the decision trees used in some nuclear waste management applications.[95] At times, the emphasis is put on the uncertain future state of either external-environment[20,21] or biosphere-related[33,56] FEPs. The definition of “stochastic uncertainty,”[2] used also in the American assessments,[25,39] is aligned with our categorization of this uncertainty as aleatory. Finally, the term *scenario uncertainty*[18,34,69] emphasizes the use of scenarios as tools in exploring system evolution uncertainty.

Scenario generation is the act of drawing samples among the infinitely many evolutions of the system. Hence, as in random sampling from a continuous distribution, the likelihood that any scenario captures the exact evolution *ex post* is zero. Therefore, the aim of scenario analysis is not to predict because the analysis still leaves residual uncertainty regarding the evolution of the system. This notwithstanding, it is important to characterize system evolution uncertainty because this characterization bounds the range of possible futures. Specifically, system evolution uncertainty can be parameterized by defining probability distributions over the states of the FEPs.[27–29,44,46,48,50,51] The three components of the resulting probability space ($\mathscr{A}, \boldsymbol{A}, p_A$) are (1) the sample space $\mathscr{A}$ consisting of all sequences of FEPs states (i.e., the set of all the possible futures), (2) a set $\boldsymbol{A}$ of subsets of the sample space that contain many similar futures and thus define the scenarios, and (3) the probabilities p_A of these subsets, as determined by the probability distributions of the FEPs.

The use of parameterization of system evolution uncertainty determines the difference between the *probabilistic* and the *pluralistic* approaches to scenario generation, as we shall discuss in Section 3. The assignment of probabilities to the scenarios has been much debated in the literature, but there are no clear solutions. In Millett,[96] for example, the suitability of one approach over another is said to depend on the particular goals of scenario developers.

Another remark is that the aleatory uncertainty regarding the evolution of the disposal system may pertain to a restricted set of FEPs. In this case,

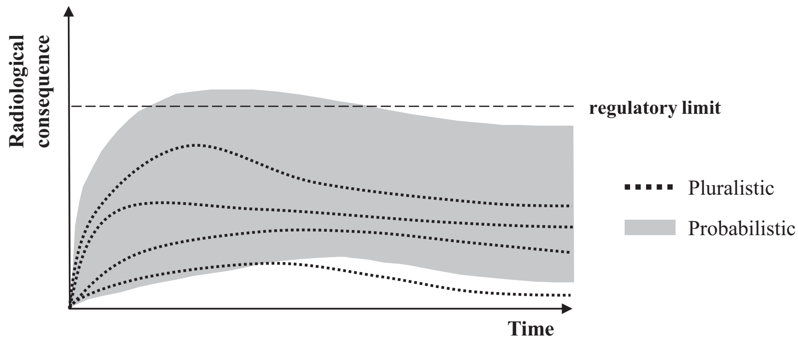

Fig. 6. Estimation of a hypothetical radiologic consequence (*y*-axis) over time (*x*-axis), and demonstration of compliance to regulatory limit (black dashed line) in pluralistic (black dotted line) and probabilistic (gray) approaches.

scenarios can be generated on the basis of these FEPs only. For example, consider a simple system formed by FEP_i and FEP_j in which FEP_i is affected by aleatory uncertainty as we do not know what state it will assume, and the dependence of FEP_j on FEP_i is represented by a model, such as the equation $FEP_j = g(FEP_i, \boldsymbol{\theta})$ as in Section 2.1.2. Here, the aleatory uncertainty of FEP_j is bound to that of FEP_i. Consequently, only the states of FEP_i need to be spanned by the scenarios, while the state of FEP_j follows unequivocally in each of these scenarios as determined by the model. This rationale has been supported by several authors. Sumerling *et al.*[17] note that "[i]f a FEP has a unique state and there is no uncertainty or little uncertainty about a FEP then it has no capacity to generate an alternative scenario," whereas the U.S. Department of Energy[38] states that "[s]cenario class formation is influenced by the types of models and calculation tools available."

For a larger example, suppose that in Fig. 3 the dependence of *Canister State* on its predecessors *Groundwater Flow*, *Groundwater Composition*, and *Isostatic Load on Canister* is represented through some hydromechanical–chemical model, and that these predecessors are affected by aleatory uncertainty. It follows that scenario generation can focus on *Groundwater Flow*, *Groundwater Composition*, and *Isostatic Load on Canister* because, once their states are fixed in a scenario, the *Canister State* is determined by the model.

