TECHNICAL ADVANCEMENTS FOR GEOLOGIC DISPOSAL OF HIGH-ACTIVITY WASTE

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This paper is the written version of an invited presentation to the Center for Nuclear Waste Regulatory Analyses (CNWRA) of the Southwest Research Institute. The paper is partly based on a report of the U.S. Nuclear Waste Technical Review Board (NWTRB 2011b) to which the author contributed and presents information and the author's views on technical matters associated with the geologic disposal of high-activity radioactive waste. Included is a brief discussion of the U.S. Nuclear Waste Technical Review Board (NWTRB), its activities and shared views, and highlights of the technical advancements made in geologic disposal. Two vital topics for geologic disposal, the radionuclide source term and probabilistic performance assessment, are covered in some detail. The paper closes with some remarks about the nation moving forward in finding a permanent solution to high-activity nuclear waste management and a summary of research and development opportunities.

U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD

A brief description of the NWTRB is in order because interaction at the technical level between the NWTRB and the CNWRA effectively ceased 3½ years ago when the U.S. Department of Energy (DOE) submitted its application to the U.S. Nuclear Regulatory Commission (NRC) for a license to construct a repository for high-activity waste at Yucca Mountain.

The Board is an independent agency in the Executive Branch. It was created by Congress in the 1987 Amendments to the Nuclear Waste Policy Act (Congress 1987). It is not part of DOE or any other agency. It is its own agency with its own line item in congressional appropriations acts. Its mission is to: (1) evaluate the technical and scientific validity of DOE's actions regarding the management and disposition of high-activity waste, and (2) report its findings, conclusions, and recommendations to Congress and the Secretary of Energy at least twice a year.

The Board has 11 members, who are named by the President from a list of at least two nominees for each position prepared by the National Academy of Sciences. The only criteria for placement on the list are eminence in a field of science or engineering and records of distinguished service. DOE employees, national laboratory employees, or employees of contractors working on high-activity waste management or disposal for DOE may not be nominated. The President designates the chairman. Biographical information about Board members, as well as more information about NWTRB, including all of its work products, reports to Congress and the Secretary of Energy, correspondence, and transcripts, agendas, and presentations from all of its meetings since its inception, is on the NWTRB website, www.nwtrb.gov.

[1] The views in this paper are those of the author and not necessarily the author's affiliations.

RECENT NWTRB ACTIVITIES

DOE submitted its license application for the proposed Yucca Mountain high-activity waste repository to NRC in June 2008; national elections were held in November of that year; and the new Administration was inaugurated on January 20, 2009. In March 2009, Secretary of Energy Steven Chu announced that the proposed repository site at Yucca Mountain was "no longer an option" and filed a motion with NRC a year later to withdraw the license application. If DOE is successful with its motion—a matter that has exhausted the administrative law process within NRC and is now in the hands of the U.S. Court of Appeals for the D.C. Circuit—not only would commercial spent fuel not have a specific final disposition path, but also DOE-owned spent fuel and high-level waste no longer would have a designated location for final disposal. In a planning meeting held just a few weeks after the Secretary's March 2009 announcement, members of the NWTRB decided to visit DOE sites caretaking significant amounts of spent fuel or high-level waste to determine how they were planning to manage those wastes for the long term and the technical bases for those plans. Accordingly, the Board visited the DOE Hanford site near Richland, Washington, in July 2009; the Savannah River Site near Aiken, South Carolina, in March 2010; the Idaho National Laboratory site near Idaho Falls, in July 2010; and finally the West Valley site in April of this year. (The West Valley site technically is a New York State site, not a DOE site, but New York has made the core portion of the site available to DOE since 1981 for DOE to carry out the West Valley Demonstration Project.) The findings from these visits form the basis for a report now in preparation with a forecasted issue date of early next year.

Several other major projects were initiated at the March 2009 planning meeting. In the fall of 2009 the NWTRB issued a survey report on waste management approaches in countries around the world (NWTRB 2009). The work to produce that report had already been underway before the planning meeting. Work continued on an extension of that report, and the extension was published in April of this year (NWTRB 2011a). In June of 2011, the NWTRB published what some refer to as a "lessons learned" report from the Yucca Mountain project (NWTRB 2011b). Its full title is: *Technical Advancements and Issues Associated with the Permanent Disposal of High-Activity Wastes: Lessons Learned from Yucca Mountain and Other Program*s. The purpose of this report is to bring out the lessons learned from Yucca Mountain, good and bad, that might be applicable to future U.S. repository programs. Some of the material and many of the thoughts in that report are used directly in later sections of this paper.

