Natural Analogues and Validation of Performance Assessment Models

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INTRODUCTION

Performance assessment for the geologic disposal of nuclear waste, like many other safety assessment methods for large, complex technologic systems, is a vehicle to describe the safety-related aspects of the system and to evaluate whether the system, in part or in its entirety, meets a specified safety standard. As with many other safety assessments, reliance is placed on mathematical models (based on physicochemical theory, phenomenological data, or both) to predict system performance under a variety of conditions. This reliance on modeling is the usual practice for large, complex systems where proof testing would be too expensive, too difficult, or too dangerous to conduct. Nonetheless the models describing system performance for these complex systems need to be validated and usually are for large, complex technologic systems other than the geologic disposal of nuclear waste. Typically this is done in a piecemeal fashion by proof testing simple systems described by the submodels, which are used in the aggregate to describe the complex system. Given certain difficulties with simultaneity among different submodels and/or feedback among different submodels, this type of piecewise validation generally provides a substantial degree of confidence on the part of the users of the safety assessment, that effective decisions about safety can be made.

For geologic waste isolation systems, validation of system performance models is extremely difficult, both for the overall system performance models and for an individual submodel aimed at describing part of the overall system. The most potent obstacle to validation is that the performance of the system and of its various components takes place on a time scale of 10^3 to 10^6 years; clearly direct observation for the purpose of validation is precluded. For example, in the U.S. the proposed EPA standard (1) requires consideration of overall system performance for a period of 10,000 years after repository closure. The NRC regulation 10 CFR Part 60 (2) requires compliance with the EPA standard for the system as a whole and, in addition, places requirements on system components. Among other requirements the waste package is required to contain the waste for 300 to 1000 years and the site is required to have a groundwater travel time of at least 1000 years. In addition to these time scales set by regulatory requirements, some studies (e.g. 3) of the performance of geologic waste disposal systems, which have been used in part to study the effectiveness of requirements for safe disposal, consider time spans up to 10^7 years. Two other major problems impede the validation of performance assessment models for waste disposal. First, some of the multiple barriers that comprise the waste isolation system are natural and not man made; hence, it is usually not possible to obtain the type of controlled conditions desireable for a validation study. Second, it appears that the significance of various important phenomena changes as the scales of time and distance are varied; consequently, the range of validity of simple scaling laws and simple scaled experiments is limited.

One solution to these problems of direct validation is the use of natural analogues to the geologic waste isolation system. These geologic and archaeologic analogues are configurations similar to the waste isolation system or its components in situations similar to the expected development conditions of a repository. These analogues are essentially unplanned experiments that have been running for hundreds to thousands of years and in some cases longer

than the time scales of interest for a repository. This paper discusses the relation of natural analogues to the validation of performance assessment methods. This is accomplished: (1) by describing performance assessment, including model validation needs, (2) by reviewing previous research on natural analogues and by evaluating the degree to which that work validates performance assessment methods, and (3) by describing the type of research and procedures that appear to have promise for improving the ability of future work on natural analogues to validate peformance assessment methods for waste disposal.

PERFORMANCE ASSESSMENT

The term "performance assessment" was described from a regulatory perspective by the NRC staff in their Draft Site Characterization Analysis report (NUREG-0960, (4)) as "the process of quantitatively evaluating component and system behavior, relative to containment and isolation of radioactive wastes, to support development of a high level waste repository and to determine compliance with the numerical criteria associated with the regulation (10 CFR 60)." Other, less broad definitions of "performance assessment" have been proposed (5); however, this more inclusive meaning of performance assessment will be used in this paper.

A performance assessment can be considered to be a set of sequential steps:

(1) system description: description of the repository and its setting as a waste isolation system

(2) scenario specification: specification, either externally or as part of the assessment procedure, of a set of states of nature (including static and dynamic conditions), usually termed scenarios

(3) consequence estimation: estimation of the response of the waste isolation system to the set of scenarios specified; this always involves estimating one and often several measures of system and/or subsystem performance

(4) uncertainty evaluation: evaluation of the type and extent (qualitatively, if not quantitatively) of the uncertainties inherent in the estimates of system response (consequences)

(5) acceptance evaluation: the estimated measures of system performance of the various scenarios are evaluated individually or collectively, against established safety criteria, considering fully the significance of the uncertainties inherent in these estimates.

Clearly, the performance assessment procedure outlined above culminates in the final step wherein the "bottom-line" question of "Is it safe enough?" is answered, given that additional safety issues beyond the scope of the performance assessment may also need resolution. The inclusion of the fourth step, uncertainty evaluation, may surprise some readers familar with waste management and performance assessment; however, it is included as a separate step to stress its importance and also to express the belief that such an evaluation is always part of the performance assessment, whether recognized and stated explicitly or not. The NRC staff has specifically required that an evaluation of uncertainty be included in the licensing submittal for a repository (6).