2.3.4. Implications for Comprehensiveness

The possibility of unidentified and, therefore, uncharacterized uncertainties in scenario analysis can make it hard for analysts to ensure comprehensiveness. An FEP list that disregards factors that significantly influence the evolution of the disposal system undermines the comprehensiveness of scenario analysis (first concern of comprehensiveness in Section 2.2). Errors in evaluating the magnitude of the interactions are also detrimental to comprehensiveness because scenarios are then generated in reference to an invalid SM. Finally, system evolution uncertainty needs to be characterized for bounding the relevant range of scenarios. Otherwise, the challenge of building a comprehensive scenario set may become insurmountable (second concern of comprehensiveness in Section 2.2).

3. APPROACHES TO SCENARIO GENERATION

Among the sample assessments, we distinguish between the pluralistic and the probabilistic approaches to scenario generation. Fig. 6 stylizes these different views in demonstrating safety by showing compliance with the stated regulatory limit to the radiologic consequence (black dashed line).

The pluralistic approach uses expert judgments to postulate a relatively small number of scenarios (the black dotted curves in Fig. 6). Scenarios represent different assumptions regarding the evolution of the FEPs. The rationale in demonstrating the safety of the repository is that the radiologic consequences should remain below the regulatory limit in all scenarios.

The probabilistic approach parameterizes system evolution uncertainty by treating the FEPs that involve aleatory uncertainty as stochastic variables. It seeks to capture the whole range of system evolutions by sampling thousands of futures (the family of gray curves in Fig. 6) from the FEPs distributions. The many generated curves can be synthetized into the expected value[44,46,48,50] or the cumulative distribution function[27–29] of the radiologic consequences. The rationale in demonstrating the safety of the repository is that the expected value of the radiologic consequences should remain below the

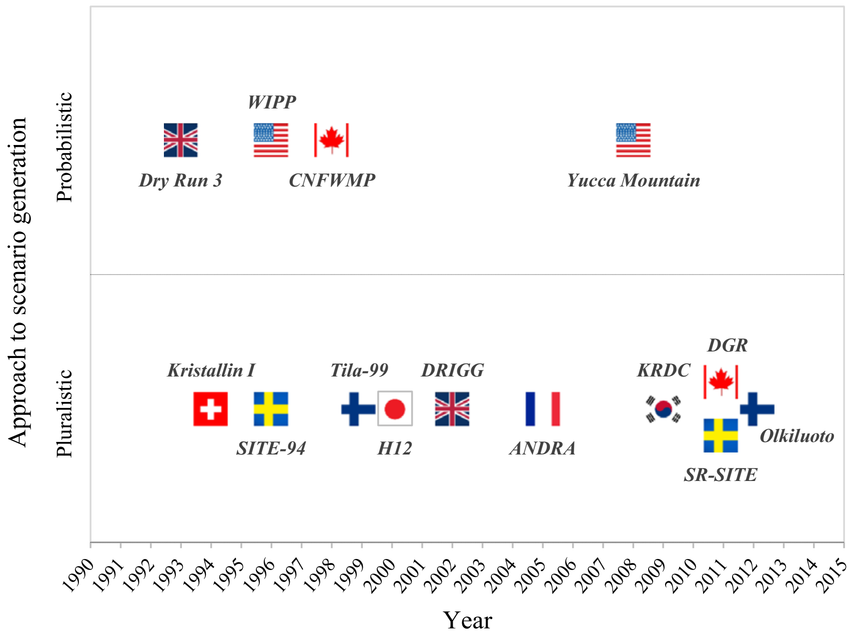

Fig. 7. Classification of the sample assessments to pluralistic and probabilistic approaches to scenario generation.

regulatory limit, and that the probability of violating this limit should be acceptably low.

Apart from aleatory uncertainty, probabilistic approaches use probability distributions to characterize the epistemic uncertainty regarding the values of the model parameters. To account for the effects of the two types of uncertainty (aleatory and epistemic), a double-loop sampling strategy is typically adopted.[(97–99)] As portrayed previously,[(38, Fig. 2.4-8)] first the model parameter values are sampled from their distributions; second, using these fixed values, the states of the FEPs are repeatedly sampled to generate many curves, as in Fig. 6. These stages are repeated several times to explore both probability spaces. Hence, the effect of epistemic uncertainty is that a different family of curves (or, more specifically, a different expected value and a different cumulative distribution function) arises at each iteration of the outer loop. Nevertheless, in Fig. 6 we show only one family of curves, thus characterizing aleatory uncertainty but not epistemic uncertainty. In fact, this section focuses on aleatory uncertainty, as the approach to scenario generation depends on how analysts intend to characterize it.