In another effort triggered by decisions at the NWTRB March 2009 planning meeting, work began in April 2009 on a personal-computer based systems analysis tool called NUWASTE[2] that can be used for evaluating the effects on nuclear waste management of various nuclear fuel-cycle approaches. The NWTRB issued a 12-page technical note on NUWASTE in April 2011 and a full report in June 2011 (NWTRB 2011c). Another project that began after the planning meeting was a study of technical needs for long term storage and transportation of commercial spent nuclear fuel. The NWTRB published a large report on that topic in December 2010 (NWTRB 2010).

[2] Nuclear Waste Assessment System for Technical Evaluation (NUWASTE)

SHARED VIEWS WITH THE NWTRB

Three fundamental views of the author follow. These views are shared by the members of the NWTRB and, it is believed, by the world technical community involved with the management and disposition of high-activity waste.

1. Geologic disposal is necessary regardless of the fuel cycle ultimately chosen.

It does not appear that current technology or technology likely to be developed in the near future could preclude the need to develop *some* geologic disposal capability. Technology does exist that would decrease the burden on geologic disposal, i.e., that would reduce the volume of high-activity waste requiring geologic disposal or its radiotoxicity, but such technology does not appear to be economic for new facilities.

2. There is international consensus in the technical community that geologic disposal is feasible.

Given the right conditions, there is widespread agreement that geologic disposal can isolate high-activity waste from the human environment for many millennia—as long as it takes. Furthermore, it appears that there are many locations and many geologic media—including clay, shale, salt, tuff, and crystalline rock—that can do the job.

3. Public apprehension about geologic disposal and transportation of high-activity waste is high and must be addressed.

Interestingly, this apprehension is not necessarily strongest in the communities that would host geologic repositories, but in the regions and states in which these communities exist. Both Nye County, which would host the Yucca Mountain repository, and Carlsbad, New Mexico, which hosts the Waste Isolation Pilot Plant (WIPP) repository for the disposal of transuranic waste, want sufficient assurance that the respective repositories are safe, but otherwise appear to welcome them. The states that house or would house the repositories do not seem to have the same expansive view.

HIGHLIGHTS OF TECHNICAL ADVANCEMENTS

Over several decades and especially the last two, there have been major advancements in the feasibility of a geologic repository as a permanent solution for the disposal of high-activity waste. The United States together with many other nations have been very active in carrying out research and development to establish a technical basis for deploying deep underground high activity waste repositories (NWTRB 2009, 2011a). Until the Administration decided to terminate it, the proposed Yucca Mountain project had advanced the furthest of any program and had developed sufficient technical information to submit a license application, which DOE has since filed to withdraw. Thus, it is the Yucca Mountain project that provides the primary source of material for highlighting the advancements that have been made although consideration is given to the international experience and current DOE activities as well.

The success of geologic disposal depends on: (1) the isolation of waste from mobilization by water for very long periods and the choice of a site with extremely low probabilities for disruptive events and processes, such as erosion and volcanism; (2) the integrity of the engineered barriers and waste form; (3) dissolution and mobilization mechanisms within the engineered barriers and waste form; (4) transport, retardation, and sequestering processes in the natural system; and (5) biological uptake. Three categories of radioactive species tend to be the principal drivers in the performance of a geologic disposal facility: (1) ^{90}Sr and ^{137}Cs (not a long-term health threat, but the dominant heat threat for the first hundred years after irradiation); (2) ^{99}Tc and ^{129}I (very long lived, abundant in the inventory, water-soluble, and migratory); and (3) the actinides of uranium, plutonium, neptunium, and americium (many of which are long lived).

Among the advances made by the Yucca Mountain program were a greater fundamental understanding of water flow in unsaturated fractured rock in arid regions; models to account for runoff, evaporation, and plant transpiration; a better understanding of the effect of capillary forces and other parameters; mapping techniques for locating faults and past volcanic activity; greatly improved understanding of seismic and igneous hazards; improved state-of-the-art expert elicitation methods; and alternatives for controlling the temperatures in the repository.

From a technical perspective, capturing in a transparent and accessible form the advances in modeling that were made on the Yucca Mountain project would be extremely important to avoid repeating mistakes and wasting time replicating results that already exist. Examples are site characterization studies that best support the performance assessment, compatibility of the component parts of the waste management system, and consistency of application of safety analyses among the different activities.

