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Chapter 17: Safety assessment for deep geological disposal of high-level radioactive waste

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Abstract

Safety assessments estimate the long-term performance of geological disposal systems for radioactive waste using quantitative models. This paper reviews regulatory standards, selection of scenarios for analysis, the development of computational models and their linkage into a system analysis, and the iterative relationship between site characterization and safety assessment. Uncertainty must be acknowledged, and can be accounted for using both conservative deterministic and probabilistic approaches. In addition to generating performance estimates for comparison to regulatory standards, safety assessments can also guide research and model development, evaluate design alternatives, enhance the scientific understanding of the system, and contribute to public acceptance.

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17.1 Introduction

Discussions of deep geological disposal of high-level radioactive waste invariably come to the question ‘is it safe?’, or perhaps to variants of the question such as ‘how safe is it?’ or ‘how can we be sure it is safe?’ These questions are central to considerations of geological disposal regardless of the perspective from which they are proposed. Industries and agencies responsible for the management or disposal of wastes, regulators charged with protecting public health and safety, and both opponents of and advocates for specific disposal options all want credible answers to these questions. Ensuring the safety of both workers and the general public while geological disposal systems are operating also requires careful attention, but public concerns have tended to focus on the long-term safety of repositories after they have been decommissioned. This emphasis on long-term risks may in part be a function of familiarity; operational safety can be observed and monitored directly, and preclosure risk assessments for disposal systems are therefore analogous to those undertaken for nuclear power plants or other industrial facilities. Ensuring the safety of disposal systems over the long geological time period during which significant radioactivity may remain has been perceived by many, however, to be a more difficult problem. A full discussion of all the lines of evidence that may be relevant to a demonstration of the long-term safety of a geological disposal system, commonly referred to as a “safety case” (e.g., IAEA 2006), is beyond the scope of this Chapter, which focuses instead on answering a narrower question. How can we estimate hazards associated with deep geological disposal of radioactive waste over thousands or hundreds of thousands of years?

As is the case for many complex problems in science and engineering, computer modeling based on well-accepted natural laws provides at least a partial answer. There is general consensus among the nations that manage long-lived radioactive waste that meaningful estimates of long-term performance of disposal systems consistent with current understanding of the geological system and reasonable assumptions about future conditions are both possible and necessary to support the decision-making process.

The importance of modeling based on thorough characterization of the disposal site and accepted principles of physics and chemistry was recognized early in the consideration of geological disposal (e.g., National Research Council 1978, p. 4), and disposal programs in many nations undertook quantitative modeling efforts, referred to generally (and essentially synonymously) as safety assessments or performance assessments, to support disposal system safety analyses (e.g., NEA 1997). Acknowledging these ongoing efforts, the International Atomic Energy Commission (IAEA) advisory standards for the Geological Disposal of Radioactive Waste, developed jointly with the Organisation for Economic Co-operation and Development Nuclear Energy Agency (OECD/NEA), have defined the process for quantifying performance estimates as ‘safety assessment’ (IAEA 2006, section 3.41):

> Safety assessment is the process of systematically analysing the hazards associated with the facility and the ability of the site and the design of the facility to provide for the safety functions and to meet technical requirements. Safety assessment includes quantification of the overall level of performance, analysis of the associated uncertainties and comparison with the relevant design requirements and safety standards.

The specification in the IAEA definition that safety assessments must include an analysis of associated uncertainties is consistent with the recognition that the uncertainties inherent in modeling the far future are potentially large, and must be fully acknowledged in any credible analysis. The IAEA definition in this regard parallels approaches taken in many national programs to acknowledging and accounting for uncertainty (NEA 2004a, NEA 2004b). For example, as early as the middle 1980s the regulatory framework in the United States required a performance assessment that:

> (1) Identifies the processes and events that might affect the disposal system; (2) examines the effects of these processes and events on the performance of the disposal system; and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events. These estimates shall be incorporated into an overall probability distribution of cumulative releases to the extent practicable. (US EPA 1985; 40 CFR 191.12(2)).

This definition remains essentially unchanged in the current United States regulatory framework governing deep geological disposal of radioactive wastes (e.g., US NRC 2009; 10 CFR 63.2), and has proven to be an important factor in determining the overall approach to probabilistic safety assessments in the United States. Although not all national programs have chosen probabilistic approaches to safety assessments, there is widespread agreement on the need for a consideration of uncertainty (NEA 2004a).

This Chapter focuses on the implementation of safety assessments for disposal systems, examining those aspects that are common to all assessments and using specific examples to demonstrate alternative approaches to achieving useful estimates of future performance. Examples are taken from published safety assessments for mined geological repositories, but the basic techniques are equally applicable to other concepts for deep geological disposal, including disposal in borehole repositories (see Chapter xxx). Sections of the Chapter comment on the goals of safety assessments, steps in the process of conducting an assessment, approaches to acknowledging and interpreting uncertainty, and applications of the results of safety assessments. The Chapter concludes with observations on possible future trends in safety assessment and a discussion of sources of additional information for interested readers.

17.2 Goals of a safety assessment

Overall, the primary goal of a safety assessment is straightforward: provide an estimate of the long-term safety of the potential facility. At a finer level of detail, the specifics of how this goal is defined become important. How should we measure safety? How safe is safe enough? Who, or what, is to be protected, and for how long? What level of uncertainty is acceptable? To what extent can future generations be protected from willful human disruption of the disposal system? In general, answers to these questions are societal, and perhaps political, decisions for which science may inform the answer but does not solely determine it. As described elsewhere in this volume in more detail (see Chapters xx and yy, safety can be evaluated in terms of the risk of future health effects, in terms of estimates of future radiation doses, or in terms of releases of radiation from the disposal system. Protection standards can be established for environmental criteria (e.g., concentrations of radioactive materials in groundwater), or to protect hypothetical future members of the general public. Standards could apply for as long as the wastes remain hazardous (potentially many millions of years), or for shorter periods of specified duration, reflecting beliefs about both the merits of regulating the distant future and the usefulness of attempting quantitative modeling over extraordinarily long times. Standards may emphasize performance of the overall system by focusing on releases or doses, but they may also require explanation of how individual components of the system provide specific safety functions that contribute to the overall demonstration of safety, to ensure that, as the IAEA recommends, '[t]he overall performance of the disposal system shall not be unduly dependent on a single safety function' (IAEA 2011, Requirement 7).

Examples exist internationally of each of these approaches. The Waste Isolation Pilot Plant (WIPP) constructed in the United States for disposal of transuranic wastes has regulatory limits set on cumulative radionuclide releases for 10,000 years (US EPA, 1985; US DOE 1996); the formerly-proposed Yucca Mountain high-level radioactive waste repository in the United States has regulatory limits set on mean annual radiation doses to a hypothetical future individual for 1 million years (US EPA 2008; US NRC 2009); and safety assessments for potential candidate sites in Sweden address the risk of harmful human health effects for up to 1,000,000 years (SSI 1998; SKB 2011). Other nations set limits on maximum allowable radiation doses or impacts on human health or the environment for an unlimited period of time (e.g., Canada [CNSC 2004], Switzerland [ENSI 2009], and others [see NEA 2006]).

