RESULTS FROM AND ISSUES RAISED BY NRC's HIGH-LEVEL RADIOACTIVE WASTE RESEARCH PROGRAM'S INTEGRATED EXPERIMENTAL, MODELING, AND MODEL VALIDATION WORK

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ABSTRACT

The Waste Management Branch of the U.S. Nuclear Regulatory Commission's Office of Nuclear Regulatory Research has been conducting a program of long range research on the phenomena relevant to making licensing decisions about the disposal of high-level radioactive waste. A major issue addressed by the program is the validity of the mathematical models that will be used in predicting the performance of HLW repositories. In addressing the issue of validity of models, the program pursues several alternative lines of inquiry, given that prototypical tests of HLW repository performance can not be done. These avenues of inquiry include examinations of currently available scientific results, a fair amount of which comes from NRC's phenomenological waste management research, that can be used in understanding expected HLW repository performance. In addition to research into the phenomena that are not well understood now but are expected to influence release and transport of radioactive material from emplaced HLW, NRC is investigating laboratory tests that are analogous to or dynamically similar to selected aspects of expected HLW repository situations, and examining natural geologic processes and events whose sequence of occurrence is somehow analogous or similar to some aspects of phenomena expected to affect the release and transport of radionuclides from emplaced HLW. This paper describes how these lines of inquiry have been pursued in NRC's HLW research program, what issues have been raised, what issues have been resolved, and what issues remain outstanding viz a viz the validity of mathematical models of repository performance.

INTRODUCTION

The disposal of high-level radioactive waste (HLW) in the United States will be done by the U.S. Department of Energy (DOE). Through its Office of Nuclear Material Safety and Safeguards, The U.S. Nuclear Regulatory Commission (NRC) will regulate and make licensing decisions concerning the disposal of HLW, as dictated by the Nuclear Waste Policy Act of 1982 (1) and its implementing regulations, Part 60 of Title 10 of the Code of Federal Regulations (2), and Part 191 of Title 40 of the Code of Federal Regulations (3), issued by the U.S. Environmental Protection Agency (EPA). EPA's regulation is a standard that sets limits on the total releases of radioactive material from a repository of HLW over a 10,000 year period following emplacement of the waste. NRC's regulation, 10 CFR 60, is a set of mandatory guidelines that DOE must follow in demonstrating compliance with the EPA standard. NRC's regulation contains additional performance requirements and repository design and siting criteria to which DOE must adhere. Because of the very long performance period of a repository, NRC expects that DOE will base much of its demonstration of compliance with regulatory requirements on estimated predictions of repository performance based on the use of mathematical models of the phenomena expected to affect repository performance.

Because a repository of HLW has never been constructed, there is no direct operating experience that NRC can use as a basis for making licensing decisions concerning HLW disposal. The NRC HLW research program, formulated and managed by NRC's Office of Nuclear Regulatory Research, is endeavoring to assemble as much of this new information as possible so that the NRC staff be able to use it in its licensing decisions. Nearly all of NRC's HLW research projects have some impact on the mathematical models that will be used to estimate repository performance. The remainder of this paper describes these projects and their impacts on NRC's technical information base for predicting repository performance.

APPROACH

The very long isolation times (thousands of years) associated with the disposal of HLW preclude the establishment and operation of prototypical tests to validate models of HLW repository performance. Hence the NRC research program on HLW disposal has examined and is pursuing several alternative lines of inquiry into ways that one can scrutinize the assumptions underlying the models and gain confidence in the models, given that prototypical tests can not be done. These avenues of inquiry include examinations of currently available scientific results, a fair amount of which comes from NRC's phenomenological waste management research, that can be used in understanding expected HLW repository performance. In addition to research into the phenomena that are not well understood now but are expected to influence release and transport of radioactive material from emplaced HLW, NRC is investigating laboratory tests that are analogous to or dynamically similar to selected aspects of HLW repository situations, and examining natural geologic processes and events whose sequence of occurrence is somehow analogous or similar to some aspects of phenomena that will affect the release and transport of radionuclides from emplaced HLW. Natural sites at which phenomena analogous or similar to those that are likely to occur in HLW disposal are loosely referred to as "natural analogues" of HLW disposal.

