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Making the Postclosure Safety Case for the Proposed Yucca Mountain Repository
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1.0 Introduction

The International Atomic Energy Agency (IAEA), in its advisory standard for geological repositories promulgated jointly with the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development, explicitly distinguishes between the concepts of a safety case and a safety assessment. As defined in the advisory standard, the safety case is a broader set of arguments that provide confidence and substantiate the formal analyses of system safety made through the process of safety assessment. [1]:

> **Definitions of safety assessment and the safety case**
>
> *Safety assessment is the process of systematically analysing the hazards associated with the facility and the ability of the site and designs to provide the safety functions and meet technical requirements.*
>
> *The safety case is an integration of arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in the safety, of the geological disposal facility.*

Although the IAEA's definitions include both preclosure (i.e., operational) safety and post-closure performance in the overall safety assessment and safety case, the emphasis in here is on long-term performance after waste has been emplaced and the repository has been closed. This distinction between pre- and postclosure aspects of the repository is consistent with the U.S. regulatory framework defined by the U.S. Environmental Protection Agency (Chapter 40 of the Code of Federal Regulations, Part 197, or 40 CFR 197) [2] and implemented by the U.S. Nuclear Regulatory Commission (Chapter 10 of the Code of Federal Regulations, Part 63, or 10 CFR 63) [3]. The separation of the pre- and postclosure safety cases is also consistent with the way in which the U.S. Department of Energy has assigned responsibilities for developing the safety case.

Bechtel SAIC Company is the Management and Operating contractor responsible for the design and operation of the Yucca Mountain facility and is therefore responsible for the preparation of the preclosure aspects of the safety case. Sandia National Laboratories has lead responsibility for scientific work evaluating post-closure performance, and therefore is responsible for developing the post-closure aspects of the safety case. In the context of the IAEA definitions, both preclosure and postclosure safety, including safety assessment and the safety case, will be documented in the license application being prepared for the proposed Yucca Mountain repository, and in the documents that support that license application.

2.0 Organization of the Yucca Mountain License Application

The Yucca Mountain license application now under development is illustrated in terms of its place in a document hierarchy in Figure 1. The license application is the green pyramid-top. In turn it is underlain by plans and reports and data, including over a hundred major documents and literally thousands of supporting documents. Consistent with the expectations of the U.S. Nuclear Regulatory Commission, the case for safety is made in the license application, referring to the supporting scientific and technical documentation as needed.