One can categorize an assessment by examining the sections on scenario generation, often titled "Scenario Development" or "Scenario Approach"[5] (or something similar). In the pluralistic approach, the scenario assumptions are presented as lists or phrases. Terms such as *identification* or *selection of the scenarios* are also typical in the pluralistic approach. In the probabilistic approach, there is either a mathematical presentation of the probability space or statements regarding how this space is used, such as "Monte Carlo simulation to generate samples of possible future evolutions."[(15)]

Fig. 7 categorizes the sample assessments based on their approach to scenario generation. The pluralistic approach has been prevalent in Northern and Central Europe and Asia, while the probabilistic one has been common in North America and the United Kingdom. There is also methodological continuity in that pluralistic assessments in a given country have been typically followed by further pluralistic assessments. In contrast, the probabilistic approaches lost the popularity they had in the 1990s, and Yucca Mountain remains the only recent example of application of a probabilistic approach.

3.1. Interpretation of the Scenarios

In the pluralistic approach, a scenario is a combination of assumptions. For example, in the Olkiluoto assessment,[(12)] the VS1-Brackish scenario[6] is: a hole in a canister located in proximity of a conductive

[5]Probabilistic approaches are sometimes associated with explicative titles, such as "Creating a scenario sample space."[(32)]

[6]In Posiva's interpretation, this is referred to as a *calculation case*.

fracture grows over time; the transport pathway from inside to outside the canister forms after 1,000 years; the buffer surface is degraded by erosion; and groundwater composition is brackish.

The assumptions are made by experts; therefore, the pluralistic approach implies scenario generation by judgment.[100] Still, this process can be well structured, as in Nykyri *et al.*;[7] however, the assumptions usually focus on a restricted set of FEPs. Specifically, these FEPs are those affected by aleatory uncertainty. The other FEPs are not included in the scenarios in the sense that their evolution is not described by any assumption. As previously discussed in Section 2.3.3, the rationale for not using an FEP to generate scenarios is that the dependence of this FEP on its predecessors is represented by a model because the aleatory uncertainty of this FEP is bound to that of its predecessors.

In the probabilistic approach, a scenario is a subset of the sample space of all the possible futures. Referring to the probability space for aleatory uncertainty ($\mathscr{A}$, $\boldsymbol{A}$, p_A), a scenario is a subset of $\mathscr{A}$, an element of $\boldsymbol{A}$, and has probability p_A.

For example, in the Yucca Mountain safety assessment,[42] aleatory uncertainty pertains to the disruptive events $DE \in \{EW, II, SG, ED, IE, SF\}$, where EW is early waste-package failures, II is igneous intrusive events, SG is seismic ground-motion events, ED is early drip-shield failures, IE is igneous eruptive events, and SF is seismic fault-displacement events. Each disruptive event is described by the FEPs n_{DE} and $\mathbf{a}_{DE}$—that is, the number of DE occurrences and a vector of properties (e.g., eruption duration, peak ground velocity) of these occurrences, respectively. Therefore, the set $\mathscr{A}$ contains all realizations of $[n_{DE}, \mathbf{a}_{DE}]$, $\forall DE$. Against this backdrop, the subset $n_{EW} \geq 1$ corresponds to the early waste-package failure scenario,[46] $n_{II} \geq 1$ corresponds to the igneous intrusive scenario,[48] $n_{SG} \geq 1$ corresponds to the seismic ground-motion scenario,[50] and so forth. By exclusion, the nominal scenario[44] is defined by $n_{DE} = 0, \forall DE$.