The general perspective of NRC's HLW research program on the interplay between experimentation and modeling has been discussed in a paper by the authors (4). As explained in that paper, the experimental program supporting NRC's HLW research is aimed at validation of models by 1) studying phenomena that are analogous to (i.e. have the same types of governing differential equations as) those that may occur in HLW repositories and affect their performance, and 2) studying the phenomena that may occur in HLW disposal directly by means of field and laboratory tests whose design is based on the principle of dynamic similarity between the tests and expected repository conditions. An example of a process analogy relevant to HLW disposal is the one that can exist between contaminant transport and heat transport. An example of an experiment based on similar phenomena is a scale model repository that NRC is funding at the Colorado State University (5-9) and is being used to investigate thermohydrological phenomena where the thermohydrological parameters have been expressed in dimensionless numbers that are in the same range as those of an actual repository. To summarize: an objective of the HLW research program is to use a combination of data from field observations, field experiments, and laboratory experiments on phenomena and conditions analogous and dynamically similar to those of a repository of HLW to test the applicability of models and portions of models used to assess, understand and predict repository performance.

LIMITATIONS ON THE USE OF NATURAL AND LABORATORY SYSTEMS AS INDICATORS OF THE VALIDITY OF MODELS

Experimental simulations of HLW disposal based on a strict application of the principle of dynamic similarity as cited above would require dimensionless parameters in the experiment to be exactly the same as those that would apply to HLW disposal and all phenomena that occur in the HLW repository would occur in the experiment. In experiments in both natural and man-made laboratory systems, there are practical limitations to attaining strict similarity. Despite these limitations, most of the experimental work being done in the HLW research program is based, with varying degrees of rigor, on examining analogous and dynamically similar phenomena.

Natural Systems

In natural systems, there are two major limitations to attaining strict dynamic similarity, both of which come about because natural systems have to be taken as given entities and can not be designed to fit model or performance requirements. The first limitation is that natural systems that have anything in common at all with HLW disposal often do not entail all of the phenomena that are expected to occur in HLW disposal. As long as one confines oneself to consideration of just those phenomena and interactions of phenomena that are common to both the natural system and the HLW repository and as long as those phenomena and interactions can be shown to be insensitive to the additional phenomena and interactions in the HLW repository, this first limitation is acceptable. The second limitation is that the natural system may have an acceptable set of phenomena and interactions occurring in it but the similarity parameters associated with these phenomena and interactions may not match those of the repository. This limitation is acceptable if the first limitation is acceptable and the dimensionless parameters of the natural system and the HLW repository can be shown to characterize the same physical regimes. For example, the Peclet number is the similarity parameter that compares convective transport to diffusive transport. Observations from natural systems characterized by Peclet numbers which are in the same range as those expected to be characteristic of an actual repository will be transferable to actual repository behavior.

Laboratory Systems

Although laboratory simulations of phenomena occurring in HLW disposal are more controllable than natural field simulations, there are practical limitations on the types of experiments that can be done. These limitations have to do with the selection of materials that are available for use in laboratory simulations and the degree of resolution of length scales that must be attained for the laboratory experiment to simulate a natural system. Given that radionuclide transport in a repository of HLW has thermal, hydrological, mechanical, and chemical influences on it; that each radionuclide has a distinct characteristic decay time; and that there may be several chemical species for each radionuclide, it becomes clear that there can be a very large set of equations that describe radionuclide transport and there are many dimensionless parameters associated with these equations. Selection of laboratory materials and design of laboratory apparatus that would provide geometric and dynamic similarity for all of these processes is intractable. With this limitation, one has to design laboratory experiments for limited sets of phenomena in much the same manner that natural systems are selected for examining particular sets of phenomena. Once a set of phenomena and associated laboratory materials has been selected for a controlled laboratory experiment to simulate some aspect of HLW disposal, one has to face a potentially difficult question of scale. There are length scales below which it is impractical for a laboratory experiment to be designed to have all of the geometric characteristics of a geologic system of a repository of HLW. Below some degree of spatial resolution, the laboratory model will not have the same pore structure or fracture network structure that the geologic system has. However, given that the models that are used to predict HLW repository performance are based on averages taken over large rock volumes, it may not be necessary for the laboratory experiment's geometry to mimic the repository's geometry below a certain degree of resolution. Just what this degree of resolution is remains an open question for both mathematical and physical models. The NRC HLW research program is examining this question with a combined program of field and laboratory tests in some of its projects (5-16).