With the exception of the cumulative release standard used for the WIPP, quantitative answers to the basic question of 'how safe is safe enough' are most commonly addressed through risk or dose-based standards. Internationally, risk-based limits range from probabilities of harmful health effects of 10^{-5}/yr to 10^{-6}/yr and dose-based limits are generally from 0.1 mSv/yr to 1 mSv/yr (NEA 2007, Appendix 2; ICRP 2007, Section 6.1.3), with 0.3 mSv/yr being the value recommended by the IAEA for the time before 'uncertainties become so large that the criteria may no longer serve as a reasonable basis for decision making' (IAEA 2006, Section 2.12). Many nations define the time during which quantitative limits apply at 10,000 years or less. For example, Finland sets a quantitative dose limit of 0.1 mSv for the most exposed individual for 'the period during which the radiation exposure of humans can be assessed with sufficient reliability, and which shall extend at a minimum over several millennia', and beyond that period 'radiation impacts caused by disposal can be equivalent to those caused by natural radioactive materials in earth's crust' (Finland 2008). The United States defines a

10,000-year standard of 0.15 mSv/yr and a separate, and higher, dose standard of 1 mSv/yr to apply between 10,000 years and 1,000,000 years for the formerly proposed Yucca Mountain repository (US EPA 2008). Several nations also set higher standards (up to 1 mSv/yr) for scenarios involving human intrusion into the repository (NEA 2007, Appendix 2).

Although each of these regulatory approaches shares a common goal of protecting future humans and the environment until such time as radioactive decay has reduced the hazard posed by the waste, differences in how regulations are structured can have significant influence on how safety assessments are designed, and, for that matter, on how repositories are designed and sited. For example, setting limits on the allowable cumulative release of radionuclides normalized to the total inventory of the disposal system, as in the regulation applied for the WIPP in the United States (US EPA 1985), can encourage the development of centralized mined repositories with large inventories by allowing proportionally larger releases from larger facilities. This approach also avoids creating a regulatory incentive for multiple dispersed repositories, with smaller inventories that might each individually result in smaller estimated releases. Regulatory approaches that specify a cumulative release also rely on a specification of a fixed time period, thereby encouraging the selection of sites that emphasize isolation of all radioactive materials during that period. Regulatory approaches that set limits on the maximum allowable annual doses or health risks to an individual during a specified time period encourage isolation during that time period, but they can also encourage the selection of sites that show a lower estimated maximum annual dose due to either a gradual release of radionuclides through time or a dilution of radionuclides in the environment. Regulations that apply a single limit regardless of the initial inventory of the disposal system unavoidably carry a potential for encouraging the selection of multiple smaller disposal sites each of which has the potential to show lower estimated releases simply because of its smaller inventory of waste. As a final example of how regulations may influence disposal system design, regulatory approaches that specify performance requirements for individual components of the disposal system, such as a minimum time before the failure of near-field engineered barriers (e.g., US NRC 1983, 10 CFR Part 60.113; STUK 2013, YVL D.5 Section 410) have the potential to provide additional confidence in the safety of some disposal concepts but can also lead to sub-optimal designs that increase costs without improving overall safety. They may also limit options for disposal concepts that do not rely on specified components, such as deep borehole repositories that rely on robust geology and seal systems rather than on long-lived waste packages.

Regulations may also prescribe assumptions to be made in the safety assessment regarding the characteristics of the future humans potentially at risk. Should they be assumed to be like the humans in the region today? Should they be assumed to have a lifestyle such as subsistence farming that might lead to higher risk? Should they be assumed to have sufficient technology to recognize and avoid or mitigate radiation risks? Answers to these questions, and others like them that address unknowable aspects of future human behavior, will define essential boundary conditions for any safety assessment, and in the absence of clear regulatory guidance, reasonable assumptions should be made and clearly stated. Typically, safety assessments rely on cautious assumptions about human culture and knowledge, assuming that the receptor groups will have lifestyles that result in at least as much risk of exposure as those of today, and that future generations will eventually cease to be aware of the dangers posed by the site. Acts of deliberate sabotage or warfare in the far future are generally considered to be outside the scope of what environmental regulations can control, although many safety assessments include some consideration of the consequences of inadvertent human disruption of the site (NEA 2007, Appendix 2).

17.3 Steps in a typical safety assessment

Once a candidate disposal site has been identified and the goals of the safety assessment have been defined, safety assessments typically develop through four steps, shown schematically in Figure 17-1. Although they are discussed here as if they were sequential activities, in practice, all four activities are undertaken together, and the safety assessment tends to develop and mature through multiple iterations. First, basic information about the potential disposal system must be developed through characterization of the geological setting, the waste, and a conceptual design of the facility. Second, scenarios must be developed that are representative of possible future states of the system relevant to the safety assessment. Third, computational models are developed that can simulate the features, events, and processes relevant to the chosen scenarios, incorporating uncertainty about the behavior of the system. Fourth, computational models are combined into a system-level analysis that provides estimates of overall performance that supports both programmatic (e.g., design optimization, research prioritization) and regulatory decisions.

22.3.1. Characterization of the disposal system

Characterization of each of the three main components of a disposal system (i.e., the waste form, the geological setting, and the facility design) is often seen as three separate lines of research, and responsibility for these tasks is often split among different entities within a single program. The safety assessment for a multi-barrier concept needs input from all three equally, however, and overall performance depends on the integration of design with the site geology and the wastes intended for disposal. The waste form itself defines the total radionuclide inventory for the disposal system and also impacts performance through its physical and chemical characteristics. For example, the heat generated by radioactive decay of spent nuclear fuel can be an important factor in disposal system design and performance, and repositories for spent fuel may need different design concepts than those primarily intended for vitrified waste from reprocessing activities.

22.3.2 Selection of scenarios for analysis

It is neither practical nor possible to analyze all possible future states of a disposal system, and essentially all safety assessments choose instead to focus their efforts on a relatively small set of scenarios that are broadly representative of important aspects of the range of future conditions. Multiple approaches have been used to develop scenarios with varying degrees of formalism and documentation (NEA 1999), but all approaches share common goals. Scenarios selected for analysis must be suitable for quantitative analysis with computer models, and the set of scenarios must satisfy programmatic or regulatory requirements regarding the comprehensiveness of the assessment.