The Yucca Mountain project demonstrated the importance of engineered barriers for delaying dependence on the waste-isolation capabilities of the natural system for extended periods. The advantage of engineered barriers is that in general there is less uncertainty in an engineered system designed to a detailed specification and built to exacting standards than a natural system with inherent heterogeneities difficult to fully characterize over many cubic kilometers of geology. There is increasing evidence that engineered barriers can be designed and constructed to last for very long periods, possibly hundreds of thousands of years. Such a delay dramatically reduces the radiotoxicity of the waste and simplifies the chemistry of the waste that might enter the natural system, thus enhancing the predictability of the long-term performance of a repository.

The key to modeling the degradation of engineered barriers is a fundamental understanding of the engineered barrier environment as a function of very long time periods. Research is needed on how best to obtain such information. Also research is needed for developing prototype testing of such barriers to produce data that increases confidence in their long term performance. While such studies only have real meaning on a site-specific basis, it is possible to identify the steps and processes needed to develop confidence in engineered barrier performance.

The radionuclide source term may be the most important contributor to performance of a geologic repository. However, its contribution to performance may be the most difficult to quantify. This author believes that quantification of the contribution of the radionuclide source term to performance is the weakest aspect in all nuclear waste performance assessments to date; thus it is covered in more detail in the next section. Also covered in the next section is the Yucca Mountain Total System Performance Assessment for the License Application (TSPA-LA) that was included in DOE's application submitted to the NRC.

It is considered important to make a few observations about the management process and how it impacted the technical activities of the Yucca Mountain project. It is clear that there are sometimes certain inherent characteristics of a federal-government-run project that make it more vulnerable to unsettling events than might be the case for a project run by a private organization. Examples are the federal budgeting process and its link to the ever-changing political process and the desire to spread the work among many different organizations geographically separated and not always happy to work with each other. Such constraints don't always translate into a tight and superbly dedicated "skunk works" type project team, which is clearly needed for a project as complex as a multibillion dollar nuclear waste management system. But probably the most disruptive characteristic of the Yucca Mountain project was its inability to effectively transition in a reasonable period from a science project to an engineering project.[3] To be sure science work had to be an integral part of the project throughout its duration. But it is this author's opinion that the absence of a strong engineering culture and a truly engineering based project structure greatly handicapped the decision making process, the efficient movement of the project forward, and the implementation of best practices in engineering for meeting project goals. It is believed that this contributed to some of the difficulties of the project.

There have been, of course, large and complex government-run projects, for example the Manhattan Project, the Apollo program, and the nuclear navy program. A great deal of problem-solving "national will" was behind those projects. Whether the same is true for the solving of the nuclear waste management problem is not obvious.

With the Yucca Mountain program now effectively terminated, there has been renewed interest in the consideration of alternative solutions to permanent disposal. In that regard, the issue of specialized versus general purpose repositories is being studied and discussed. One scenario is the possible use of very deep bore holes (3 to 5 kilometers) for waste not expected to have current or future value and mined retrievable repositories for spent fuel. Clearly there is need for more research and development on the tradeoffs, especially with respect to the technical and economic requirements.

From an international perspective, there is increasing evidence that suitable geology for a high-activity waste repository is not limited to any single medium. Experience indicates many geologic options, including intrusive or extrusive igneous rocks (e.g., granite or tuff) and sedimentary rocks (e.g., salt and clay) are suitable. DOE's current research and development

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[3] The transition was finally made while Ward Sproat was Director of DOE's Office of Civilian Radioactive Waste Management (May 2006-January 2009).

program has plans to document the advantages and disadvantages of different geologic media in its Used Fuel Disposition Campaign, discussed later.

NWTRB reviews of the Yucca Mountain work make it clear that research is needed to better predict the emplacement environment for long time periods. Knowing the physical and geochemical conditions in the emplacement environment is critical to model waste degradation and mobilization confidently. Factoring such detail into the choice among geologic media could alter the priorities on which medium to favor. How much DOE intends to consider the effect of the mix of engineered barriers, waste packages, waste forms, and geologic media on the evolution of the emplacement environment in its research program is unclear. There is more on the requirements and reasons for researching the emplacement environment in the next section.

At the international level there continues to be some research on the impact of a partitioning and transmutation (P&T) program on geologic disposal. At present in the United States there is little more than academic interest in P&T because studies by such entities as the National Research Council and the Swedish Nuclear Fuel and Waste Management Company (National Research Council 1996; SKB 2004) appear to indicate lack of technology or economic incentive to deploy P&T in the near or medium term. The primary need is cost-benefit assessment of partitioning and transmutation of selected radionuclides as a function of different nuclear power plant scenarios. The scenarios should be considered on the basis of the best available technical information and realistic cost projections should be made, preferably in a probabilistic format to communicate the uncertainties involved and the quality of the supporting information. The studies should be of sufficient depth to provide a realistic basis for scoping a research and development (R&D) program that serves as an aid in decision making about future waste management activities.