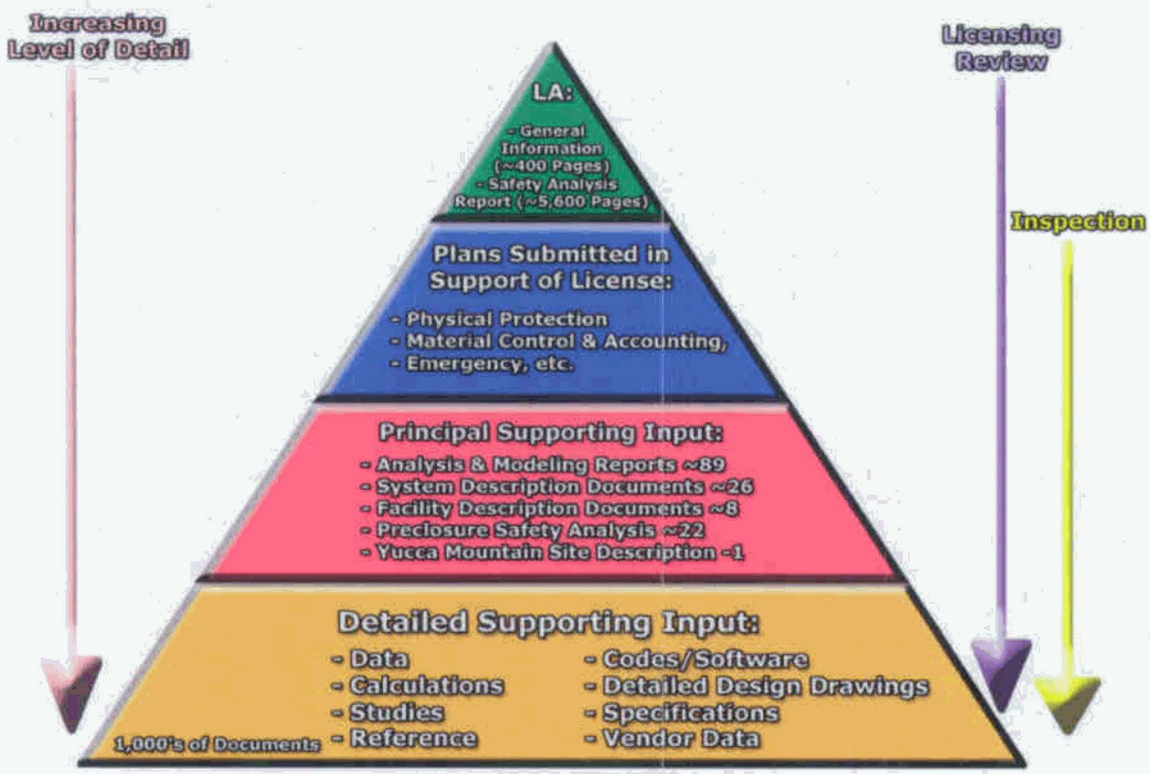

Figure 1, the License Application Document Hierarchy

The license application will consist of two sections, one giving general information, and one giving a report on safety analyses for both the operational and post-closure phases (Table 1):

Table 1. Content of the two major parts of a License Application for the proposed Yucca Mountain repository.

- **General Information (GI)**
    - **General Description**

- **Proposed Schedules for Construction, Receipt and Emplacement of Waste**
    - **Physical Protection Plan**
    - **Material Control and Accounting Program**
    - **Site Characterization**

- **Safety Analysis Report (SAR)**
    - **Repository Safety Before Permanent Closure**
    - **Repository Safety After Permanent Closure**
    - **Research and Development Program to Resolve Safety Questions**
    - **Performance Confirmation Program**
    - **Administrative and Programmatic Requirements**

The safety case consists mainly of the items in Table 1 labeled "Repository Safety Before Permanent Closure," and "Repository Safety After Permanent Closure." Elements of these two sections that contribute to the overall safety case are summarized in Table 2, along with institutional aspects of the program that provide confidence in the implementation of the technical programs.

Table 2. Elements of the Safety Case

- **Preclosure Safety Case (the case for operational safety)**
    - **Preclosure safety analysis - event sequences categorized by frequency**
    - **Safety margin and defense in-depth**
    - **Analysis of Category 1 & 2 event sequences**
    - **Industry precedent and experience**
    - **Technical specifications and surveillance**

- **Postclosure Safety Case (the case for passive safety after final closure)**
    - **Total system performance assessment (TSPA)**
    - **Identification and description of multiple barriers**
    - **Analysis of potentially disruptive events**
    - **Insights from natural analogues**
    - **Performance confirmation**

- **Institutional Assurance (the case for an institutional environment that provides confidence in the technical bases for the safety case**
    - **Quality Assurance**
    - **Safety Conscious Work Environment**

The focus of this paper is on the postclosure case for repository safety.

3.0 Overview of the Technical Basis for Postclosure Performance

The proposed Yucca Mountain repository will be placed into an unsaturated volcanic mountain ridge, about halfway between the surface and the water table (Figure 2). Post-closure safety is dependent on the characteristics of the unsaturated zone through time (e.g., flow and contaminant transport as climates change), on the characteristics of the engineered system within that unsaturated zone (e.g., resistance to corrosion and physical damage and waste form dissolution behavior over time, and stability of the mined openings as seismic activity occurs), and on the characteristics of the saturated zone over time (elevation of water table, flow and contaminant transport to the accessible environment).