Formal proof that a scenario development process has considered the complete set of all possible future events is impossible, and emphasis instead is placed on documenting a sound process that demonstrates comprehensiveness. If any aspect of the future needs to be considered quantitatively in the safety assessment, it must be accounted for in one or more of the scenarios chosen for analysis. If relevant scenarios can be identified that are not accounted for in the existing analyses and that cannot be shown to be insignificant, the set of scenarios should be expanded to include them.

One commonly adopted approach to demonstrating the comprehensiveness of the scenario development process begins with the identification of a list of all factors potentially relevant to the long-term performance of the disposal system. Typically, these factors have been categorized as features, events, or processes, using common-sense definitions for the terms. For example, the US NRC (2003, Section 3) defines a feature to be ‘an object, structure, or condition that has a potential to affect disposal system performance’, an event to be ‘a natural or human-caused phenomenon that has a potential to affect disposal system performance and that occurs during an interval that is short compared with the period of performance’, and a process to be ‘a natural or human caused phenomenon that has a potential to affect disposal system performance and that operates during all or a significant part of the period of performance'. In practice, the distinction of whether a specific phenomenon is a feature, an event, or a process is secondary to the recognition that whatever it is, it needs to be evaluated, and features, events, and processes are often grouped together with the generic acronym 'FEPs'.

As shown in Figure 17-2, after potentially relevant 'FEPs' are identified and cataloged in an initial list, they are then evaluated, or screened, using criteria such as the probability of occurrence or the significance of the consequences associated with their occurrence, and FEPs that meet the screening criteria are then used to construct the scenarios for analysis. The comprehensiveness of the process is demonstrated by the comprehensiveness of the final FEP list considered for screening and the documentation of the screening evaluations. All potentially relevant FEPs should be mappable to a FEP that has been evaluated, and there should be clear traceability to documentation of either how the FEP has been accounted for in the system-level analysis or how its exclusion has been justified.

Lists of potentially relevant FEPs are unavoidably subjective, in the sense that any individual FEP can be subdivided narrowly or lumped coarsely (for example, a single FEP could be identified as 'colloidal transport of radionuclides', or many tens of separate FEPs could be defined if transport of each radionuclide in each environment is treated separately). In practice, subjective distinctions like this make little difference in the comprehensiveness of the list; a single FEP describing how colloidal transport has been evaluated for each radionuclide of interest is fully equivalent to multiple separate FEPs. In general, FEPs are most useful if they are defined at the broadest level for which a coherent technical discussion can be presented; little value is added by defining thousands of similar FEPs each of which will require separate documentation. FEP lists have been developed using various techniques, including formal elicitation using top-down classification schemes, freely-structured brainstorming, and reviews of relevant literature. FEP lists have been published by the NEA and multiple repository programs (NEA 2000 and references cited therein, SNL 2008a,b; SKB 2010; Posiva Oy 2102a). The use of a FEP list to demonstrate comprehensiveness of the analysis is an expected part of the regulatory process in the United States (US NRC 2003, section 2.2.1.2.1.2), and the FEP approach has been used in regulatory settings in the US (US DOE 1996, US DOE 2008), Sweden (SKB 2011), and Finland (Posiva Oy 2012b)

Screening criteria for FEPs are most useful if they are explicitly documented and agreed upon in advance by regulators and stakeholders. In the United States, screening criteria are provided directly in the US EPA regulations: a FEP may be excluded from a performance assessment if it can be shown to have an annual probability of occurrence less than one chance in 100,000,000 or if it can be shown that results of the performance assessment would not change significantly if the FEP were omitted (US EPA 2008, 40 CFR 197.36(a)(1)). If formal FEP screening criteria are not specified by regulations, FEP analyses may still provide valuable justification for the choices made in constructing the system-level models, and documentation of the FEP process can be an important step in building confidence in the safety assessment.

Additional confidence in the completeness of the treatment of FEPs that are included in the system-level modeling can be gained through systematic evaluation of possible interactions. Both influence diagrams and interaction matrices have been used to confirm that safety assessment models provide a comprehensive treatment of plausible interactions among FEPs (see, for example, SKI 1996; Pers et al. 1999; Posiva Oy 2012a). Analyses such as these help identify coupled processes that may have been overlooked in initial screening. Grouping of FEPs retained for analysis into scenarios can logically be done by mapping FEPs to the safety functions of the associated components (both natural and engineered barriers) (e.g., ONDRAF/NIRAS 2001, Section 11.2). This approach allows identification of those FEPs that are potentially important to the performance of the system or subsystem components and the evaluation of their impacts, either quantitatively or qualitatively through separate analyses (e.g., ANDRA 2005a, Section 6.1.5.5).

22.3.3 Developing computational models for relevant processes

Once preliminary scenarios have been selected for analysis, computational models are developed to simulate the major physical and chemical processes relevant to the behavior of the system. At a minimum, safety assessments require models for the behavior of engineered barriers in the geological setting, including degradation mechanisms; release of radionuclides from the waste form and engineered barriers; and the transport of radionuclides away from the emplacement zone to the human environment. Full development of a safety assessment is likely to require detailed models for groundwater flow in the region, corrosion and degradation of engineered materials in a changing chemical environment, dissolution and mobilization of waste forms, and contaminant transport both as dissolved and colloidal species. Depending on programmatic and regulatory requirements, models may also be needed for human exposure pathways and estimation of radiation doses. Models may need to consider boundary conditions that change through time, for example, because of long-term climate change, and they should take into account coupled interactions such as those between hydrology, chemistry, and the heat generated by the waste. Sufficient data must be collected to support the development and parameterization of these models, creating a need for ongoing iterations between model development and site characterization work. As discussed in Section 17.4, uncertainty in both the choice of models and the parameter values used in them should be acknowledged and characterized.

In many programs, development of these process models, and the information needed to provide values for their input parameters, is the largest part of the work needed to support the safety assessment. Some programs have found it advantageous to construct underground research laboratories dedicated in part to developing and testing process models specific to the performance of their potential repository concept (see Chapter 4 of this book).

22.3.4 The system-level analysis

Process models are used to build a system-level model capable of estimating the overall performance measures of interest. Depending on the complexity of the processes, regulatory and programmatic expectations, and available computational resources, the system-level model may be built by developing and coupling simplified abstractions of the process models that capture only the most important processes, by linking process models by transferring inputs and outputs as response surfaces or look-up tables, or by directly coupling process models. In practice, system-level models are typically constructed using a hybrid approach that involves multiple techniques. Because safety assessments may develop over periods of several years and add different component models at different stages of development, the final products may reasonably be expected to be composites with varying levels of complexity.

The performance assessment model used for the 1996 WIPP Compliance Certification Application (US DOE 1996) is illustrated schematically in Figures 17-3 and 17-4 as an early but representative example of a relatively simple system-level model that relied on direct coupling of computer codes, transfer of information among models via response surfaces, and the use of simplified abstractions for computational efficiency. Although specific details of the implementation of the 1996 WIPP performance assessment are beyond the scope of this chapter, concepts introduced in the summary below are broadly applicable to many safety assessment system models.