These scenarios are used to calculate the expected dose to humans D according to Equation (7.15) in Helton *et al.*[42] (we omit epistemic uncertainty and time dependence, for simplicity):

$$E[D] \doteq D_N + \sum_{DE} E\left\lfloor D_{DE}^{inc} \right\rfloor, \tag{1}$$

where D_N is the dose in the nominal scenario and D_{DE}^{inc} is the dose increment because of the occurrences of the disruptive event DE. In Equation (1), the superimposition of the doses is allowed by hypotheses that guarantee the separation of the effects of the scenarios.[39] Next, as shown by Equation (7.20) in Helton *et al.*,[42]

$$E[D_{DE}^{inc}] \doteq p_A(n_{DE} \geq 1) \cdot \frac{1}{N} \sum_{i=1}^{N} D_{DE,i}^{inc}, \tag{2}$$

the expected dose increments are estimated as the product of the probability of occurrences of DE and the arithmetic mean over a N-sized sample of dose increments $D_{DE,i}^{inc}$. Operatively, the ith joint realization of n_{DE} (conditioned on $n_{DE} \geq 1$) and $\mathbf{a}_{DE}$ is drawn by sampling techniques,[15,25,31] such as Monte Carlo,[101–104] and input into the models that calculate the corresponding $D_{DE,i}^{inc}$.

Traditionally, probabilistic assessments have relied on models to represent most FEP interactions. Thus, once the disruptive events are fixed by sampling, the evolution of the other FEPs and the resulting dose increment follows unequivocally, as determined by these models. Accordingly, analysts have treated only disruptive events as stochastic variables. As discussed in Section 2.3.3, and earlier in this section about the pluralistic approach, this rationale for focusing on a restricted set of FEPs is well motivated.

Nonetheless, in a generic safety assessment, FEPs other than disruptive events can be affected by aleatory uncertainty if there is no model to represent the dependence of these FEPs on their predecessors. In this case, it may be necessary to generate scenarios to span the states of these FEPs.

In both pluralistic and probabilistic approaches, it is then advisable that the FEPs that are affected by aleatory uncertainty be indicated before scenario generation. In a safety assessment, this indication can make it clearer why the scenarios focus on a restricted set of FEPs. Here, the SM of the disposal system can be useful because it displays the set of all FEPs, so that it is practical to indicate which ones are affected by aleatory uncertainty.

Whether an FEP is affected by aleatory uncertainty depends on whether the dependence of this FEP on its predecessors is represented by a model. Therefore, the indication of the FEPs affected by aleatory uncertainty builds on the indication of how the interactions between the FEPs in the SM are represented.

3.2. Interactions Between the FEPs

The scenarios must take the interactions between the FEPs into account. From this angle, it is

Table IV. Techniques for Building the System Model of the Disposal System (Influence Diagrams, Interaction Matrices, Influence Tables) and Assessment-Model Flowcharts Adopted (Black Squares) in the Sample Assessments, Classified by Approach to Scenario Generation (Pluralistic or Probabilistic)

Pluralistic				
Assessment	Influence Diagrams	Interaction Matrices	Influence Tables	Assessment-Model Flowcharts
Kristallin-I	■	□	□	■
SITE-94	■	□	□	■
TILA-99	□	□	□	□
H12	■	□	□	□
Drigg	□	□	□	□
ANDRA	□	□	□	□
KRDC	■	■	□	□
DGR	□	□	□	□
SR-SITE	■	□	■	■
Olkiluoto	□	■	■	■
Probabilistic				
Assessment	Influence Diagrams	Interaction Matrices	Influence Tables	Assessment-Model Flowcharts
Dry Run 3	□	□	□	■
WIPP	□	□	□	■
CNFWMP	□	□	□	■
Yucca Mountain	□	□	□	■

first necessary to identify all interactions. This task is typically achieved when building the SM of the disposal system. Table IV categorizes the sample assessments by approach to scenario generation, and it reports the techniques that the assessments adopt for building the SM. The last column of the table refers to assessment-model flowcharts (AMFs).[20]

An AMF shows all the models (typically elaborated into computer codes) that are used for representing system interactions. It represents the connections between these models, whereby a connection means a transfer of information from one model to another. An illustrative example is given in Fig. 2 in Hansen *et al.*[43] Although AMFs do not exactly use the definition of SM in Section 2.1.2, they are treated here in the context of SMs because they clarify how interactions are analyzed in the pluralistic and the probabilistic approaches.

The pluralistic approach is usually combined with the SM of the disposal system. With the support of the SM, experts can postulate scenarios that better consider the interactions between the FEPs. Fewer pluralistic assessments have contained an AMF, whereas an AMF is present in all reviewed probabilistic assessments. This use of AMFs reflects the fact that analysts who chose the probabilistic approach have relied on models for representing most of the interactions. Consequently, an AMF is substantially equivalent to an SM in these assessments.