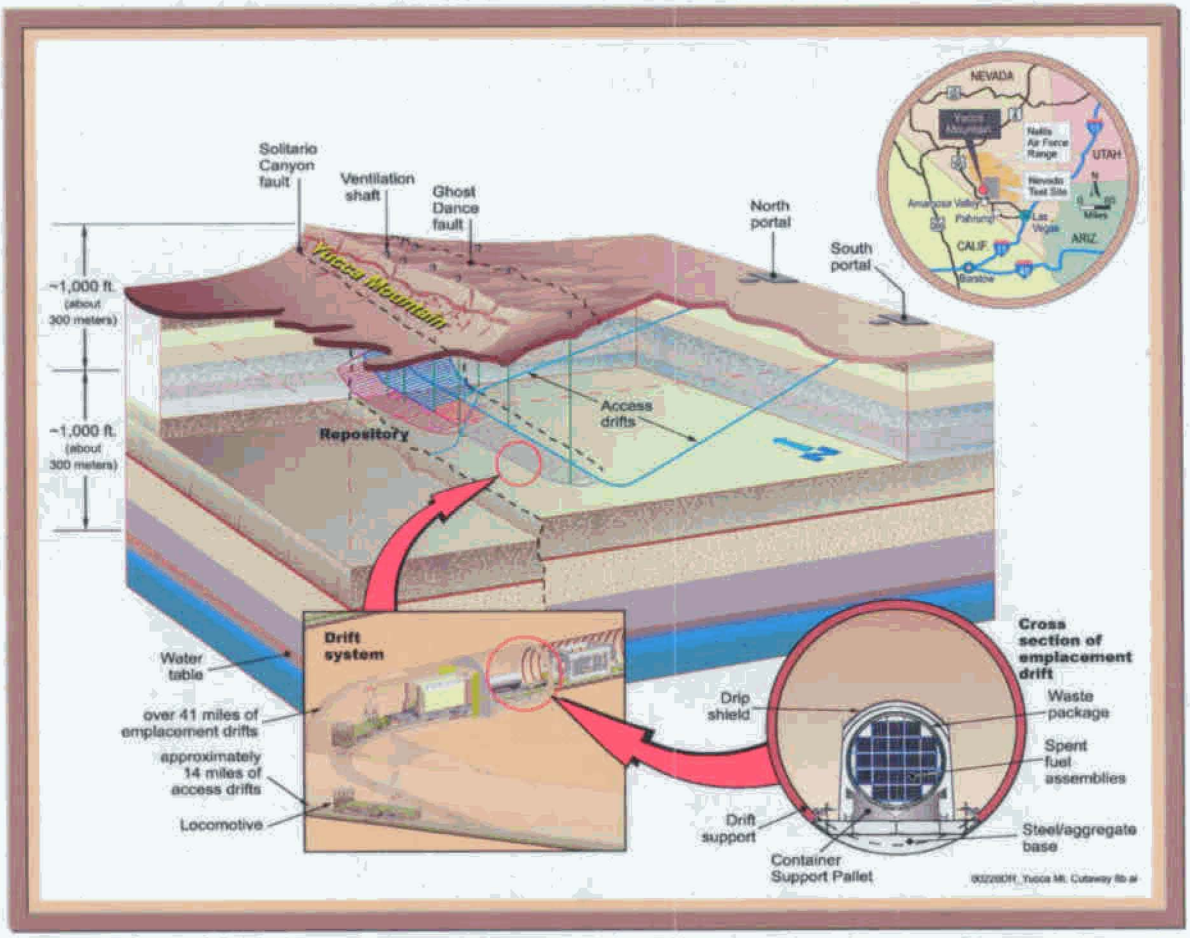

Figure 2. The Proposed Yucca Mountain Repository in its Unsaturated-Zone Setting (inserts illustrate general location, the engineered system in a drift, and a conceptual drawing of the automated emplacement scheme).

The quantitative aspects of the post-closure safety case will be based on computer modeling of the potential evolution of the system over time. These models will account for the uncertainty that is unavoidably present in estimates of the future behavior of natural and engineered systems through a Monte Carlo approach in which multiple simulations will be performed using sampled values of uncertain model inputs. Model results will be displayed as a set of estimates of annual dose to a hypothetical individual, whose lifestyle and characteristics are prescribed by regulation. Results will be shown with a mean, median, 5th and 95th percentile outcome denoted, to provide decision makers with a clear representation of the uncertainty in modeled performance. Figure 3 provides an illustration from a past total-system performance assessment. The multiple grey curves illustrate the uncertainty in the results.