This listing of procedural steps is sufficiently inclusive for virtually all types of performance assessment methods, e.g. design basis standard, probabilistic risk assessments, geosphere simulation. For some of these methods, especially risk assessments (7, 8, 9, 10, 11, 12), considerable attention is paid to quantifying the probabilities of scenarios and using probability values to estimate performance measures. This is brought up, since the listing of steps above is not explicit about these additional steps. In order to keep the focus of this paper on applying natural analogue research to validation of performance assessment methods, the description of performance assessment has been intentionally truncated.

Although several performance assessment methodologies (7, 10, 11) incorporate a full suite of consequences models, depending upon the application, or more particularly the performance measure, the consequence modeling may be truncated at any step. For example, assessment of compliance with certain provisions of the NRC high-level waste standard (10 CFR 60) requires, among other things, estimation of the waste form leach rate, the container life, and the groundwater travel time. Assessment of compliance with the proposed EPA standard for high-level waste (40 CFR 191) would require estimation of radionuclide transport to the accessible environment. In neither case would the use of biosphere transport or health effects models be required. However, a set of consequence models more complete than required to measure compliance with a particular standard have been employed to help formulate and assess those requirements (13, 14, 15).

Validation Needs in Performance Assessment

A safety evaluation performed on an engineered system (e.g., a nuclear power plant, a space shuttle) would include most of the broad features of the performance assessment discussed above. For these systems, however, field or laboratory testing could be used to validate the consequence models; furthermore, the key scenarios and failure rates could be observed by life testing the system. For the geologic waste disposal system such validation tests are not possible because: (1) the time span of interest is large and (2) the systems involved are natural systems, for which controlled experiments are difficult. Nevertheless, because natural and man-caused events occurring long ago have observable manifestations now, natural and archaeological analogues may provide a degree of validation for performance assessment. The degree of validation is not expected to be perfect or exact, but these analogues appear to have a significant potential in satisfying the scientific community, regulators, and the general public that the performance assessments

are adequate. The degree of validation will depend upon how well the operative process are identified and how well the natural analogue matches the model to be validated. Challenge to the adequacy of performance assessments are likely to be on the basis of completeness, accuracy, or counter-examples. Studies of natural analogues may help to assure that the quantitiative models used in performance assessment include all the significant phenomena and that all significant disruptive events or other states-of-nature are included in the analysis. The scientific community is likely to be most concerned about the accuracy, completeness, and appropriate use of the quantitative models. Validation of models using natural analogues, presuming that some quantitative models can be so validated, can demonstrate that the models have sufficient accuracy and completeness for their intended use, when applied over time periods and distances similar to those encountered in waste isolation. Prudent study of natural analogues should be able to equip the users of performance assessment with sufficient knowledge so that counter examples will not cast doubt upon a safety assessment, because the counter examples will have either been included in the analysis or omitted, based on substantiated grounds that the example is unimportant.

It is anticipated that the validation provided by natural analogues would apply to either consequence modeling or system-related behavior. The discussion of natural analogue research that follows is therefore subdivided into the following categories:

A. Component Studies

1. Waste Form
2. Engineered Barriers
3. Geological Site

B. System Studies

1. Scenarios
2. Sensitivity and Uncertainty
3. Overall System Performance

Most current and past research on natural analogues appears to fall into the component studies category.

Natural Analogue Research and Performance Assessment Validation

In the following, research on natural analogues is reviewed to determine the degree to which past and current research may be used to validate performance assessment methods. This review is not intended to be comprehensive or exhaustive, but rather representative. This discussion is subdivided into the categories of component and system studies presented above. For convenience the degree of validation provided by a given research effort may be placed into four broad categories:

(1) Process/phenomena identification. The research identifies, for a given set of circumstances, the processes or phenomena which appear to influence the behavior of one or more components of the waste isolation system. The behavior of the component may be qualitatively or semiquantitatively

described and the importance of the processes or phenomena in affecting component behavior may be described qualitatively or semiquantitatively. The use of natural analogues for this purpose has been suggested by others (16).

(2) Parametric quantification. The research quantifies the values of parameters used in performance assessment models. Generally in these natural analogue studies parametric values for use under a certain set of conditions are deduced by adjusting model parameters until the model predictions match observed behavior. Clearly some means other than data matching must be used to attempt to deduce the conditions under which these parametric values are operative. This can be an alternative or adjunct to direct measurement of parametric values.