The Nuclear Energy office within the Department of Energy (DOE-NE) is implementing an R&D program on high activity waste disposal options. The program is under the general banner of the DOE-NE Used Fuel Disposition Campaign. The roadmap for the program considers such factors as the draft recommendations of the Blue Ribbon Commission (BRC) for America's Nuclear Future (BRC 2011), the history of disposal R&D, a ranking of issues based on a DOE systems scoring and weighting process, and an overall conclusion for moving forward (DOE 2011). Priorities are grouped into categories such as natural systems and engineered systems. For the natural system R&D, areas that rank high are flow and transport studies in crystalline and shale media, the impact of the excavation disturbed zone for borehole disposal, hydrologic processes for salt media, and chemical and thermal processes for shale media. The highest ranked engineered systems are waste forms, waste package materials, buffer and backfill materials, seal and liner materials, other engineered barrier materials, and the chemical processes in the engineered barrier systems. DOE claims that sufficient information now exists to support a site-screening process in the United States, if a decision is made to begin one.

FOCUSING ON SELECTED ISSUES

The Source Term

This author believes that the most important analysis in the performance assessment of a geologic repository is the quantification of the rate, timing, quantities, form, and species of radionuclides leaving the engineered barrier system and entering the natural system. This is referred to in this paper as the radionuclide source term. The TSPA-LA of the proposed Yucca Mountain repository advanced the modeling of repository performance in many specific areas such as the transport of radionuclides in the unsaturated zone and developed a credible degradation (corrosion) model of the waste packages but did not develop a similarly comprehensive, transparent, and realistic model of the actual mobilization of the waste.

Some features of the source term model were done well, such as taking into account the geochemical environment in establishing the composition of the water that degraded the barriers; quantification of the solubility limits of radionuclides; accounting for some sequestration of radionuclides in the waste package (but not in the invert); and some consideration of the variability and uncertainty of the environment of the emplacement area (near-field). However, the Yucca Mountain source term model in the TSPA-LA did not account for many other features that could have a significant impact. For example, the effect of anthropogenic materials (e.g., the metals of the waste package, the pallet, and the invert) on the waste-form environment was not taken fully into account (BSC 2005: pp. 6-41). Also, no detailed effort was given to quantifying the alteration products of the degradation process and the disposition of the surrounding debris and rock material in terms of their physical and chemical interaction with the waste. Reaction of engineered barrier materials, e.g., waste packages and waste forms, with gas, water, and rocks in the Yucca Mountain environment could produce relatively stable materials with the capacity to sequester some radionuclides for indefinite periods. More accurate characterization of coprecipitation of radionuclides in thermodynamically stable secondary solids could have improved quantitative estimates of repository performance (e.g., Murphy and Grambow 2008). The rate of diffusive transport of radionuclides through waste package alteration materials provides transient retardation of radionuclide migration to the natural environment in performance assessment models (SNL 2008).

Other candidate conservatisms were no corrosion resistance of the stainless-steel waste package inner vessel or the stainless-steel TAD (transportation-aging-disposal) canister; no corrosion resistance of the zircaloy cladding; no plugging of waste package breaches by corrosion products; and no effect due to corrosion products in the invert. The assumed oxidation potential of the engineered barrier environment is also a possible source of conservatism. The presence of abundant reduced material and the ability of corrosion products to limit the access of water and oxygen are likely to cause substantial lowering of the in-package reduction-oxidation potential. For example, despite strong evidence that the presence of large amounts of iron-based waste-package or invert materials significantly reduces the rate of degradation of uranium dioxide or spent fuel by making the local environment less oxidizing (Cui et al., 2009; Ferriss et al., 2009), the effect of these materials on the environment was only partially taken into account (SNL 2007a: Appendix VI). Thus, there was a lack of knowledge of the different chemical and mineral forms of radionuclides released into the natural system to allow quantification of the transport, retardation, and sequestering of radionuclides. Given that the form determines the behavior of radionuclides in the natural system, the TSPA-LA model for the source term introduced considerable uncertainty in the overall results of the performance assessment.