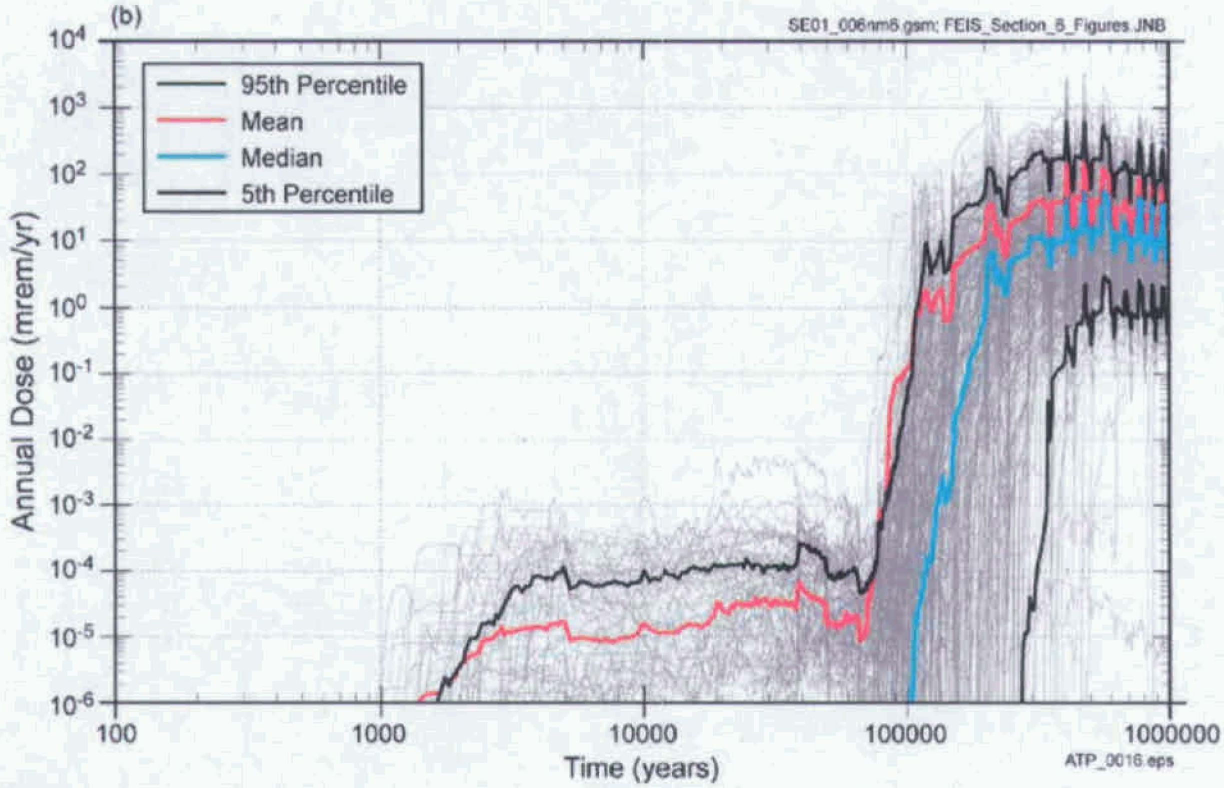

Figure 3, Illustration of Previous [4] Nominal Case Safety Evaluation for the Proposed Yucca Mountain Repository (300 Monte Carlo realizations, no disruptive events, ICRP 30 dose model). As noted in the document in which these results were originally published [4] the absolute value in these outcomes may be divided by 4, approximately, if one uses the internationally accepted ICRP 72 (International Commission on Radiological Protection Publication 72) [5] dose model rather than the older ICRP 30 [6,7,8] model used in these calculations.