(3) Component submodel validation. The study of behavior of a component of the waste isolation system is sufficient to validate the performance assessment submodel describing the behavior of that component given that the regime of validation may be limited and the uncertainties of validation may be large. The data demands required for submodel validation are considerably greater than those required for parametric quantification. If one set of data is used to fix parametric values used in performance assessment models, then another set of data, applicable to the same field conditions must be used to determine whether the model predictions agree with field observations. If there is not one more set of data than that required to fix parametric values, then the degrees of freedom in the model equal that of the data and validation is not possible. Additional data sets may be required if the analogue is to (1) fix parametric values, (2) compare model predictions with field data, (3) determine the conditions under which these parametric values apply.

(4) System model validation. A repository-like configuration is studied in sufficient depth so that either (a) the coupled behavior of two or more surrogate components of a waste isolation system validates (as for components) the performance models for those components or (b) behavior of a component, a coupled set of components, or the entire waste management system surrogate validates the probabilistic predictions of the performance assessment methodology. Clearly for the second type of validation a sufficient number of similar structures or events must be observed of a variety of evolving states of nature, so that a comparison to behavior under the various scenarios generated by the performance assessement can be made. An example of the first type would be validation of waste form leaching and radionuclide migration models by studying leaching and migration from ancient glasses or ceramics containing actinides. An example of the second type would be validation of radionuclide migration models by studying transport of species away from a number of similar plutons intruding into the same type of country rock, but at a variety of sites experiencing different climatic, geologic, and hydrologic histories.

Component Studies

Most of the natural analogue studies to date focus on one of the waste isolation barriers, rather than on the entire waste isolation system or partial system comprised of two or more components. Most of these studies appear to be concerned with the identification of the significant phenomena and processes. A few estimate parametric values used in performance assessment modeling.

Waste Form

Most natural analogue research directed toward the waste form component of the waste isolation system appears to be concerned primarily with understanding the phenomena and processes that may be important in waste isolation and with obtaining a qualitative ordering of the importance of various processes. Thus, for example, a study of ancient glass artifacts (17) defines five categories of observed weathering: weeping, crizzling, layer formation, pitting, and crust formation. The type of weathering observed, which appears to depend on the chemical composition of the glass, seems to proceed by leaching of alkalis rather than dissolution of the silica matrix. An important observation is that the same physical mechanism is able to produce more than one type of weathering.

By studying the occurrence and alteration of minerals similar to proposed waste forms, other investigators (18, 19) have identified compatibility of the waste form with the host rock as an important influence on waste form stability. Although these studies are highly suggestive, without thermodynamic and kinetic data, which are currently largely unavailable, the bridge to predictive, quantitative methods is not clear. Another study (20) compares the thermal and chemical stability of waste glasses and naturally occurring volcanic glasses. The study concludes that volcanic glass is more stable because of a higher silica content, yielding a higher formation temperature. Some of the evidence supporting this conclusion was that high temperature caused a phase change in the waste glass, but esentially none in the volcanic glass. Since most volcanic glasses are less than 2 million years old, this age is tentatively adopted as an upper age limit of stable glass.

One study (21), that attempts to quantify the process rates relevant to waste form stability, discusses the hydration of obsidian glass. This study points out that a dating method based on obsidian hydration has been employed in archaeological and geological studies for decades. The hydration rates for obsidian samples from a variety of sources are given for both natural hydration and laboratory tests. The discrepancies between the natural and laboratory rates are not explained (natural rates are usually higher). External variables affecting the hydration process are time and temperature; intrinsic variables most important in determining hydration rate appears to be CaO, TiO_2, and H_2O concentrations in the obsidian.

Engineered Facility

Natural analogue studies of components of the engineered facility include studies related to the waste canister, backfill materials, and shaft sealing materials. A rather comprehensive compendium (22) of the behavior of archaeological objects, metal meteorites, and native metals subject to

corrosive environments of varying intensities provides evidence for metal durability over hundreds to thousand of years. Early human uses of metals included gold, silver, copper, lead, iron, tin, and mercury. Some of these early metallic artifacts have survived to the present. Earliest uses of metal probably began 8000 to 9000 years ago with gold and copper. Clearly gold is the most durable. Metal meteorites are iron-nickel alloys. Weathering of metallic meteorites is variable, depending on the conditions where they fell; but some meteorites estimated to be 5000 to 20,000 years on earth show little weathering. Deposits of native metals such as copper, gold, silver, and mercury, indicate that conditions existed at some time permitting the formation of such deposits. Some deposits appear to have persisted in an unaltered state for at least several millenia. For all three cases (meteorites, native metals, and ancient artifacts) dry or mildly moist environments generally promote greater metal durability. In addition to determining general trends for durability and factors affecting it, this study also discusses the details of corrosion processes obtained by metallographic examination of the objects under study. Also from data obtained from archaelogical specimens, linear corrosion rates over long time spans are estimated for iron and copper based alloys.