PROGRAM ACTIVITIES

Organization

With respect to mathematical modeling, NRC's HLW research program can be viewed as having three aspects: identification of modeling needs, implementation of existing models, and understanding of phenomena that have to be modeled. Although all three aspects of NRC's HLW research program are covered to some degree in every one of its projects, each project tends to emphasize one of the aspects over the others.

The project, "Uncertainties in Assessment of Long-Term Collective Does and Health Effects from Geologic Disposal of High-Level Waste," was conducted by the Oak Ridge National Laboratory (ORNL) to give the NRC staff a broad view of the quantifiable and unquantifiable uncertainties that arise in connection with calculation of long-term collective dose and health effects due to geologic disposal of HLW. This project identified sources of and made a priori judgments about the importance of uncertainties in the natural and engineered barrier systems of a repository but generally did not quantify the uncertainties. The project's investigators also were asked to categorize the various uncertainties according to whether or not they could be quantified. Geologic evolution of a repository site was considered to be a potentially important source of uncertainty that could not be quantified. Uncertainties in estimating groundwater flow and radionuclide transport in the absence of geochemical retardation effects were judged to be quantifiable. Uncertainties in estimating geochemical effects were judged to be quantifiable in principle but much work on understanding geochemical phenomena needed to be done so that they could be represented by models that could be used to estimate the uncertainties. Reports and papers (17-23) from the ORNL uncertainties project have been used by NRC in planning its research program.

In addition to assessing uncertainties for research planning purposes, NRC wanted to have access to computational tools that implemented, to the extent possible, existing mathematical models of phenomena that affect repository performance. To this end, NRC initiated two projects at the Sandia National Laboratories, "Development of a Methodology for Risk Assessment of Nuclear Waste Isolation in Bedded Salt," and "Development of a Methodology for Risk Assessment of Nuclear Waste Isolation in Alternative Geologic Media." In these projects, Sandia has prepared computational methodologies for assessing the performance of HLW repositories in bedded salt and basalt. Under its computational methodology project for alternative geologic media, Sandia currently is preparing a computational methodology for assessing the performance of HLW repositories in unsaturated tuff. These methodologies are based primarily on existing mathematical models of the relevant phenomena and Sandia is not charged with developing new models or making major improvements of existing models. However, Sandia is charged with the responsibility to keep NRC informed about the confidence that one can have in the models that have been incorporated into the computational methodologies. There are numerous computer programs and reports that have been prepared by Sandia under its two computational methodology projects (24-31).

While the ORNL uncertainties project provided NRC with an a priori assessment of uncertainties in predicting repository performance and Sandia's computational methodology projects provided means for quantifying some of these uncertainties, none of the three projects was charged with finding ways to reduce uncertainty in estimating repository performance. Those NRC HLW research projects that are devoted to understanding phenomena that have to be modeled have as their principal aim the reduction of uncertainty in predicting those phenomena. Such projects constitute the majority of NRC's HLW research program, both in number and funding levels. The impact of these projects on modeling is described in the remainder of this paper.

Natural Systems

Since the late 1970's, the waste management research program has supported several projects involving the examination of natural systems for indications of behavior that can be expected in HLW repositories. These systems fall into three general categories: natural analogues (a misnomer because these systems are nearly full-scale similar systems) in which several of the phenomena that are expected to occur in HLW disposal have been taking place over thousands of years; specific field testing in which rock masses that are similar to expected HLW repository rock masses and in which just a very few of the phenomena that may occur in HLW disposal can be isolated for examination; and laboratory experiments, which focus on specific phenomena and are a complement to the field tests.

Natural Analogues: Radionuclide Transport

NRC's major natural analogue project, "Radionuclide Migration around Uranium Ore Bodies - Analogue of Radioactive Waste Repositories," has been active since 1981 (32-36). This project is being conducted by the Australian Atomic Energy Commission at the Koongarra ore body in Australia. A major finding of this project is that the use of laboratory-measured ratios of solid concentrations to liquid concentrations of radionuclides do not serve well as indicators of geochemical retardation when used in mathematical models applied to field situations. Work currently being done under the Australian natural analogue project involves an effort to test the mathematical models of radionuclide transport models implemented in the computer program SWIFT (prepared for NRC by Sandia under its computational methodology projects).