In all approaches to scenario generation, it is important to build an SM of the disposal system because all interactions between the FEPs are identified, and because it is possible to indicate how each interaction is represented in the SM (e.g., conditional probabilities, models). This indication reveals which FEPs do not depend on their predecessors through models; therefore, these FEPs can be indicated as those affected by aleatory uncertainty, as advised in Section 3.1.

For indicating how interactions are represented, the approach proposed by Chapman *et al.*[20] and applied in the SITE-94 and SR-SITE assessments is a useful reference. First, the SM of the disposal system and the AMF of the available models are built. Subsequently, the SM is "mapped onto the AMF,"[20] meaning that any interaction between two FEPs is matched with the corresponding model in the AMF. By exclusion, the interactions that do not have a corresponding model, and hence need some other representation (e.g., conditional probabilities), are effectively indicated.

3.3. Interpretation of Comprehensiveness

In the pluralistic and probabilistic approaches, it is a challenge to attain completeness. In the pluralistic approach, experts postulate a limited number of scenarios[15] and thus cover only some of the possible futures. On the other hand, completeness can be achieved in the probabilistic approach if the probability distribution of the radiologic consequences can be derived from the probability distributions of the FEPs.[32] This derivation is usually performed numerically by generating a random sample of futures. However, attaining an adequately large sample[105] can be challenging, if it is not possible to execute sufficiently many model runs.[106]

The two approaches, then, address the comprehensiveness issue differently. The pluralistic approach presents its views on comprehensiveness by arguing for the *representativeness* of scenarios describing the evolution of the FEPs; for example, the postulated scenarios describe representative,[35,57] or illustrative,[21,33] futures. In contrast, the interpretation of the probabilistic approach is quantitative; the parameters used to represent the FEPs included in the scenarios are sampled to provide the broadest possible coverage of the whole set of system evolutions. The goal of comprehensiveness is likely achieved if the appropriate FEPs and their interactions are included in the analysis and if the sample is large enough to guarantee that the estimate of the radiologic consequences is statistically significant. Attaining an adequate sample size is not straightforward because the computational burden of the models (e.g., groundwater flow, contaminant transport)[107,108] can make it impractical or impossible to run the substantial number of simulations needed. As a result, probabilistic assessments use intelligent computation strategies, such as simplified models,[15,25] application of the law of total probability upon partition of the probability space,[32,42] accelerated Monte Carlo sampling,[109] and metamodeling.[110–112]

4. CHALLENGES IN SCENARIO ANALYSIS

In this section, we recapitulate the challenges identified in this review and propose advances for the scenario analysis for the safety assessment of nuclear waste repositories. For ease of reference, the challenges are summarized in Table V. We do not promote any *ex nihilo* final analysis of the many studies that have been performed over the years. Rather, we compile the information from past assessments for identifying areas of methodological advancement that seem promising.

The first challenge is to clarify why scenarios usually focus on a restricted set of FEPs. In the pluralistic approach, scenarios are combinations of assumptions that describe the evolution of some FEPs only. In the probabilistic approach, scenarios are sets of similar futures in which similarity is typically determined by the FEPs related to disruptive events. Thus, both approaches recognize that aleatory uncertainty usually affects few FEPs. This recognition motivates the focus of scenarios on these FEPs. Nonetheless, it is advisable that the FEPs affected by aleatory uncertainty be indicated before scenario generation. In a safety assessment, this indication can make it clearer why the scenarios focus on a restricted set of FEPs.

The FEPs affected by aleatory uncertainty can be indicated effectively upon indicating how the interactions between the FEPs are represented. If the interactions of FEPs with predecessors (i.e., the FEPs on which they depend) are represented by a model of the underlying physical and chemical phenomena, the aleatory uncertainty of this FEP is bound to that of its predecessors and can hence be disregarded. Otherwise, if these interactions are represented, for example, through conditional probabilities, the aleatory uncertainty about the state assumed by the dependent FEPs will prevail.

Against this background, the SM of the disposal system can be useful. Specifically, analysts can follow the approach of Chapman *et al.*[20] Next to the SM, an AMF displays the available models. The comparison between the SM and the AMF indicates the interactions that are represented by models and those that are not. Therefore, the FEPs that do not depend on their predecessors through models can be indicated as those affected by aleatory uncertainty.