Part of the reason for taking a more simplistic and bounding approach of modeling the source term was the confidence in the performance of the waste package and the drip shield with respect to complying with the federal regulations. The strategy of the project was to provide an engineered barrier system that would delay the mobilization of the waste for tens of thousands of years and possibly even hundreds of thousands of years. A possible motivation for such a strategy is the belief that it is much easier to design an engineered barrier system to a detailed engineering specification than it is to characterize and thus specify with comparable confidence the subsurface of a mountain.

Holdup times of tens or hundreds of thousands of years obviously would greatly simplify the source term to the natural system not only in terms of the inventory and mix of radionuclides but the modeling of their movement in the natural system taking into account sorption, matrix diffusion, dispersion, and dilution, and their ultimate retardation and sequestration. On the other hand, the possibility exists that had a more thorough source term model been developed for mobilizing the waste, the case could have been made for a less complicated engineered barrier system including the possible justification for excluding the drip shield. The result could be major savings in the cost of the repository. To be sure there would be much less uncertainty in the overall performance of the repository.

The question is what additional technical requirements are necessary to quantify the mobilization of the waste and the ultimate radionuclide source term to the natural system. The key to modeling the mobilization of the waste and for that matter the degradation of engineered barriers is a fundamental understanding of the engineered barrier environment as a function of very long time periods and changes of state of the barrier system. By environment is meant both physical and chemical conditions (SNL 2007b). The physical environment involves such phenomena as seepage of liquid water, combined with temperature, relative humidity, and evaporation rate. For example, the Yucca Mountain waste package environment was expected to evolve to high relative humidity, but at different rates, thus affecting the timing of changes in equilibrium brine composition and seepage. The physical environment also includes the potential for rockfall, which could damage the drip shields or waste packages. The chemical environment involves the composition of water and gas in the host rock around the drifts that can enter drift openings; composition of waters within the drift that can further evaporate and form precipitates and salts; the effect of microbial activity on the chemical environment; the effect of engineered materials such as steel; and the chemical environment at the surfaces of the drip shield and waste package. Underground research (including analogs) and laboratory experiments are needed to quantify such environments as a function of long time periods.

Quantification of the source term requires an interdisciplinary approach of numerous chemistry and materials disciplines as well as the engineering issues of what is necessary to understand the performance of the individual barriers. For example, research is needed for developing prototype testing of such barriers to produce data that increases confidence in their long term performance. While such studies are most meaningful on a site-specific basis, it is possible to identify the steps and processes needed to develop confidence in engineered barrier performance.

Probabilistic Performance Assessment

One of the major achievements of the Yucca Mountain project was the TSPA-LA. Its main contribution was putting issues in context for the post closure long-term safety performance of the repository. As noted in the NWTRB report (NWTRB 2011b: p. 49), the "TSPA-LA represented the culmination of the most thorough study of the performance of a geologic repository for high-activity waste ever performed by U.S. scientists and engineers."

Among the greatest challenges to the TSPA-LA was the period of performance that had to be assessed, which was one million years. Models were developed for all the major components of the repository including the engineered barrier system, the hydrogeologic unsaturated and saturated zones, and the biosphere. The models were abstractions from major studies performed on features, events, and processes (FEPs) associated with the repository. The figure-of-merit was a probability-weighted radiological dose to humans. A major effort was made to quantify the contributions to uncertainty by propagating FEP uncertainties through the entire model. The results included the importance ranking of the contributors to the overall dose to humans. While the TSPA-LA had the benefit of the previously prepared performance assessment of WIPP and the probabilistic risk assessments performed on nuclear power plants and other facilities, there were scoping requirements not before encountered with the one million year period of performance being obviously the most outstanding. There were many lessons learned about doing probabilistic performance assessments involving very long term performance requirements from the TSPA-LA.

While the accomplishments are far greater than its deficiencies, this author believes that there are opportunities to better align the TSPA-LA with what is evolving as a general theory of probabilistic risk assessment (Garrick et al., 2008) and thus be able to take greater advantage of the probabilistic risk assessment (PRA) experience base. There are also believed to be ways of presenting results that are better understood than how they were presented in the TSPA-LA. With respect to better alignment with traditional PRA practices, one important difference is that the TSPA-LA was structured to demonstrate compliance with the regulations rather than simply answering the question, what is the risk, a precursor to demonstrating compliance. Thus, the driver becomes compliance requirements rather than necessarily a fundamental understanding of the risk. There is great temptation to bound the problem and move on if the analyst believes that the results are good enough to demonstrate compliance rather than push for a more fundamental understanding of the risk contributors. An example of presenting results for ease of comprehension is to avoid qualified answers such as "probability weighted doses." Generally, the practice in the PRA field is to calculate and display the risk of different consequences, or for the case in point probability versus dose, thus not burying the actual consequence even though the consequence must be linked to its probability of occurrence.