As described in detail in Section 6.4 of US DOE 1996 (see also Helton and Marietta 2000), computational models were developed for the major processes of interest in each of the components of the disposal system. As shown schematically in Figure 17-3, the BRAGFLO code simulated two-phase fluid flow (gas and brine) in the repository and surrounding host rock. Three codes, FMT, PANEL, and NUTS, were used to estimate radionuclide concentrations in brine within the repository and in near-field rocks. One code, SANTOS, was used to characterize creep deformation in the salt surrounding the excavated areas. Two codes, CUTTINGS_S and BRAGFLO_DBR, were used to estimate the release of radionuclides to the land surface following a hypothetical drilling intrusion event, and two additional codes, SECO-FL2D and SECOTP2D, were used to model groundwater flow and contaminant transport away from the intruding borehole in the Culebra dolomite aquifer overlying the repository. One code, GRASP-INV, was used to develop multiple geostatistical realizations of possible transmissivity fields in the Culebra aquifer.

Figure 17-4 shows how these codes were linked computationally to construct a system model. The major flow and transport codes (shown in the shaded box in Figure 17-4) were linked directly into a single simulation tool that drew input parameters from a common database. Transfer of information among these codes was fully automated. Two codes, the detailed process model NUTS and the simplified abstraction PANEL, were available in the performance assessment model for estimating radionuclide concentrations, and for most purposes PANEL was used for computational efficiency. Direct couplings of rock creep processes (using SANTOS) and geochemical processes (using FMT) were not included in the performance assessment, in part because of the complexity of the couplings and in part because preliminary analyses indicated that sufficient resolution could be obtained by running these models independently as stand-alone models and then providing their output to the relevant performance assessment components as response surfaces. Similarly, the GRASP-INV code was run independently of the performance assessment to generate multiple realizations of transmissivity fields that were then sampled for use in the system-level analysis. Output from the linked component models was then used as input to a post-processing code, CCDF_GF, that compiled consequence results for individual scenarios into the probabilistic outcomes summed over all scenarios that were required for comparison to regulatory standards.

The 1996 WIPP performance assessment was constructed to allow a Monte Carlo approach to the treatment of uncertainty (see Section 17.4), facilitating the relatively rapid calculation of large numbers of realizations. As such, the system-level model represented a compromise between the level of resolution and realism possible through the use of increasingly detailed process models and the computational efficiency needed to run hundreds or thousands of realizations in a reasonable period of time. This compromise appears, in varying forms, in all safety assessments. Computational power has increased through time, but so too has the complexity possible in process models, and, as discussed further in Section 17.6, it appears that safety assessments will always need to rely on system models that are a judicious simplification of the full understanding developed at the level of individual processes. For example, the 2008 Yucca Mountain Total System Performance Assessment (US DOE 2008, Section 2; Helton et al. 2014) relied heavily on the use of response surfaces developed by detailed process models for input to a simplified linkage of abstractions, but even so, the overall system model for the proposed Yucca Mountain repository is significantly more complex than the WIPP model shown in Figure 17-4.

22.3.5 The iterative nature of safety assessments

Early iterations of safety assessments provide information to decision makers regarding the viability of the site and facility design, informing interim decisions regarding the future direction of the program. Preliminary safety assessments can help guide research and design activities by identifying and confirming the safety functions associated with specific features of the disposal system, and by identifying the uncertainties associated with these functions that have the largest impact on confidence in the performance estimates. Sensitivity and uncertainty analyses, in particular, can be powerful tools for focusing research activities on the most important uncertainties, as discussed in the following section.

As site characterization and disposal system design activities progress and safety assessments mature, long-term performance estimates become increasingly suitable for direct comparison to programmatic goals and regulatory standards. Details of the regulatory process differ from nation to nation, but in most programs the safety assessment ultimately becomes a key component of the safety case, informing the final decision to operate the disposal system. As such, final iterations of the safety assessment must meet high standards for both technical excellence and thorough documentation, and must be suitable for review in a legal and regulatory environment.

22.4 Acknowledging uncertainty

Uncertainty is unavoidable in all large-scale environmental protection undertakings, and radioactive waste disposal is no exception. Sources of uncertainty in safety assessments can be categorized and analyzed in various ways, and a full review of uncertainty analysis techniques is beyond the scope of this Chapter. What is important from the perspective of the utility and credibility of the safety assessment is that uncertainty from all sources be openly acknowledged and accounted for in the analysis. Chapman and McCombie (2003) usefully describe four primary types of uncertainty: system uncertainty associated with incomplete characterization of the disposal system; scenario uncertainty associated with the comprehensiveness of the scenarios chosen for analysis; model uncertainty associated with the choice of conceptual and computational models used to represent the behavior of the system; and parameter uncertainty associated with incomplete knowledge of the specific parameter values used to characterize material properties used as inputs to models.

As described in detail in Chapter 18 of this volume, uncertainties can also usefully be categorized consistent with their intrinsic properties and treatment in the models. Thus, it can be helpful in designing a safety assessment to distinguish between aleatory uncertainties, which in general derive from uncertainty about the occurrence of future events, and epistemic uncertainties, which derive from incomplete knowledge about the physical properties of the system. Aleatory uncertainties can be thought of as irreducible; for example, no amount of additional research will provide a definitive answer about whether or not an earthquake will occur on a given date in the far future. Epistemic uncertainties, on the other hand, can be thought of as reducible. In principle, a more complete characterization of rock properties could be collected at any given site through additional drilling and testing programs. In practice, however, a significant amount of epistemic uncertainty will remain even in a mature safety assessment. It is simply not practical to reduce epistemic uncertainties indefinitely, nor is it necessary if a safety assessment that takes uncertainty into account shows performance to be acceptable.

17.4.1 Using probabilistic and deterministic approaches to account for uncertainty

Options for accounting for uncertainty in safety assessments broadly fall into two types: safety assessments may choose to use a probabilistic uncertainty analysis to display a range of outcomes consistent with uncertainty in model inputs, or they may choose to bound uncertainty with conservative choices for selected inputs. Probabilistic uncertainty analyses have numerous advantages: they provide sensitivity analysis results that can help guide research programs; they provide decision makers with an unbiased estimate of a measure of the central tendency of estimates of future performance (i.e., mean or median), as well as a display of uncertainty about that measure; and, importantly, they help guard against unintended nonconservatisms that can enter into a system analysis when choices believed to be conservative at a subsystem level result in unforeseen consequences at the system level as models are coupled together. It can be difficult to make confident *a priori* assertions that certain conditions will always result in poorer performance and greater radionuclide releases; for example, higher rates of water flow through a disposal vault may cause greater mobilization and transport of radionuclides, but they may also result in a cooler environment with less aggressive water chemistry, and could, under some circumstances, prolong the life expectancy of engineered materials. Using an uncertainty analysis in which a range of flow rates are considered allows analysts, and ultimately decision makers, to confirm the relative importance of specific uncertainties. Some regulators, including the US EPA (2008) and US NRC (2009), specifically call for probabilistic uncertainty analyses in the safety assessment that supports licensing, emphasizing that the safety assessment should focus on a reasonable expectation of what may actually occur.