A different perspective on naturally occurring metals is used to investigate the use of a backfill in a repository. A study (23) on the formation of natural iron-nickel alloys finds empirical support for the chemical thermodynamic concepts advanced to explain the formation process. From this base of understanding the authors propose that altered ultrabasic rocks, e.g. serpentinite, might provide a superior backfill material for waste cannisters made of iron-nickel alloys, because the formation of such alloys in these rocks demonstrates the thermodynamic stability of the alloys in that environment. A different type of potential backfill material, clay, was studied (24) for possible use in a salt medium. The chemical composition of clay minerals found in evaporite sequences was studied. Rare earth elements are found to remain in the clay minerals, rather than migrating into the surrounding evaporite. It is proposed that clay minerals used as backfill in a salt repository would retard both lanthanides and actinides. In another clay backfill study Brookins (25) considers data from uranium deposits near Grants, New Mexico. This study concludes that clay minerals appear to be a useful overpack material, based on the preferential retention of actinides and lanthanides by these minerals in uranium deposits. These minerals also appear to have the capacity to retain Cs and other fission products.

Samples of ancient (4,400 to 3,000 year old) cement containing building materials are studied (26) in an attempt to identify common factors related to the longevity of the cement. A key factor appears to be low porosity of the hydraulic cement, usually achieved by low water to cement ratios, which reduce workability. Clean, well graded, inert aggregates also appear to promote longevity. These same factors are projected as influencing the longevity of borehole seals.

Site

Natural analogue studies of the repository site have succeeded in identifying certain phenomena influencing the ability of the site to isolate waste as well as determining the numerical values for parameters of models used to describe the site behavior. Thus a study (27) of the migration of elements

from igneous intrusions (pegmatite) into country rocks (amphibolite and quartz-mica schist) shows that some elements (K, Li, Rb, Cs, As, Sb, Zn, Pb) migrated over 40 m, during contact metamorphism. Other elements (rare earths, Al, Sc, Cr, Hf, U, and Th) did not migrate appreciably. The authors proposed that the behavior of these igneous intrusions are analogues of the behavior of a repository over a time scale of thousands to millions of years. A similar study (28) in a different geologic medium considers the alteration of a vitrophyre at Yucca Mt. as a natural analogue of changes anticipated to result from waste emplacement in welded tuff. Anticipated changes include crystallization of glassy rock to zeolites and smectite. Although secondary porosity would increase as glass dissolved, countering this effect would be the partial filling of fractures by newly precipitated minerals. Extensive studies have been conducted of the fossil natural reactor at Oklo, Gabon (29, 30). This is considered to be an important natural analogue, because certain actinides (including transuranics) and other fission products, which are important constituents of reactor waste, have not been discovered in significant quantities elsewhere in the earths crust. One study (31) of the migration behavior of alkali and alkaline earth elements at Oklo concludes that post reaction migration of Rb and Sr from the reactor zones occurs, while Cs appears to be retained for at least 26 million years after cessation of the reaction. A study by Curtis and Gancarz (32) of the mineralogy at Oklo shows that rocks in the reactor zones are significantly altered and that nearby rocks are mineralogically modified compared to normal uranium bearing rocks. The authors attribute these changes to the production of oxidizing and reducing species by the radiolysis of water. Among the study's conclusions are: (1) iron was chemically reduced and accumulated in the reactor zones; (2) U and multivalent fission products were oxidized and transported from the reactor zone; (3) about 10 percent of these mobilized species moved as far as a few meters from the reactor zones; (4) an effective radiation yield of 0.06 molecules of hydrogen per 100 ev of energy imparted to the fluid phase is deduced. For an active reator this study indicates that radiolysis produces significant geochemical, thermal, and groundwater flow effects.

Other natural analogue studies related to site behavior have succeeded not only in determining important processes and phenomena, but also in quantifying parametric values for use in performance assessment models. One study (33) of the migration of naturally occurring radionuclides (^{238}U and ^{232}Th chains) in brine aquifers concludes: (1) Ra does not appear to be retarded by sorption, (2) Th is strongly sorbed, (3) the retardation factor for Th is estimated to be greater than or equal to 40 for these aquifers, and (4) for similar half lives, isotopes of Th and U behave similarly suggesting that uranium remains in the quadravalent oxidation state. Shea studied (34) radionuclide migration, viz. migration of uranium-235 from veins and veinlets, microcracks, secondary minerals sealing microcracks, etc., and concludes that migration over short distance (1-5cm) yields apparent diffusivities of 10^{-19} to $10^{-16} m^2/sec$ in the rock matrix (several orders of magnitude less than laboratory measurements) and K_D values of 1 to 100 m^3/Kg (several orders of magnitude greater than laboratory measurements). Postulated causes for these discrepancies include: (1) more microfracturing in the field, (2) secondary mineral formation in microcracks in the field, (3) differences in temperature and nuclide oxidation state, (4) time dependence of the system process. Another study (35) of elemental (including uranium) migration considered movement of elements from a thin layer deposited during a period of seawater intrusion into lacustrine