Besides the matter of the methodology, it is important to take full advantage of the PRA thought process in the evolution of a complex project such as a geologic disposal facility for high-activity waste. Indeed in the case of the Yucca Mountain project there were several performance assessment iterations as the project progressed. These were very constructive exercises; each progressive iteration resulted in a more robust and defensible performance assessment. What was not apparent was the feedback from the performance assessments to the project and how performance assessments impacted the actual project activities such as the scope of the site characterization program and the engineering design of the repository. For example, sometimes the links between the site characterization work and the input to the performance assessments and vice versa were difficult to see. A solution to this would be mini-successive performance assessments to guide site characterization in the spirit that if one wants to learn what is needed (data and information) to understand something, try calculating it. In particular, performance assessments were the calculations that could have provided the focus on the scope and depth of the site characterization program, thus iterating between the two would have enhanced the credibility of both. The same idea applies to all phases of the project, including the surface facilities and the underground facilities design.

Suppose we take note of some of the above observations and ask how one would approach performing a probabilistic performance assessment following the emerging general theory of PRA. The approach this author would take is basically the same as has been taken on all manner of complex systems such as nuclear power plants, defense systems, space systems, natural systems, chemical complexes, and other nuclear waste facilities over the past several decades while taking advantage of advancements made in the modeling. While the approach would be basically the same, the boundary conditions and the phenomena involved would of course be different. The elements of an evolving general theory of probabilistic risk assessment are (Garrick et al., 2008: p. 17): "(1) a definition of risk that can serve as a general framework for what we mean by risk and can be applied to any type of risk, (2) a scenario approach that clearly links initial *(initiating events* or *initial conditions*) and final states *(consequences)* with well defined intervening events and processes, (3) the representation of uncertainty by a probability distribution *(the probability of frequency* concept), (4) a definition of probability that measures the credibility of a hypothesis based on the supporting evidence, and (5) the information processing according to Bayes theorem, the fundamental principle governing *inferential reasoning*."

The cornerstone of the general theory is the "set of triplets" definition of risk which has its roots in Garrick (1968) and Kaplan and Garrick (1981). That definition is

$$R = \{<S_i, L_i, X_i>\}_c,$$

where "R" denotes the risk attendant to the system or activity of interest. On the right, S_i denotes the ith risk scenario (a description of something that can go wrong). L_i denotes the likelihood of that scenario happening, and X_i denotes the consequences of that scenario if it does happen. The angle brackets < > enclose the risk triplets, the curly brackets { } are mathspeak for "the set of," and the subscript c denotes "complete," meaning that all, or at least all of the important scenarios, must be included in the set.

In accordance with this “set of triplets” definition of risk, the actual quantification of risk consists of answering the following three questions:

1. What can go wrong? (S_i)
2. How likely is that to happen? (L_i)
3. What are the consequences if it does happen? (X_i)

The first question is answered by describing a structured, organized, and complete set of possible risk scenarios. As above, we denote these scenarios by S_i. The second question requires us to calculate the “likelihoods,” L_i, of each of the scenarios, S_i. Each such likelihood, L_i, is expressed either as a “frequency,” a “probability,” or a “probability of frequency” curve.

The third question is answered by describing the “damage states” or “end states” (denoted X_i) resulting from these risk scenarios. These damage states are also, in general, uncertain. Therefore these uncertainties must also be quantified, as part of the PRA process. Indeed, it is part of the PRA philosophy to quantify all the uncertainties in all the parameters in the risk assessment.

If the system is a high activity waste repository, the approach would be to conceptually model the system in the following manner.