Deterministic bounding approaches to uncertainty also offer advantages, both in allowing significant simplifications in the analysis and in increasing confidence and public acceptance regarding the safety of the proposed system, and many regulatory programs encourage the use of conservatism (e.g., NEA 2004b, NEA 2007). Bounding approaches have drawbacks, however, in that they may obscure understanding of how the system is believed to function, and they greatly complicate the design of sensitivity analyses that can help guide the program. Bounding approaches that combine and compound conservative assumptions have the potential to decrease public acceptance of repositories by causing performance to appear worse, and perhaps much worse, than it will actually be. These observations notwithstanding, conservatism has a role even in fully probabilistic assessments, allowing the implementer to develop simplified screening justifications for potentially complex FEPs, or to forgo potentially costly research or modeling programs that would have little or no impact on performance. Consider for example, the assumption made in the 1996 WIPP performance assessment (US DOE 1996) that radionuclides will transport without retardation in interbeds within the host salt formation. Even without accounting for retardation processes, these units did not provide a significant release pathway, and there was no need for an experimental program to support a reactive transport model. In other cases, conservatism may allow the implementer to simplify the treatment of difficult or intractable technical issues in a way that satisfies both the public and the regulator that safety has not been compromised. As the authors of the NEA's *Post-Closure Safety Case for Geological Repositories* (NEA 2004a) note, 'Conservatism is inevitable, and greatly to be preferred to optimism, but should be used and managed judiciously.'

22.4.2 Design of probabilistic safety assessments

Safety assessments have relied on two basic approaches to incorporating uncertainty. In one approach, an analysis can be designed using multiple deterministic scenarios, each representing a different possible state of the system (for example, two separate scenarios might consider the same system with either high- or low-permeability release pathways), and uncertainty can be quantified through the probabilities, or weights, assigned to each scenario. Consequences can be calculated for each scenario, and, if desired, the weighted sum of consequences can then be presented as an estimate of mean performance accounting for uncertainty. Alternatively, safety assessments can rely on Monte Carlo simulation-based techniques, in which values for uncertain parameters are sampled from predetermined distribution functions (appropriately accounting for possible correlations among parameter values) and multiple deterministic simulations are conducted using different sets of sampled values. Each simulation represents a different possible realization of the future state of the system, conditional on the chosen models and the specific set of sampled input values, and, for sampling schemes that do not introduce bias into the weighting, each realization provides an equally likely outcome of the model. The mean of the outcomes provides an estimate of the mean performance of the system, and the full population of outcomes provides a measure of uncertainty associated with uncertainty in the model inputs.

Figure 17-5 provides a simplistic representation of the choices available between scenario and Monte Carlo approaches. At one endpoint of a continuum of options, a fully-probabilistic analysis could be constructed using a large number of scenarios, with all relevant uncertainty incorporated into the scenario probabilities. At the other extreme, an analysis could be envisioned in which the future is reduced into a single scenario, with a probability of occurring equal to one, and all uncertainty is incorporated through a single large Monte Carlo sampling. Examples exist of safety assessments using approaches close to either endpoint: for example, the Electric Power Research Institute (EPRI) of the United States designed its analysis of the formerly proposed Yucca Mountain repository incorporating all uncertainty through scenarios (EPRI 2005; Apted and Ross 2005; EPRI 2009), and preliminary iterations of the US DOE's Yucca Mountain performance assessment relied on a Monte Carlo sampling for a single scenario for their million-year analyses (US DOE 1998, US DOE 2002).

Most probabilistic assessments have chosen approaches that correspond to intermediate positions on the continuum shown schematically in Figure 17-5, generally defining a relatively small number of scenarios based on the occurrence (or nonoccurrence) of major events, and incorporating uncertainties associated with the ongoing processes that describe the behavior of the system through separate Monte Carlo analyses for each scenario. An advantage of this approach is that it allows a full sampling of uncertainty for consequences associated with rare events, which otherwise might occur only in a small number of realizations of a single-scenario analysis. Extremely rare but potentially consequential events, such as volcanic disruptions, might require millions of Monte Carlo realizations before a sufficient number of random samplings created a stable mean outcome and a useful uncertainty analysis.

22.5 Applications of safety assessment

The primary application of safety assessments can be described broadly as informing decision makers regarding the long-term safety of a proposed disposal system, either with respect to direct comparisons to applicable regulatory standards or in the less formal context of supporting programmatic decisions regarding the viability of the site and conceptual design. Multiple ancillary applications arise during the multi-year development of a disposal program and its supporting R&D activities, reinforcing the value of undertaking safety assessment modeling.

22.5.1 Direct comparison to regulatory standards

Direct comparison of performance estimates to regulatory standards is a fundamental application of safety assessments in those programs for which regulations prescribe compliance with quantitative limits. The presentation of model results must be consistent with applicable regulatory requirements; for example, for regulations that set a total allowable dose limit over all scenarios, performance measures for each scenario must be summed into an appropriate total dose history. For regulations that prescribe separate standards for performance following unexpected disruptions, results must be displayed separately for separate scenarios. For regulations that require identification and evaluation of safety functions associated with individual components of the disposal system, the safety assessment may provide the basis for understanding component performance in the context of the full system. As noted above, the way in which quantitative standards are defined can be a major factor in the design of the safety assessment.

22.5.2 Providing guidance to research and model development

Because the selection and evaluation of mined geological repositories takes years or even decades, there are multiple opportunities for safety assessments to help guide programs for field testing, experimental research, and model development. Systematic identification and screening of potentially relevant FEPs early in a program's history can identify information needs that might otherwise be overlooked. Uncertainty and sensitivity analysis results from early iterations of system-level modeling can provide quantitative confirmation of the uncertainties that contribute most to uncertainty in overall performance. Equally importantly, both FEP screening and early sensitivity analyses can identify technical areas where existing knowledge is sufficient to support decision-making, even though uncertainty remains. If potentially relevant FEPs can be shown to have no impact on performance with bounding analyses, or if uncertainty about parameters that characterize FEPs that are included in the system model can be shown to have acceptably small impacts on overall performance regardless of the magnitude of the uncertainty, limited resources can be focused elsewhere.