A logical question, seeing results of this nature, is why one should have confidence in decisions based on statistics applied to such an uncertain range of outcomes? The answer, in terms of confidence, lies in the observation that decisions can be based on the central tendency (e.g., the mean, median, or other measure) of the distribution, with consideration of the full range of uncertainty. Human decisions invariably must accommodate uncertainty, and sound decisions are best made with full consideration of the range of uncertainty. Choices about what values within the range of uncertainty to emphasize in decision making are fundamentally societal decisions, rather than scientific ones. Although a decision could, in principal, be based on any specified value from the range of outcomes, including extreme outliers, confidence in the reliability of the model results is greatest for values that correspond to stable statistical measures of the full distribution. The U.S. Environmental Protection Agency and the U.S. Nuclear Regulatory Commission acknowledge this observation through their requirements to regulate on the peak of the mean annual dose estimated for the system.

The U.S. National Academy of Sciences provides further support for the use of uncertain model results in decision making. In the context of a report on the conduct of probabilistic seismic hazard assessments [9] the Academy notes that decisions informed by calculations of this nature ought to be based on the central tendency of the distribution of outcomes, and on the robustness of that central tendency as new information becomes available with time. This expectation that the measure of central tendency be shown to be robust as new information becomes available is specifically acknowledged in U.S. Nuclear Regulatory Commission requirements for performance confirmation activities that continue scientific investigations of the repository system after construction and waste emplacement has begun. As required by regulation and as planned by the DOE, performance confirmation activities [10] will be designed to challenge basic data and assumptions underlying the safety assessment, allowing the DOE to confirm (or refute) the technical basis for the post-closure safety case during the operational period.

Additional confidence comes from objective demonstration that the quantitative estimates of performance have been developed following sound scientific processes including thorough analysis, documentation, and review. Relevant to achieving that goal, Table 3 lists representative conditions that will help support the conclusion that the safety evaluation is credible.

Table 3. Conditions that support a finding that a safety evaluation is credible

- **The evaluation draws from a design and scientific data basis that is sufficient to support a meaningful total-system level evaluation**
- **The evaluation uses calculational tools that have been independently reviewed and found to be competent in structure**
- **Analyses that support the evaluation use the input data and exercise the calculational tools competently**
- **The evaluation considers and explains uncertainties and other features of the calculational outcomes to demonstrate knowledge of the system and understanding of its behavior**
- **In all of the above, the evaluation includes consideration of additional lines of evidence:**
    - **Data and information about comparable natural and technological systems**
    - **Comparisons in terms of structure and approach with comparable but independently created calculational tools**
    - **Comparisons with other models applied to the same system, or with the current model applied to different systems with selected analogous features and processes**
    - **Comparisons with, and explanations of differences in, previous analyses of the same system by the same organization, reflecting known changes in calculational tools and in supporting design and scientific data**

Producing and documenting these arguments is a complex and time- and labor-intensive undertaking. Fortunately, for the proposed Yucca Mountain repository effort, there have been two independent safety evaluations with independently developed tools. One organization also performing safety evaluations for a repository at this location is the regulator, the U.S. Nuclear Regulatory Commission (NRC) [11]. Another is the nuclear electric power industry, through its Electric Power Research Institute (EPRI) [12]. Understanding the differences in outcomes between the DOE, NRC and EPRI safety evaluations, in terms of tools, data, and assumptions, is a powerful additional line of evidence for having confidence in the DOE safety evaluations.

Independent technical reviews also can add confidence if properly responded to. Failure to respond to constructive criticism from independent reviewers, including taking substantive corrective actions where appropriate, would not lead to enhanced confidence.

System-level safety evaluations of a potential Yucca Mountain repository have been performed by DOE since the mid to late 1980s [4, for a recent example]. These analyses have been reviewed by NRC as part of a pre-licensing Key Technical Issue (KTI) [13] identification and resolution process. As previously noted, both NRC and EPRI have performed system-level analyses over this same time period [11,12].

All of the above analyses have been reviewed by technical oversight boards (US Nuclear Waste Technical Review Board or NWTRB, and the Advisory Committee on Nuclear Waste or ACNW). The DOE TSPA has been peer reviewed in the past, including by Budnitz, Ewing, Moeller, Payer, Whipple and Witherspoon [14] and by the Organisation for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA) and the International Atomic Energy Agency (IAEA) [15]. Some of the observations from the NEA/IAEA review that provide confidence regarding the reviewed system-level analysis are given in Table 4.