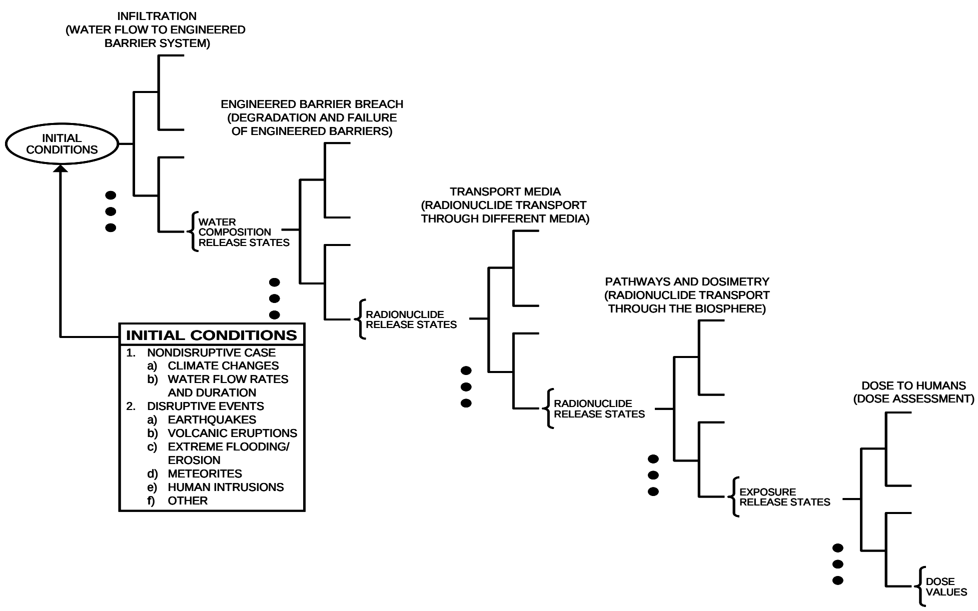

Figure 1. Event Tree for Performance Assessment of a Geologic Repository

Figure 1 is the framework for developing the scenario set for the total system. The scenario set includes the “success” scenario and the “what can go wrong” scenarios. The approach is to linearize the model such that it represents a linear vector space in which case each module can be represented by a matrix. So doing allows for the use of matrix mathematics, which facilitates the assembly of the model and the performance of diagnostics to answer such questions as what is the importance ranking of the scenarios as well as individual inputs and outputs such as initiating events and damage states (Kaplan et al., 1983).

To further test the approach as a general theory, a probabilistic risk assessment was performed on a West Valley, New York, Site Disposal Area (SDA) for nuclear waste (Garrick et al., 2009).[4] The SDA is a pre-10 CFR Part 61 near-surface disposal facility operated and managed by the New York State Energy Research and Development Authority. The measure of risk is the frequency of occurrence of different levels of radiation dose to humans at prescribed locations. The risk from each scenario is determined by (1) the frequency of disruptive events or natural processes that cause a release of radioactive materials from the disposal area; (2) the physical form, quantity, and radionuclide content of the material that is released during each scenario; (3) distribution, dilution, and deposition of the released materials throughout the environment surrounding the disposal area; and (4) public exposure to the distributed material and the accumulated radiation dose from that exposure. The risks of the individual scenarios are assembled into a representation of the total radiation risk from the disposal area. In addition to quantifying the total risk to the public, the analysis ranks the importance of each contributing scenario, which facilitates taking corrective actions and implementing effective risk management.

The SDA PRA added to the many other assessments based on the evolving general theory and provided additional confidence in the generality of the approach. The structured framework of the event trees in this approach provides important transparency of the "what can go wrong" scenarios.

MOVING FORWARD

In many nations the commitment has been made to construct a deep underground geologic facility for the disposal of high level radioactive waste or spent nuclear fuel or both. Finland, France, Sweden, and the United States have all been through the site evaluation and selection process. Finland, France, and Sweden have indicated approximate dates in the 2020 decade for the beginning of operations (NWTRB 2009: p. 10). Underground research laboratories have played an important role in all of the site selections and are necessary to avoid costly surprises when the actual construction begins and to build public confidence. Many other nations have indicated that they are going forward with plans to develop a repository (NWTRB 2009, 2011a). And, as noted earlier, there is an international consensus that deep geological disposal is a feasible approach to the permanent disposal of high-activity radioactive waste.

Moving forward for the United States at present is in a "back to the drawing board" mode following the Administration's decision to withdraw the license application and the funds from the Yucca Mountain program. As discussed in the last section, DOE has developed a roadmap of research and development for the disposition of used fuel including general studies on the

[4] The SDA is a 15-acre shallow land burial radioactive waste site that operated from 1963 to 1975. The SDA received waste from offsite locations and waste generated by the onsite nuclear fuel reprocessing operations.

disposal of all high-activity waste. It is yet to be seen how much of the program will actually engage in significant research and development activities. Meanwhile, the position of this author and the U.S. Nuclear Waste Technical Review Board chaired by this author is that the nation should keep a focus on a permanent solution to the disposal of high-activity waste for the following reasons (NWTRB 2011b: p. 69). "(1) a permanent solution is critical to building public confidence that there is a way of isolating nuclear waste radioactivity from the biosphere to acceptable levels; (2) given the long duration of the hazard of high-activity waste, undue delay in a permanent solution could make tenuous a concept of waste management dependent on institutional stability; (3) experience to date has indicated that deploying a permanent solution to isolating high-activity waste could take decades; and (4) there is an international consensus that a permanent solution to high-activity waste isolation is feasible via geologic disposal. These reasons are believed to be compelling for a focused effort to implement a permanent solution for disposing of high-activity waste."