Caution is appropriate, however, when using safety assessments to guide scientific programs. Justifications for excluding FEPs from the system model should be revaluated in subsequent iterations to confirm that new information has not changed earlier conclusions. Results of system-level uncertainty and sensitivity analyses should be interpreted with the recognition that conclusions are conditional on the models and parameter values used to characterize uncertainty in the component subsystems. Model results can only reveal sensitivity to uncertainties that were acknowledged and included in the model inputs, and changes to either the models or their inputs may change conclusions about the relative importance of different processes and parameters. Characterizations of uncertainty in models and parameter values should be evaluated and confirmed with each iteration of the safety assessment to ensure that they are consistent with current understanding.

22.5.3 Evaluating design alternatives

Safety assessments can be used to evaluate and compare alternative designs for the engineered components of a disposal system, including the waste form. Early in a disposal program, valuable insights may come from comparisons of multiple alternatives at a conceptual level: for example, what types of canisters will perform best in the estimated range of disposal environments? As design concepts and the safety assessment mature, comparisons of design alternatives can become increasingly specific; for example, safety assessments can evaluate how increasing the thickness of the canister wall will change estimates of long-term performance. The resulting information may be valuable for decision makers considering operational safety and cost as well as long-term performance, helping programs achieve design goals that must meet multiple competing criteria.

As discussed in Section 17.4.1, probabilistic approaches to the treatment of uncertainty have advantages over deterministic bounding approaches in this regard, because they are less likely to introduce conservatisms that may mask the significance of design changes. If overall performance is dominated by conservative assumptions about one aspect of the system, potentially meaningful changes in the performance of other components may be overlooked. Similarly, if no credit is taken in a safety assessment for the long-term performance of an engineered component, the analysis will be unable to distinguish among alternatives that may provide benefit. Analysts should be aware of the possible impacts of conservatisms, and should consider providing comparisons of design alternatives at both subsystem and system levels to provide insight into the extent to which capabilities of components may be masked by other aspects of the safety assessment.

In some cases, the design alternatives under consideration may represent very different disposal concepts, such as comparisons of the performance of a given site for disposal of either spent nuclear fuel or vitrified waste from reprocessing operations (e.g., Andra 2005a). Comparisons among alternatives that fundamentally change the concept or mission of the disposal system can be useful, but analysts should be careful to verify that component models remain appropriate for the altered components and conditions. Assumptions that change the extent to which results are truly comparable (for example, changes in the inventory emplaced in the disposal system) should be clearly stated whenever results are presented. Assumptions that transfer costs and risks to locations away from the disposal site, such as reprocessing of spent fuel, or that result in additional societal benefits, such as the production of additional energy, should be noted, but analysis of their impacts is outside the scope of what is generally included in a safety assessment for geological disposal

Safety assessments may also be called upon to provide probabilistic evaluations of disposal system performance for a range or envelope of possible designs using uncertainty analysis techniques, rather than direct comparisons of alternatives, but the limitations of the available approaches should be understood. Uncertainties associated with choices about design alternatives differ from uncertainties about future behavior of the system in that design uncertainties will no longer exist after the disposal system has been constructed, operated, and decommissioned. Design choices should not, therefore, be generally included in sampling for Monte Carlo uncertainty analyses, and probabilistic safety assessments should not be used as the basis for formal *a priori* arguments that all designs within a specified envelope will result in a mean performance estimate that is in compliance with regulatory criteria. Sampling over ranges of values for a variety of design parameters (or for material properties associated with alternative designs) carries the implicit assumption that any of the sampled values could be chosen for construction and operation of the disposal system. Rigorous evaluations of performance for each combination of design alternatives would require completing separate samplings of all other uncertainties for each combination of design parameters, which is likely to result in an unreasonably complex analysis. In practice, safety assessments can address the desire to evaluate an envelope of possible design choices by focusing on a single preferred design for the primary analysis, and providing a limited set of supplemental analyses on representative alternative designs that are chosen qualitatively to represent reasonable bounds for the desired envelope. The resulting set of analyses can then provide a strong qualitative basis for arguing before disposal system construction begins that there is a wide range of final design specifications that could result in acceptable performance. A final safety assessment based on the final design, once it is known, could then confirm the earlier conclusion.

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22.5.4 Enhancing scientific understanding of the behavior of the system

In meeting their primary goal of evaluating long-term performance, safety assessments fulfill a corollary function that should be acknowledged to be of equal and perhaps greater importance: safety assessments enhance the scientific understanding of the behavior of the system and thereby become a key component of the technical basis for confidence in the safety of a proposed disposal system. Safety assessments are not simply descriptive models of what is already known. Rather, they become research tools for expanding knowledge about how coupled processes interact in the complex natural and engineered environments of the repository. Results of safety assessments should be thoroughly analyzed to verify that they are consistent with basic understanding of the underlying processes, and apparent inconsistencies should be resolved. When approached as an iterative process that emphasizes interpretation, analysis, and explanation, safety assessment is a scientific discipline in its own right, and one that has the potential to provide new insights that go beyond the sum of its parts. Done well, successive iterations of safety assessments build confidence among the technical peer community, both within a disposal program and externally, that project scientists and engineers have a sound understanding of how the proposed system could function in a range of uncertain future conditions.

22.6 Future trends in safety assessment

There is little doubt that scientific understanding of physical processes relevant to disposal system performance will continue to advance, and improvements in computational models and hardware will allow for the possibility of increasingly more realistic simulations at both the subsystem or process and system levels. Safety assessments of the future could be capable of doing much more than those of today, without question. It is not clear, however, if increases in scientific understanding and the corresponding increased complexity will materially improve the usefulness of the safety assessment. Significant uncertainties will always remain about how best to characterize future events and their interactions with complex natural and engineered systems regardless of advances in computational tools, and for many applications models analogous to those that are available today may be entirely adequate for the purpose.

The potential for increasing realism and complexity in future safety assessments will bring with it a potential for increasingly complex documentation, highlighting competing goals of clarity and realism. Both the public and the scientific peer community reasonably expect a safety assessment to be informed by the best available understanding, because confidence comes in part from the knowledge that the assessment has been as comprehensive and realistic as reasonably possible. However, confidence also comes from clear and straightforward statements of how the system works, what matters and what doesn't matter, and why. Comprehensive and complete documentation of complex system-level models, regardless of how well prepared it may be, may not meet expectations of clarity for all audiences, and managers of large safety assessments are likely to find themselves being asked to simplify the system model to focus only on the most important processes. This is a reasonable request, and simplified safety assessment models have clear advantages. They run more rapidly, allowing quick turnaround of analyses considering alternative input assumptions (for example, more or less favorable assumptions about important parameters, or alternative designs for engineered components), and documentation can be far less cumbersome. Simplifications must be made with care, however, because once a process or parameter is removed from a model its importance can no longer be evaluated, and some insights may be lost from consideration.