Table 4. Observations and suggestions from the NEA/IAEA (2002) peer review of the DOE Total System Performance Assessment in Support of the Site Recommendation

—. . . the general approach to TSPA, and the USDOE approach of building on an iterative series of performance assessments, conform to international best practice. . . .

—. . . structure of the TSPA-SR methodology, and . . . [the] approach of building on an iterative series of performance assessments, conform to international best practice.

—The structured abstraction process linking process-level models to assessment models is at the forefront of international developments.

—. . . the FEP [Features, Events and Processes] methodology. . . [is] in agreement with international best practice . . .

—. . . places far greater emphasis on probabilistic assessment than equivalent programmes in other countries . .

—. . . does not emphasise natural analogues as much as in some other international studies.

—"While presenting room for improvement, the TSPA-SR methodology is soundly based and has been implemented in a competent manner."

Several critical observations were also made in the NEA/IAEA review, suggesting a need to develop a more comprehensive safety case (the product reviewed was only a safety assessment), and a need to update the regional saturated zone flow model that provided boundary conditions to the site-scale flow (and thus determines radionuclide transport) model.

Natural analogues are generally seen as providing additional, independent lines of evidence for process behavior, and may be particularly useful for evaluating models of processes that span tens of thousands of years and are therefore not amenable to corroboration by direct observation [16]. Among the scientific documents providing a general level of support to the License Application effort is one that provides a synthesis of natural analogue work done and considered in the Yucca Mountain program of work [17]. This document summarizes information that has appeared in many analysis and modeling reports that provide supporting information to process-level models. Each technical document that directly supports the scientific content of the License Application will, where appropriate, cite specific aspects of the analogue work that gives insight, or otherwise supports, the data and assumptions fed into the safety evaluation.

An example of an analogue being studied by both the DOE and the NRC to provide insight, and hence build confidence in the Yucca Mountain safety assessment is the Nopal I uranium ore body and mine in the Sierra Peña Blanca, north of Chihuahua city in Mexico. The Nopal I analogue (Figure 5) is comparable to Yucca Mountain in a number of important ways.

(1) Its UO_2 uranium ore deposit is analogous to spent nuclear fuel
(2) Its fractured, welded, and altered rhyolitic ash flow tuffs overlie carbonate rocks
(3) Its climate is semiarid to arid
(4) Its geochemistry is oxidizing, and has been for more than 3 million years
(5) Its ore lies in the unsaturated zone above the water table.