Several techniques can be used for identifying and modeling the interactions in a disposal system. For example, Bayesian networks (BNs),[113,114] analogously to Fig. 3, consist of nodes that can assume multiple states and represent interactions through conditional probabilities. Therefore, as Pearl[115] notes, "the model [i.e., the BN] can be used to generate random samples of hypothetical scenarios." For tailoring BNs to disposal systems, models of physical and chemical phenomena can be integrated into these probabilistic networks. Integrated probabilistic and deterministic safety assessment (IDPSA) techniques also combine models and probabilities

Table V. Challenges in Scenario Analysis: Summary Discussions and Research Directions

Challenge	Discussion	Research Directions
Scenario generation usually focuses on a restricted set of FEPs.	This is well motivated because aleatory uncertainty usually affects few FEPs. However, these FEPs need to be indicated before scenario generation, to make it clear why scenarios focus on few FEPs. The aleatory uncertainty of FEPs, in turn, depends on how interactions are represented.	In the SM of the disposal system, we indicate how each interaction is represented (conditional probabilities, models), and hence which FEPs are affected by aleatory uncertainty.
		To do so, for example, compare the SM to an AMF.[20]
		Other techniques, such as Bayesian networks[113–115] and IDPSA methods,[116,117] may be also relevant.
Use a widely accepted interpretation of comprehensiveness.	Comprehensiveness undergoes approach-dependent interpretations: Pluralistic → Representativeness Probabilistic → Large sample size	Discard scenarios without performance target violations[1,8] and/or less probable than nonnegligibility thresholds.
Establish solid approaches to the characterization of epistemic uncertainty.	Comprehensiveness of the FEP list is arduous to characterize.	Use existing debiasing techniques[79,80] and new characterization methods (e.g., FEP probabilities by share of experts, FEP importance measures).[66]
	The uncertainty about the magnitude of the interactions involves uncertainties in the tools for representing the interactions: Conditional probabilities → Values Models → See model uncertainty below	With conditional probabilities, we aggregate different values from different sources (e.g., experts), or use interval-valued probabilities[81] (see below for models)
	Authors in literature disagree on the characterization of the uncertainty about the validity of model assumptions.	Maintain the distinction between epistemic and aleatory uncertainty.

FEPs = features, events, and processes; SM = system model; AMF = assessment-model flowchart; IDPSA = integrated probabilistic and deterministic safety assessment.

for discovering failure scenarios.[116–118] Specifically, a substantial sample of scenarios is postprocessed to identify patterns of system behavior.[116–118] BNs and IDPSA may have synergies, as BNs can be used to postprocess the IDPSA scenarios by their ability to identify hidden interactions in raw data.[113] Other relevant techniques include dynamic event trees,[119] Muir webs,[120] and goal tree success tree–dynamic master logic diagrams.[121] Because there are many techniques, it is increasingly important to learn how to customize and combine them into scenario analysis.

Once the SM has been built, the challenge is to span the future comprehensively. Comprehensiveness improves the quality of safety assessments in all fields, including nuclear power production,[122,123] hazardous waste landfill monitoring,[124] and aerospace exploration.[125] However, current interpretations of comprehensiveness are rather approach dependent. Thus, we encourage the following more general interpretation of comprehensiveness, which is inspired by the approach recommended[1] and adopted[8] for the repository at Olkiluoto.

If only a limited number of scenarios can be analyzed because of time or budget constraints, comprehensiveness can be interpreted as the ability to cover all scenarios in which one or more performance targets are violated. Indeed, no radiologic harm can be expected otherwise (Section 2.1.3). Therefore, safety can be demonstrated without having to analyze scenarios that are known to be safe. The identification of performance-target-breach scenarios depends on the modeling of the FEP interactions, as in the following example (also illustrated in Fig. 8).

Let the FEPs *Isostatic Load on Canister* (σ), *Canister State* (intended as copper thickness, d), and *Radionuclide Release to Surface* (r) from Fig. 3 form a simplified system. These FEPs (all classifiable as features) assume discrete ordinal states obtained, for example, through discretization of continuous ranges.