Choices between realism and simplicity, and between complexity and clarity, are likely to remain open questions in safety assessments of the future because there are sound rationales underlying both goals. Individual radioactive waste management programs will find their own paths, consistent with their own national needs, and resulting safety assessments will likely include both large analyses emphasizing full realism while accepting the burden of complexity and simpler analyses that focus only on the major processes. Regardless of the approaches taken, all safety assessments must address the challenge of building confidence with the technical peer community, with regulators, and with the public.

22.7 Sources for further information

Publications of the NEA, as indicated in the references for this paper, provide one of the best sources of summary information about repository programs internationally, and typically provide excellent citations to primary sources. Chapman and McCombie (2003) provide a good overview of all aspects of radioactive waste disposal, including a clear discussion of the essential elements of safety assessments. Definitive information on regulatory requirements in each nation must come from the individual regulatory agencies; citations are given in this paper for representative examples. The definitive sources for information on safety assessments are in all cases the technical reports prepared by the organizations that performed the assessment. The examples discussed in this report, including the US WIPP Compliance Certification Application (US DOE 1996 with updates in 2004, 2009, and 2014) , the Dossier 2005 in France (ANDRA 2005a,b), US EPRI analyses (EPRI 2005; Apted and Ross 2005, EPRI 2009), the US Yucca Mountain License Application (US DOE 2008), the SR-Site safety assessment in Sweden (SKB 2010), and the 2012 safety assessment supporting the license application for the proposed repository in Finland (Posiva Oy 2012b) are available on the internet, and although each represents a daunting volume of information, there is no simple substitute for reviewing the original documentation.

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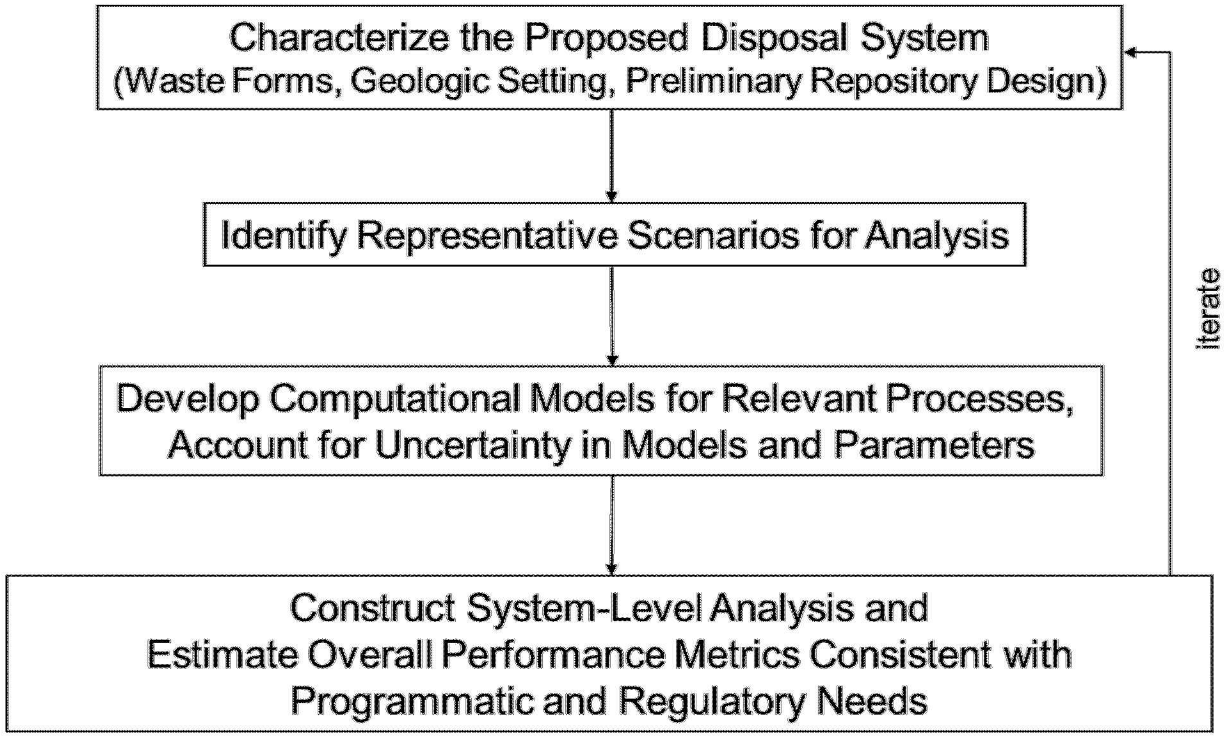

Figure 17-1. Four steps in a typical safety assessment

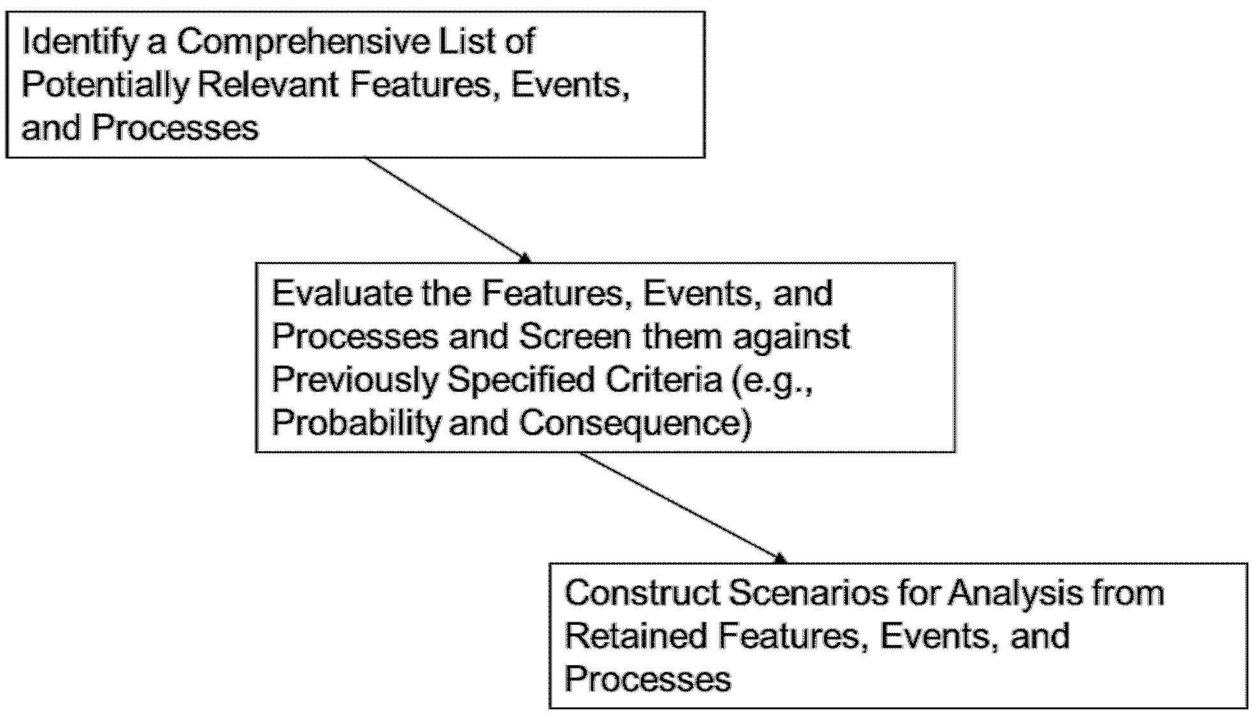

Figure 17-2. Using a Feature, Event, and Process list to develop scenarios for safety assessments