sediments. Certain elements deposited during the intrusion were remobilized at rates different from other elements so deposited, during a period of about 10^4 years. Uranium effective dispersivity was estimated to be $1.2 \times 10^{-4} m^2/s$ and K_D was estimated to be 0.4 m^3/Kg. By conducting a series of laboratory experiments on these sediments these investigators found that in most cases it appears that sorption is poorly reversible. Also they conclude, "Simple sorption measurments show little qualitative agreement and no quantitative correlation with the observed profiles [of element concentration vs. distance].". An extensive study by Airey et. al. (36, 37) of radionuclide migration around ore bodies in the Alligator Rivers region of Australia has succeeded in shedding light on the physicochemical processes important to radionuclide migration and in determining values for some parameters used in quantitative models. Some of the significant qualitative findings include: (1) U and Th are associated with iron minerals in the weathered surface of the ore body; (2) Ra concentrates on clay; (3) Ra formed by α-recoil on clay particles has a higher K_D than Ra adsorbed from solution; (4) U appears to migrate mainly in solution, while ^{230}Th appears to migrate signficantly through groundwater colloids. The retardation factor for uranium was estimated to be 250, downgradient from an ore deposit.

System Studies

Because only a few systems studies using natural analogues have been conducted, this discussion is not subdivided as was the previous discussion of component studies. Most of these studies consider the coupled behavior of two or more components of the waste isolation system. For example, one study (38) of an igneous dike intruding into evaporite rocks near the WIPP site is proposed as an analogue to migration from the waste form (a source term model) into a salt host rock (a groundwater transport model). Studies of the chemical composition of the halite and lamprophyre (dike rock) indicate that little migration of heavy metals from the dike into the halite occurred. A rather comprehensive study by Wollenberg et al. (39) investigated element migration from intrusive rocks into a variety of country rocks. Contact zones between quartz monzonite intruding into Precambrian gneiss and Tertiary monzonite intruding into tuff were studied in depth; less detailed study was given to contact zones between a rhyodacite dike cutting into basalt and Kimberlitic dike cutting into bedded salt. Actinides, rare earths, and alkaline earths showed little movement from contact zones in gneiss and tuff. Work on the monzonite intrusion into tuff, reported elsewhere (40), showed that only limited migration (~10m) of the most mobile elements (Cs, Cr, Co) occurred, even in the presence of convective flow. Actinides appear to migrate very little from contact zones in salt and basalt. A similar analogue was proposed based on the study (41) of the migration of Tc, Pb, and Ru around the Oklo natural reactor. All three elements were shown to migrate from the reactor zones into rocks about 10 m away. ^{99}Tc was fractionated from Rn within one million years after the reactor ceased operating. Pb/U fractionation has been occuring throughout the history of the deposit, about two billion years. Lead loss appears to be due to diffusion followed by groundwater transport.

As an analogue of groundwater flow and transport of radionuclides, one study (42) compares field measurements on the migration of naturally occurring ^{14}C, ^{234}U, and ^{238}U to model predictions. This is one of a few studies in which the predictions of an advanced quantitative model (SWENT in this case)

are compared to field data. Because these field data were used to fix model parametric values, satisfactory model validation was not achieved. Nevertheless the ability of the model to match a broad range of data is encouraging. Simulation distance was approximately 100 km and time was 10^5 to 10^6 years. For ^{14}C, $K_D = 0$, while for U, $K_D = 0.006$ m^3/Kg.

Studies (43, 44) of radionuclide migration from the soil through the biosphere at the Moro do Ferro in Brazil have succeeded in identifying significant phenomena and in determing some parametric values used in models. Mobilization rates for Th (considered to be an analogue for quadravalent plutonium) from the ore body into the biosphere is estimated to be $5.9X10^{-7}$ per year for erosion and $7.5X10^{-10}$ per year for groundwater solubilization. Apparently organic acids, especially humic acid, complex with the thorium and help to mobilize it. The presence of naturally occurring radioisotopes in humans was used in another study as a natural analogue to the uptake of radionuclides from waste disposal (45). The overall transfer factors for the processes dispersing radionuclides from a source to human receptors, as obtained from quantitative models of biosphere transport, are compared to natural occurences. In general these models are more optimistic than field measurements would indicate. Discrepancies as high as approximately 10^2 have been observed.