Natural Analogues: Coupled Processes

A project involving the consideration of data from natural analogues was "Investigation of Coupled Interactions in Geothermal and Hydrothermal Systems for the Assessment of HLW Isolation," at the Lawrence Berkeley Laboratory (LBL) (37-46). The objective of this project was to provide NRC with an understanding of the coupled interactions that are likely to have a significant effect on the performance of a geologic repository, especially during the initial period during which significant heat is generated by the waste, by drawing from investigations of coupled interactions in geothermal, hydrothermal and ore genesis systems and determining whether and under what conditions similar interactions are important to the behavior of a repository of HLW. No field work is being done in this area by NRC as yet, but extensive field experience with geothermal and hydrothermal systems and geotechnical mining projects has been useful as a guide to data bases from natural and engineered systems that could serve in some respects as physical models of HLW repository performance. Research to date has shown that certain mathematical models developed for geothermal applications are applicable to predicting aspects of HLW repository performance such as resaturation. Another finding of this project is that there are phenomena, e.g. silica redistribution, that may be important to HLW repository performance but for which there are no existing mathematical models.

Field Tests: Categories

The NRC HLW research program has several projects in which field testing is being done or has been done in order to examine the behavior of just a few isolated phenomena related to the natural barrier system of a repository of HLW. The phenomena examined are the flow of groundwater, the nonchemical transport of contaminants through saturated and unsaturated fractured rocks, and the mechanical behavior of borehole seals and the rock surrounding the seals.

Field Tests: Saturated Media

Field work done in the NRC HLW research project "Field and Theoretical Investigations of Mass and Energy Transport in Subsurface Materials at Waste Disposal Sites," at the University of Arizona (10-16, 47) indicated that it is possible to simulate saturated fractured rock masses as anisotropic porous media. A technique was devised for measuring the anisotropic permeability tensor. Further research showed that a statistical analysis of the permeability tensor could provide a way of predicting the spatial dependence of the dispersion coefficient. Such a prediction, if valid, would be a very economical alternative to measuring the dispersion coefficient directly through field tests. Other research in this project also showed that there is no apparent correlation between fracture density and permeability. The assumption of such a correlation, based on an idealization of fractures as smooth parallel plates, is the basis for some mathematical models of fracture networks.

The work done in the University of Arizona's project on flow and transport in saturated fractured media raised several additional issues that are now being addressed in the recently begun project "Flow of Groundwater and Transport of Contaminants through Saturated Fractured Geologic Media from High-Level Radioactive Waste," by In-Situ, Inc. Major issues being examined in this project are the validity of the dispersion theory derived under the University of Arizona's project on flow and transport in saturated fractured media, the development of quantitative indicators of groundwater flow regimes (porous, doubly porous, discrete fracture, etc.) in saturated fractured rocks, field identification of matrix diffusion, and the use of groundwater dating data for calibrating flow and transport models.

The issues raised by the results of the University of Arizona's project on flow and transport in saturated fractured media have also led NRC to initiate another project at the University of Arizona: "Improved Methods of Characterizing and Modeling Contaminant Transport around High-Level Radioactive Waste Sites." These issues include the effect of measurement length scale on permeabilities measured from cross-hole hydraulic tests, the feasibility of heat tracer experiments, the modeling of non-Fickian transport, uncertainties in transport modeling due to uncertainties in measuring or predicting groundwater velocity, and the use of integrated sets of hydraulic and chemical data for calibrating models using parameter estimation by inverse methods.

Field Tests: Unsaturated Media

In the area of flow and transport in unsaturated media, the major HLW research project is "Unsaturated Flow and Transport through Fractured Rock Related to HLW Repositories," at the University of Arizona (48-51). Due to the paucity of models and data collection methods for predicting flow and transport in unsaturated fractured rocks, this project has had to proceed from a very fundamental level. Laboratory and field methods adapted to fractured rocks have been devised for providing data to existing models of flow and transport but the validity of the models themselves still has to be tested. In order to form a consensus on what models should be used and what the important problems are in predicting flow and transport in unsaturated fractured rocks hosting HLW repositories, the University of Arizona and Sandia, through the auspices of their NRC HLW research projects on unsaturated media, have organized and held three workshops in 1982, 1984, and 1986 on problems of predicting HLW repository performance in unsaturated rocks. Participants from NRC, DOE, the U.S. Geological Survey, and several universities have participated in the workshops. Research done under the University of Arizona's project on flow and transport in unsaturated media and the LBL coupled processes project has suggested the possibility that unsaturated fractured media near emplaced HLW may act has a heat pipe and draw liquid water to waste packages. Very tentative plans have been discussed by the University of Arizona for a carefully designed field test to examine this issue.