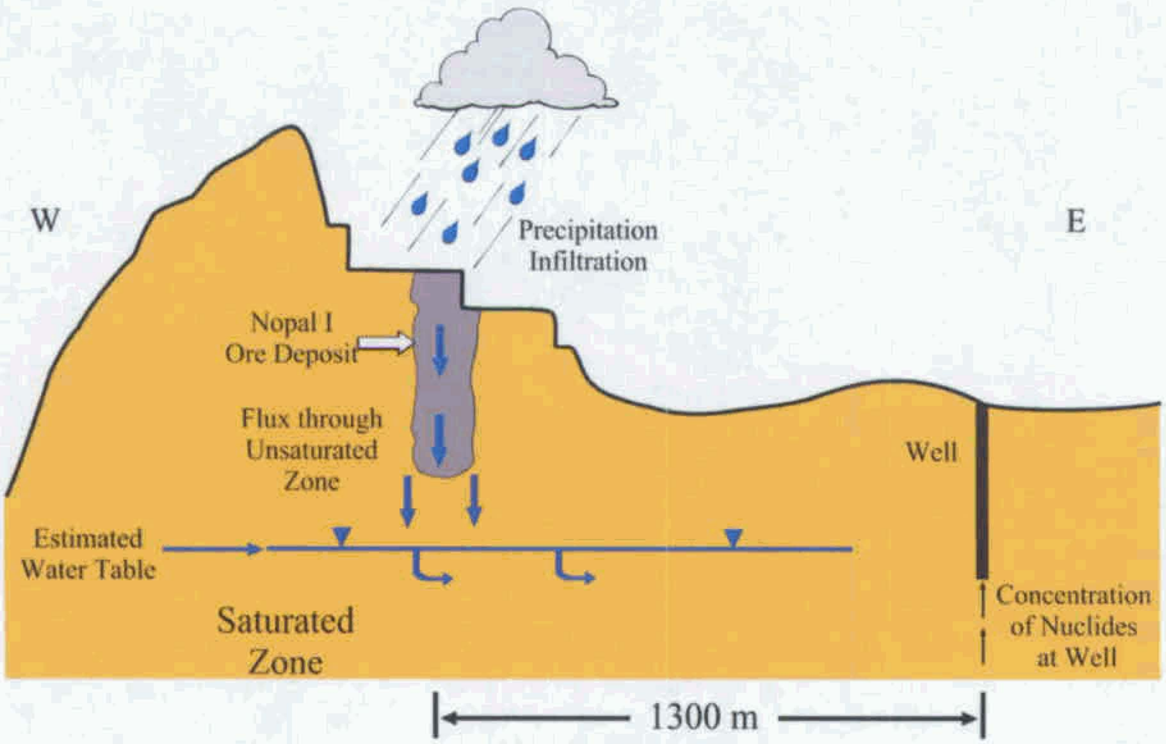
W
E
Precipitation
Infiltration
Nopal I
Ore Deposit
Flux through
Unsaturated
Zone
Well
Estimated
Water Table
Saturated
Zone
Concentration
of Nuclides
at Well
1300 m

Figure 5, Conceptual Model for the Nopal I Uranium Deposit Implemented in the Peña Blanca Natural Analogue Model [18]

The DOE has developed a Peña Blanca Natural Analogue Performance Assessment Model based on and simplified from its Yucca Mountain Total System Performance Assessment model [18]. Results of field investigations and laboratory analyses of rock and water samples from Nopal I were used to calibrate the Peña Blanca Natural Analogue Model, and the model was tested using Monte Carlo simulations of the mobilization and transport of radiouclides from the ore to withdrawal wells downgradient in the saturated zone. Comparisons of model results with data from water samples are encouraging (Figure 6), and additional sampling from an ongoing program of investigations in and around the ore body will help refine the model. The ultimate goal of this work is to lend confidence to the modeling approach being used for the comparable processes at the proposed Yucca Mountain repository.