Conclusions and Recommendations

In reviewing these four categories of natural analogue studies, the following conclusions are reached. Most of the natural analogue research has been directed toward and successful in identifying and qualitatively describing the processes and phenomena that are important in natural analogues of components of the waste isolation system or the system as a whole. A few studies are more quantitative and have determined values of parameters used in models of component or system performance. Still fewer studies are sufficiently quantitative and complete to provide validation of performance assessment models. Since performance assessment uses quantitative models, validation of those models must proceed beyond qualitative to quantitative studies. Thus, with a few notable exceptions, the studies of natural analogues have not been as helpful in providing validation of performance assessment methods as the users of such models desire. It is believed that this dissappointment results from a number of technical difficulties, which include the following:

(1) Because naturally occurring events initiated long ago are used to replace the role of experiments in model validation, investigators cannot, as in laboratory or field studies, carefully control the experimental variables, the environmental conditions, the physical configuration, the timing, etc.

(2) The lack of control over variables and environmental conditions is often confounded by an inability to determine what conditions prevaled and what events occurred over geologic time spans in the natural system.

(3) The large heterogenities inherent in many geological systems produces large uncertainties in the knowledge attainable for the system.

(4) Many, if not most, geologic systems are extremely complex, with numerous physical and chemical processes occurring simultaneously; this complexity generally precludes the use of natural analogues to validate a single aspect or regime of modeling at a time, as with laboratory validation.

(5) Because of the complex nature of the interacting processes involved, the state-of-the-art of quantitative models for geologic systems is not as advanced as for certain other sciences and engineering.

(6) Natural analogues are often data poor in the sense that the same data must be used to specify model parameters and to validate the model; without a second independent data set only data matching is achievable.

These problems are formidable, but perhaps are not insurmountable. Although no easy solution appears to be at hand, some of the following suggestions may provide some avenues of relief: (1) natural analogues, that are simpler systems, may provide more useful quantitative data for comparison to predictive models, than more complex systems that are closer to a repository component or configuration; (2) to answer some of the fundamental issues of groundwater flow and transport and how best to model these processes, natural analogues involving species other than those found in nuclear waste may provide very valuable information; (3) for all analogue studies, greater pains taken to attempt to determine the environmental conditions (thermal, chemical, hydraulic, etc.) operative during the period studied would be helpful; the behavior of species unrelated to the waste analogue may provide valuable clues to these conditions, (4) some consideration might be given to collecting data to validate (or not) the scenario formulation and probability determinations inherent in many performance assessments; (5) Natural analogue studies that yield more quantitative data better coordinated with modeling efforts would serve the purpose of validation better.

REFERENCES

1. Environmental Protection Agency, Environment Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High Level and Transuranic Radioactive Wastes, 40 CFR 191 (working draft No. 19), Federal Register, March 19, 1981

2. U.S. Nuclear Regulatory Commission, Disposal of high-level radioactive wastes in geologic repositories, licensing procedures 10 CFR Part 60.

3. Pigford, Thomas. The National Research Council study of the isolation system for geologic disposal of radioactive wastes in Scientific Basis For Nuclear Waste Management, Volume 7, ed. by Ganj L. McVay, North Holland, 1984, New York.

4. U.S. Nuclear Regulatory Commission. Draft site characterization analysis of the site characterization report for the Basalt Waste Isolation Project, March 1983. NUREG-0960, p. 9-1

5. Ross, Benjamin and Michael S. Giuffre. Handbook for users of repository safety analyses. Prepared for Battelle Office of Nuclear Waste Isolation by The Analytical Sciences Corp., April 1981. ONWI-127.

6. U.S. Nuclear Regulatory Commission. Draft Generic Technical Position on Licensing Assessment Methodology for High-Level Waste Geologic Repositories, July, 1984.

7. Cranwell, R. M., et al., Risk methodology for geologic disposal of radioactive waste: Final report December 1982; NUREG-/CR-2452. Prepared for the U. S. Nuclear Regulatory Commission by Sandia National Laboratories.

8. U. S. Department of Energy, Draft Environmental Impact Statement, Management of Commercially Generated Radioactive Waste, April 1979; DOE/EIS-0046-D.

9. Girardi, F., G. de Marsily, J. Weber, "Risk analysis of geological disposal of radioactive waste" in Radioactive Waste Management and Disposal ed. by R. Simon and S. Orlowski, Harwood Academic Pub., 1980, N.Y., pp. 531-551.