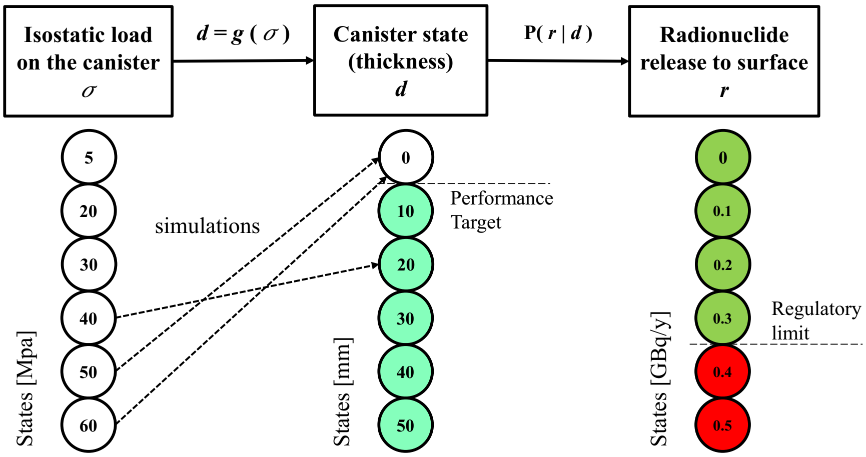

Fig. 8. Exclusion of scenarios. The features, events, and processes *Isostatic load on canister* (σ), *Canister state* (d), and *Radionuclide release to surface* (r) assume discrete states. The interaction between σ and d (performance indicator, with performance target $d > 0$, light green) is described by the monotonically increasing function g. The interaction between d and r (radiologic consequence, with regulatory limit $r \leq 0.3$ GBq/y; green) is represented by conditional probabilities.

Radionuclide Release to Surface is the radiologic consequence of interest, subjected to the regulatory limit $r \leq 0.3$ GBq/y (i.e., the limit for ^{14}C, ^{36}Cl, and ^{135}Cs according to STUK),[1] and *Canister State* is assumed to be a performance indicator. The interaction between *Isostatic Load on Canister* and *Canister State* is represented by a model. This model consists of a function $d = g(\sigma)$, which is known to be monotonically decreasing (i.e., the higher the load, the deeper the breaches in the copper) and can be calculated by a computer code. Instead, the interaction between *Canister State* and *Radionuclide Release to Surface* is represented by conditional probabilities $P(r|d)$. Because the probability of exceeding the regulatory limit on *Radionuclide Release to Surface* is zero as long as the copper maintains some thickness, the performance target $d > 0$ is set on *Canister State*.

Because d is bound to σ by a model, scenario generation can focus on the latter. However, because the computation of g can be burdensome, strategies are needed to find a comprehensive set of scenarios (i.e., states of σ) to be simulated. By first simulating the most critical load $\sigma = 60$ MPa (see Fig. 8) and progressively simulating lower ones, it is found that $\sigma = 40$ MPa already leads to a state of d within the performance target. Because of the monotonicity of g, analysts can infer that the states of σ from 5 MPa to 30 MPa are also safe and hence need not be simulated. If probabilities are assigned to the states of σ, the number of scenarios can be reduced further. All states of σ below a risk-negligibility threshold on probability can be omitted.

This notion of comprehensiveness is robust because the exclusion of safe scenarios reduces the computational effort without changing the conclusions regarding the safety of the repository. Nevertheless, the application of this approach to comprehensiveness in large-scale scenario analyses is a matter of future research because FEP networks are more complex than this simplistic example: discretization might not be appropriate, the identification of all performance targets might be difficult, and monotonicity might not be guaranteed.

This section has thus far discussed challenges in addressing the aleatory uncertainty about system evolution. In addition to these challenges, there are existential challenges in characterizing the epistemic uncertainties related to the representation of the system and its evolution. Specifically, these epistemic uncertainties concern the comprehensiveness of the FEP list, the magnitude of the interactions, and the validity of models.

First, the FEP list is comprehensive if all the FEPs that significantly influence the disposal system are identified. In this review, this has been referred to as the first concern of comprehensiveness (whereas the second concern pertains to the scenarios), and has been argued to be truly difficult to guarantee. Still, possible biases in the expert-based FEP-elicitation process can be mitigated through debiasing or nominal-group techniques.[79,80]

Furthermore, uncertainties regarding comprehensiveness of the FEP list can be characterized through probabilities reflecting the share of experts who have identified each FEP or by measuring the importance of the FEPs, still through expert judgments.[66]

The second scenario-development step is the identification of system interactions. At this stage, there is uncertainty concerning the magnitude of such interactions. Because the magnitude of the interactions is to be captured by the tools through which the interactions are represented, the characterization of this uncertainty depends on the specific tool used. If the interactions are represented by conditional probabilities, analysts need to characterize the uncertainty regarding the values of these probabilities. Possible approaches include aggregating different values from different experts or other sources or using interval-valued probabilities. If the interactions are represented by a model, then analysts need to characterize model uncertainty more specifically.