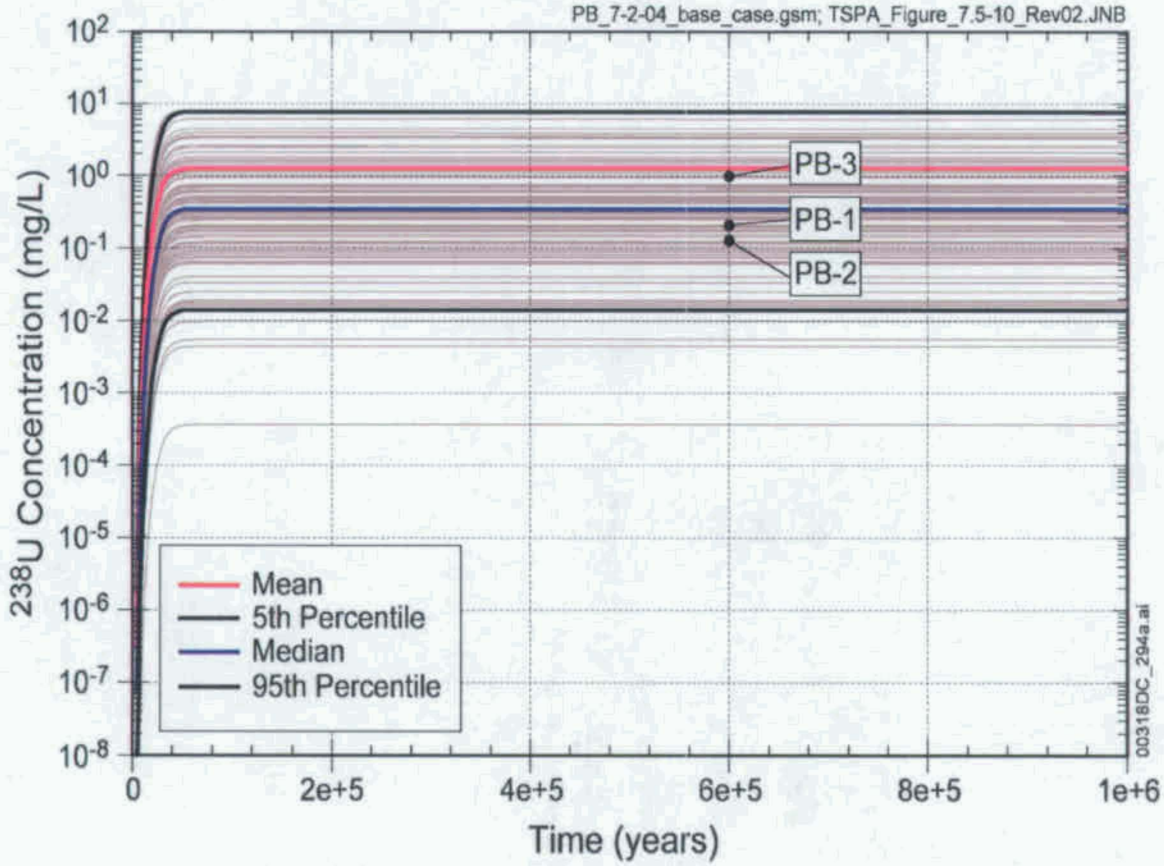

Figure 6. Base-Case Simulation for ^{238}U for 100 Realizations Compared With Observed Concentrations in Three Saturated-Zone Boreholes Near the Nopal I Uranium Deposit [18]

4.0 Conclusions

Does all of the above taken together constitute a safety case? We believe that it does. As in times past, however, the DOE will also create less-technical documents to explain to audiences that are not composed of specialists what the basis is for our asking for a license to construct a repository. These less-technical documents will communicate why we believe there is a basis in our license application for the regulator to find, with sufficient confidence, that there is a reasonable expectation of safety should the DOE be allowed to build this repository.

In the spirit of confirming the stability of the primary performance measure of regulatory interest, scientific work will continue during construction and will inform the license amendment request to allow us to enter the operational phase. Thereafter, scientific work will continue to support any changes in operations or design during the decades that the repository will be loaded with waste. Prior to final closure, all changes in knowledge and design from these previous decades will be used to show that there is sufficient confidence in the passive safety of the system to allow it to be closed and sealed. Even then, however, there will be continued monitoring and protection of the site, using both passive and active means, as long as (future) society deems it necessary.

Finally, it should be noted that an essential component of this safety case, and perhaps of any safety case, is a high level of confidence that there are strong institutional processes in place to ensure that execution of the scientific work and its documentation is sound, and that potential problems with the site are identified and addressed fairly and openly. If there are significant doubts about the quality of the technical work or the openness and fairness with which it is presented, confidence in the safety case will be diminished. The creation and use of an effective Quality Assurance program is vital to ensuring that technical work is sound and correctly documented. Similarly, the creation of an open environment in which those persons most knowledgeable about the project, i.e., the scientists and engineers engaged in evaluating the safety case themselves, are free to raise concerns will help ensure confidence that potential problems are not overlooked. If the proponent and its experts have doubts about system safety, confidence can not legitimately be expected in others. The NRC requires, and the DOE strongly endorses, the creation of a "safety conscious work environment" (SCWE) in which all participants in the project have the right and obligation to raise concerns potentially related to the safety (both operational and long-term) of the facility, without fear of retribution. Demonstrating that such an environment exists and works is a required part of the documentation supporting the License Application. This policy empowers the Yucca Mountain work force, at any level, to voice concerns and even to stop work if there is a legitimate safety issue. The effectiveness of this program adds credibility to the declaration by DOE and its analysts that there is sufficient confidence in the safety case to allow progression to the next phase in the life of this repository project.

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