10. Girardi, F., et al. "A risk analysis methodology for deep underground radioactive waste repositories and related experimental research" in Underground disposal of radioactive wastes. International Atomic Energy Agency, 1980, Vienna, pp. 407-420.

11. Dove, F. M. et al. AEGIS technology demonstration for a nuclear waste repository in basalt. Pacific Northwest Laboratory, September 1982, Richland, Washington, PNL-3632.

12. Dormuth, K. W. and G. R. Sherman, SYVAC-A computer program for assessment of nuclear fuel waste management systems, incorporating parameter variability. Atomic Energy of Canada Limited, Whiteshell Nuclear Research Establishment; August, 1981; Pinawa, Manitoba, AECL-6804.

13. U.S. Nuclear Regulatory Commission. Staff analysis of public comments on proposed rule 10 CFR Part 60, "Disposal of high-level radioactive wastes in geologic repositories," December 1983. NUREG-0804.

14. Chu, M. S., et al. An assessment of the proposed rule (10 CFR 60) for disposal of high-level radioactive wastes in geologic repositories. Prepared for the U. S. Nuclear Regulatory Commission by Sandia National Laboratories, June 1983. NUREG/CR-3111.

15. Ortiz, N. R., et al. Technical Assistance for regulatory development: review and evaluation of the EPA Standard 40 CFR 191 for disposal of high-level waste. Prepared for the U. S. Nuclear Regulatory Commission by Sandia National Laboratories, April 1983. NUREG/CR-3235 Vols. 1-6.

16. Birchard, G. F. and D. H. Alexander. "Natural analogues--a way to increase confidence in predictions of long term performance of radioactive waste disposal" in Scientific Basis For Nuclear Waste Management, Volume 6, ed. by D. G. Brookins, North Holland, 1983, N.Y., pp. 323-329.

17. Kaplan, Maureen F. "Characterization of weathered glass by analyzing ancient artifacts" in Scientific Basis For Nuclear Waste Management, Volume 2, ed. by Clyde J. M. Northrop, Jr., Plenum Press, 1980, New York, pp. 85-92.

18. Haaker, Richard F. and Rodney C. Ewing, "Natural analogues for crystalline radioactive waste forms, part II: non-actinide phases" in Scientific Basis For Nuclear Waste Management, Volume 3, ed. by John G. Moore, Plenum Press, 1981, New York, pp. 299-306.

19. Haaker, Richard F. and Rodney C. Ewing. "Uranium and Thorium minerals: natural analogues for radioactive waste forms" in Scientific Basis For Nuclear Waste Management, Volume 2, ed. by Clyde J. M. Northrop, Jr., Plenum Press, 1980, New York, pp. 281-288.

20. Malow, Gunter and Rodney C. Ewing. "Nuclear waste glasses and volcanic glasses: A comparison of their stabilities" in Scientific Basis For Nuclear Waste Management, Volume 3, ed. by John G. Moore, Plenum Press, 1981, New York, pp. 315-322.

21. Ericson, J. E., "Durability of rhyolitic obsidian glass inferred from hydration dating research," in Scientific Basis For Nuclear Waste Management, Volume 3, ed. by John G. Moore, Plenum Press, 1981, New York, pp. 283-320.

22. Johnson, A. B., Jr., and B. Francis. Durability of metals from archaeological objects, metal meteorites, and native metals. Pacific Northwest Laboratory, January 1980. PNL-3198.

23. Apps, John A. and Neville, G. W. Cook. "Backfill barriers; the use of engineered barriers based on geologic materials to assure isolation of radioactive wastes in a repository" in Scientific Basis For Nuclear Waste Management, Volume 3, ed. by John G. Moore, Plenum Press, 1981, New York, pp. 291-298.

24. Register, J. K., et al. "Clay mineral-brine interactions during evaporite diagenesis: lanthanide distribution in WIPP Samples" in Scientific Basis For Nuclear Waste Management, Volume 2, ed. by Clyde J. M. Northrop, Jr., Plenum Press, 1980, New York, pp. 445-452.

25. Brookins, D. G. "Clay minerals suitable for overpack in waste repositories: evidenced from uranium deposits" in Scientific Basis For Nuclear Waste Management, Volume 2, ed. by John G. Moore, Plenum Press, 1981, New York, pp. 427-435.

26. Langton, Christine A., and Della M. Roy. "Longevity of borehole and shaft sealing materials: characterization of ancient cement based building materials " in Scientific Basis For Nuclear Waste Management, Volume 7, ed. by Ganj L: McVay, North Holland, 1984, New York. pp. 543-549.

27. Laul, J. C., et al. "Chemical migration by contact metamorphism between pegmatite and country rocks; natural analogues for radionuclide migration" in Scientific Basis For Nuclear Waste Management, Volume 7, ed. by Ganj L. McVay, North Holland, 1984, New York, pp. 951-958.