Model uncertainty concerns model assumptions and parameters. Probability distributions for the parameters can be elicited through well-known methods. Uncertainties related to model assumptions can be more controversial, as discussed in Section 2.3.2. For this reason, it is even more challenging to choose the characterization technique for model uncertainty. At any rate, we advocate that the characterization of epistemic uncertainty be kept separated from that of the aleatory uncertainty regarding system evolution, as well exemplified by the American assessments.[24,42] This separation can facilitate the tasks of uncertainty and sensitivity analysis for identifying the uncertainties that contribute most to the overall uncertainty of the results.

5. CONCLUSION

We have reviewed the literature on scenario analysis for the safety assessment of nuclear waste repositories. Specifically, we have analyzed the key properties of scenario analysis and have identified several challenges, such as those in ensuring comprehensiveness.

We have described scenario analysis as a process consisting of scenario development, which provides the set of scenarios, and consequence analysis, in which the radiologic consequences of these scenarios are calculated. In scenario development, we have advocated the development of the SM of the disposal system. We have also argued why it is difficult to account for all the possible futures (completeness), whereas comprehensiveness is a more meaningful objective of scenario analysis. We have also discussed the mathematical characterization of the uncertainties in relation to system scope and structure, model assumptions and parameters, and system evolution.

We have also examined methodological differences between the pluralistic and the probabilistic approaches to scenario generation: (1) different interpretations of scenarios either as a combinations of assumptions or as subsets of the sample space of all the possible futures, respectively; (2) different techniques for building an SM of the disposal system; and (3) different interpretations of comprehensiveness either as representativeness or as generation of a substantial sample of futures, respectively. Our review suggests the following avenues for further methodological research.

First, it may be beneficial to indicate before scenario generation which FEPs are affected by aleatory uncertainty. Whether this is the case depends on the representation of the interactions of that FEP with its predecessors (i.e., the FEPs on which they depend). Hence, we suggest indicating how each interaction in the SM is represented (e.g., conditional probabilities, models).

Second, different methodological approaches have led to different interpretations of comprehensiveness. Arguably, a more general and less approach-dependent interpretation would help to ascertain the comprehensiveness of the set of scenarios for assessing repository safety. To this end—and building on the approach for the repository at Olkiluoto—we have suggested interpreting comprehensiveness as the ability to cover all scenarios (i.e., FEPs and their evolution) in which one or more performance targets are violated. The identification of such scenarios can benefit from systematic strategies. For example, the number of scenarios to be examined can be reduced if the relationship between a performance target and other FEPs is monotonic (see Section 4). Further scenario-screening criteria may be applicable, such as probability. Indeed, it may be possible to screen those scenarios whose probability is so low that the risk remains below a stated threshold. Still, possible pitfalls in making such probabilistic inferences need to be recognized and avoided; for instance, when scenarios are derived by discretizing continuous distributions, the introduction of a more specific discretization (e.g., by subdividing states to generate more scenarios) must not lead to the exclusion of more specific scenarios that are deemed irrelevant because their probability is too low, while the probabilities of the original less specific scenarios would exceed the threshold (see the "Paradox of the Lottery" evoked in Andres and Goodwin[32]).

Third, we have discussed challenges in the characterization of epistemic uncertainties in scenario analysis. For addressing the uncertainty about the comprehensiveness of the FEP list (which in scenario development is addressed earlier than the comprehensiveness of the scenarios), we have proposed the use of debiasing techniques in eliciting expert judgments and, if need be, the use of probabilities and FEPs importance measures. To characterize the uncertainty about the interactions between the FEPs, when interactions are represented through conditional probabilities, one can aggregate different values from different sources (e.g., experts) or use interval-valued probabilities. When interactions are represented through models, there are other epistemic uncertainties. Here, the main suggestion is to recognize that these uncertainties are different from the aleatory uncertainty about system evolution and hence should be characterized separately from it, as illustrated by the assessments for the WIPP and Yucca Mountain repositories.[24,42]

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