There are particular actions that should be taken to keep the nation moving forward in finding a permanent solution to the disposal of high activity waste. They include: (1) not allowing the loss of what we have already learned about geologic disposal and developing a deliberate and systematic process for capturing lessons learned into a formal knowledge base; (2) developing a site selection process that is systematic and based on the fundamental concepts of decision analysis while engaging the public in a meaningful and productive way in the process; (3) developing a site characterization process that is interactive and strongly coupled with probabilistic performance assessments of the site to enable a truly risk based foundation of knowledge, including its uncertainties; and (4) developing a transparent roadmap of the phases of a geologic disposal project including decision making points, site characterization, design, licensing, construction, operation, and closure.

As much as we scientists and engineers would like to think to the contrary, experience indicates that solving the technical problems is but a pittance of the issue of moving forward with a viable project of developing a permanent disposal site for high-activity radioactivity waste or any other large public interest project. And while technocrats in a democratic society should not be able to force important societal decisions, there has to be a way to set up major projects that are in the national interest to provide some assurance to the citizenry that their funds are being used for their intended purpose and not wasted by the whims of the political process—a process that allowed some 15 billion dollars of public money (GAO 2011) spent on repository development since 1983 to be potentially wasted.[5] It is clear that there is a need for a decision-making model at the federal level that is compatible with democratic principles while providing assurance that rational thought will prevail in the spending of huge sums of public funds on major projects that are in the national interest. There has to be a much greater consciousness on the part of our decision makers of the conditions surrounding such projects, including the baggage they carry such as for the case of a nuclear waste project the general "fear of anything nuclear." Such

[5] Fiscal 2010 dollars. Expenditures for the period 1983-1987 were for characterizing prospective repository sites in salt in Deaf Smith Texas, in basalt in Hanford, Washington, and in tuff at Yucca Mountain. From 1987 forward, expenditures were only for Yucca Mountain. About 65% of the $15 billion came from the Nuclear Waste Fund, with the balance from general U.S. Treasury funds.

baggage includes an inevitable population group who will be clearly against the project regardless of the circumstances. It seems that there has to be a means for the national interests to be served, at least beyond a certain point in the development of the project. Projects such as a geologic disposal facility span multiple election cycles, and there is a desperate need for a process that is sensitive to such changes, but can provide the legal safeguards necessary to protect public interests and generally avoid political intervention once the project reaches a certain critical point.

Of course, it isn't all a political problem. The scientific and engineering community also has to be conscious of the importance of doing their work in a transparent, competent, and understandable manner to provide the politicians and decision makers with the necessary information to assure the public of the merits of such projects as nuclear waste management systems and that their funds are being appropriately managed. Thus, finding a process that minimizes wasting public funds on major science and engineering projects that end up terminated for political reasons requires extensive interaction of those with the knowledge about the project and those having to lead the way in the decision making process. As demonstrated by the Yucca Mountain project, we don't seem to have an effective framework for doing this.

Finally, it is very clear that there are opportunities to conduct research and analyses that will greatly facilitate the more efficient deployment of any future geologic disposal program. Among such research and analyses opportunities are (1) field and laboratory work as well as improved methods of analyses that will lead to a better definition of near-field environments as a function of very long time periods; (2) development of prototype testing procedures and processes for engineered barrier systems that will provide data for reducing performance uncertainties; (3) definition of processes, models and analyses on how to quantify the radionuclide source term to the natural system; (4) establishment of a science and engineering strategy that will facilitate the integration and interaction of site characterization activities with the site performance assessment; and (5) development of a specification for underground laboratories associated with any proposed site linked to the requirements of the performance assessment.

Of course, there are other research opportunities such as quantifying the impact of emerging technologies on high-activity radioactive waste or the decision to recycle spent nuclear fuel. An example of an emerging technology is partitioning and transmutation. Also there are the merits of alternative or combined methods of deep geologic disposal such as deep boreholes for selected waste forms having no future value and mined repositories for those cases where retrievability is desired. Whatever technical work is done in these areas, there should be an equal emphasis on the economics of implementing any program that might affect the disposition of waste streams as a function of different scenarios of operating nuclear power plants.

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