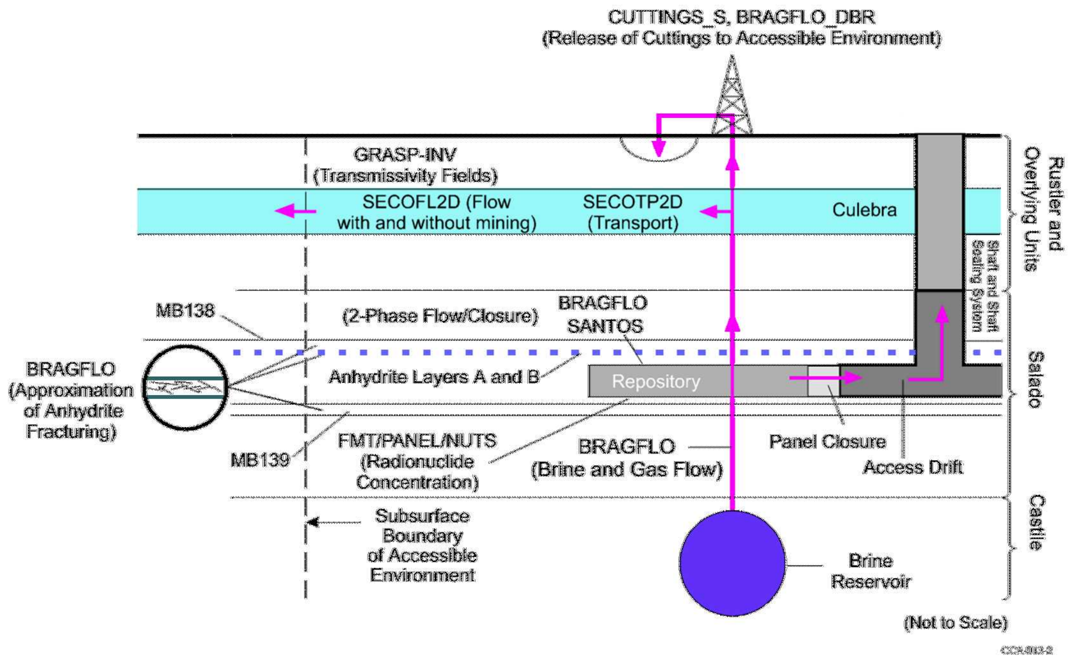

Figure 17-3. Schematic view of the system model for the 1996 Waste Isolation Pilot Plant performance assessment (from US DOE 1996, figure 6-26)

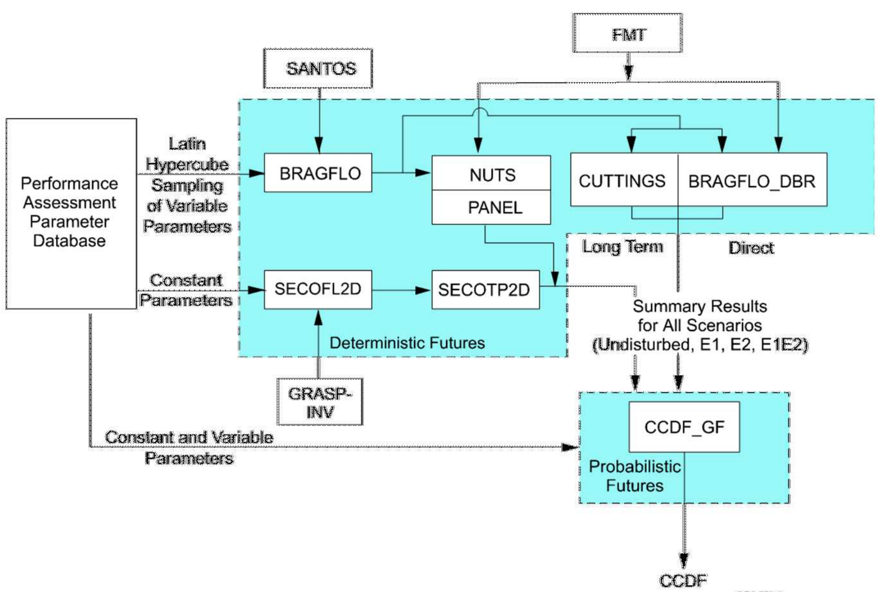

Figure 17-4. Linkage of the major codes in the 1996 Waste Isolation Pilot Plant performance assessment (from US Doe 1996, figure 6-25)

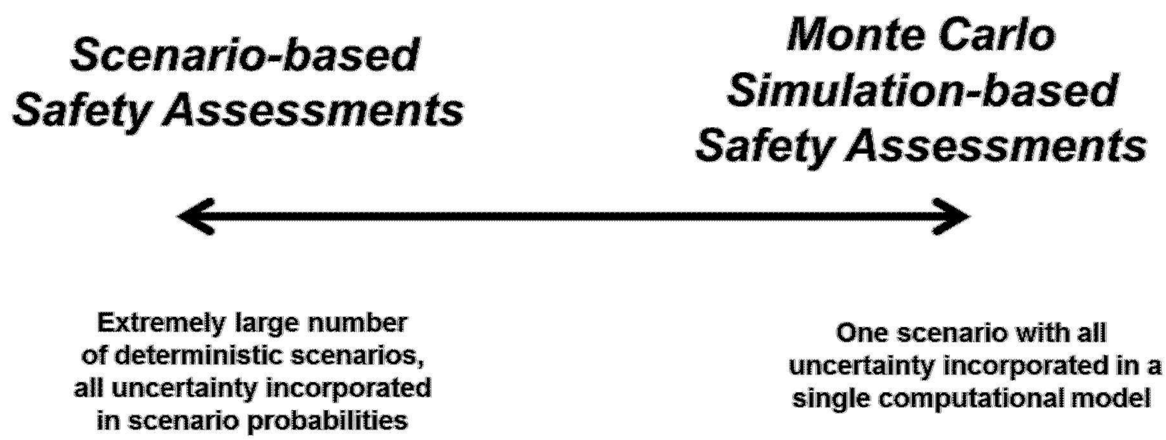

Figure 17-5. Scenarios and Monte Carlo simulation: two endpoint approaches to uncertainty