28. Levy, Schon S. "Studies of altered vitroplyre for the prediction of nuclear waste repository-induced thermal alteration at Yucca Mountain, Nevada" in Scientific Basis For Nuclear Waste Management, Volume 7, ed. by Ganj L. McVay, North Holland, 1984, New York, pp. 959-966.

29. International Atomic Energy Agency, The Oklo Phenomenon, proceedings of a symposium held in Libreville, Gabon, June 23-27, 1975, Vienna.

30. International Atomic ENergy Agency, Natural Fission Reactors, proceedings of a meeting of the technical committee held in Paris, France. December 19-21, 1977. International Atomic Energy Agency, 1978, Vienna.

31. Brookins, Douglas G. "Alkali and alkaline earth element studies at Oklo" in Scientific Basis For Nuclear Waste Management, Volume 3, ed. by John G. Moore, Plenum Press, 1981, New York, pp. 275-82.

32. Curtis, David B. and Alexander J. Cancarz. Radiolysis in nature: evidence from the Oklo natural reactors. SKBF, February, 1983, Stockholm, KB3 83-10.

33. Hubbard, N. et al. "The use of natural radionuclides to predict the behavior of radwaste radionuclides in far-field aquifers" in Scientific Basis For Nuclear Waste Management, Volume 7, ed. by Ganj L. McVay, North Holland, 1984, New York. pp. 891-897.

34. Shea, Michael. "Uranium migration at some hydrothermal veins near Marysvale, Utah: a natural analog for waste isolation" in Scientific Basis For Nuclear Waste Management, Volume 7, ed. by Ganj L. McVay, North Holland, 1984, New York, pp. 227-238.

35. McKinley, Ian G., et al. "A natural analogue study of radionuclide migration in clays," in Scientific Basis For Nuclear Waste Management, Volume 7, ed. by Ganj L. McVay, North Holland, 1984, New York. pp. 851-7.

36. Airey, P. L. et al. "Radionuclide migration around uranium ore bodies in the Alligator Rivers region of the Northern Territory, Australia--analogue of radioactive waste repositories" in NRC Nuclear Waste Geochemistry '83. U.S. Nuclear Regulatory Commission, May 1984, NUREG/CP-0052, pp. 343-374.

37. Airey, P. L. et al. Radionuclide migration around uranium ore bodies--analogue of radioactive waste repositories, Annual Report 1982-83, AAEC/c40 (Contract NRC-04-81-172).

38. Brookins, D. G. "Geochemical study of a Lamprophyre dike near the WIPP site" in Scientific Basis For Nuclear Waste Management, Volume 3, ed. by John G. Moore, Plenum Press, 1981, New York, pp. 307-313.

39. Wollenberg, H. A. et al. "Uranium, thorium, and trace elements in geologic occurrences as analogues of nuclear waste repository conditions" in NUREG/CP-0052, pp. 464-491.

40. Brookins, D. G. et al. Natural analogues: Alamosa River monzonite intrusive into tuffaceous and andesitic rocks" in Scientific Basis For Nuclear Waste Management, Volume 6, ed. by D. G. Brookins, North Holland, 1983, N.Y.

41. Gancarz, A. et al. "^{99}Tc, Pb, and Ru migration around the Oklo natural fission reactors" in Scientific Basis For Nuclear Waste Management, Volume 2, ed. by Clyde J. M. Northrop, Jr., Plenum Press, 1980, New York, pp. 601-608.

42. Andrews, Robert W. and F. J. Pearson, Jr., Transport of ^{14}C and uranium in the Carrizo aquifer of south Texas, a natural analog of radionuclide migration" in Scientific Basis For Nuclear Waste Management, Volume 7, ed. by Ganj L. McVay, North Holland, 1984, New York. pp. 1085-1092.

43. Miekeley, Norbert et al. "Some aspects of the influence of surface and groundwater chemistry on the mobility of thorium in the 'Morro do Ferro'-environment" in Scientific Basis For Nuclear Waste Management, Volume 5, ed. by Werner Lutze, North Holland, 1982, N.Y.

44. Eisenbud, M. et al. "Studies of the mobilization of thorium from the 'Morro do Ferro'" in Scientific Basis For Nuclear Waste Management, Volume 5, ed. by Werner Lutze, North Holland, 1982, N.Y.

45. Gilbert, Thomas L. "A natural analogue approach for estimating the health risks from release and migration of radionuclides from radioactive waste" in Scientific Basis For Nuclear Waste Management, Volume 7, ed. by Ganj L. McVay, North Holland, 1984, New York. pp. 935-942.