Field Tests: Borehole and Shaft Sealing

Both field work and laboratory work have been done at the University of Arizona to investigate the performance of borehole and shaft seals under a project called "Rock Mass Sealing" (52-55). Based mainly on experimental work, this project has raised several issues about the performance and design of borehole and shaft seals. Future work in an extension of the project will consider the effectiveness of sealing boreholes and shafts in salt repositories. What is lacking in this area in both NRC's and DOE's programs is the existence of any adequate models to predict the long-term performance of borehole and shaft seals.

Laboratory Experiments: Categories

In addition to its integrated field and theoretical program for evaluating models of HLW repository performance in the natural barrier system, the NRC HLW research program also has a complementary set of integrated laboratory and theoretical projects for examining modeling issues about the natural barrier system. These projects are examining issues in geochemistry and thermohydrological phenomena in HLW repositories.

Laboratory simulations of aspects of repository behavior have been performed in NRC's HLW research program to examine geochemical retardation in basalt and thermohydrological interactions in porous and fractured media. The geochemistry experiments were based only roughly on the principle of similarity while the design of the thermohydrological experiments involves extensive application of the principle of dynamic similarity.

Laboratory Experiments: Geochemistry

Laboratory experiments done in the NRC HLW research project "Site Geochemistry," at LBL (56-62) have considered interactions between mineral surfaces and radionuclide ions, assessment of the thermodynamic data base needed for phenomenological modeling of retardation, hydrothermal interactions between the groundwater and its host rock, and redox controls and buffers far from the emplaced HLW. All of these aspects of the geochemical retardation are important to radionuclide transport. However, to date they are not reflected explicitly in current modeling practices that, instead, use laboratory-measured solid/aqueous concentration ratios and retardation factors instead of treating geochemical effects mechanistically. In another geochemistry project, "Valence Effects on Adsorption," at ORNL (63-66), the solubilities of various radionuclide species and the validity of using single values of electrochemical potentials to characterize the geochemistry of whole sites are being examined. Solubilities of species and speciation of radionuclides in general are not reflected in the current simple retardation models. The work done in the ORNL valence effects project has highlighted the ambiguity in the usage of electrochemical potentials in geochemistry and has raised serious doubts about the use of the concept in HLW applications.

What is lacking in NRC's HLW geochemical research projects, and what DOE and NRC need, is a reliable phenomenological model of retardation that can be used for repository simulations and take the various mechanisms considered by the LBL geochemistry project and the ORNL valence effects project into account. Although the Nuclear Energy Agency in Paris has made some progress on phenomenological geochemical modeling (67), the NRC staff has determined that it should support a project on this topic. In this connection, several tasks have been formulated and a contractor has to be selected to carry them out. These tasks include continued examination of the thermodynamic data base for actinides, modification of thermodynamic data for high temperatures and high ionic strengh, phenomenological modeling of individual retardation mechanisms, and coupling of the geochemical models with radionuclide transport models.

Laboratory Experiments: Geochemical Retardation

In the project "Laboratory Analogue of Leaching and Migration," done at Argonne National Laboratory (ANL), a set of experiments was done in which water with radionuclides in solution was passed through a chamber with basalt samples and retardation of the radionuclides was observed (68-69). The results of the experiments indicated that expectations about the ability of basalt to retard radionuclides may be wrong, i.e. basalt may not be as good a retardant of radionuclide migration as claimed by DOE. Although results from the ANL experiments can be viewed with skepticism because the experiments were somewhat simplistic in design, more carefully designed experiments performed under the LBL geochemistry project and the ORNL valence effects project indicated that the general trends observed in the ANL leaching and migration project's experiments may be correct. The lack of a good phenomenological geochemical retardation model, an issue that has been discussed already, was a key factor in the simplistic design of the ANL leaching and migration project's experiments.

Laboratory Experiments: Thermohydrological Interactions

In the NRC HLW research project "Laboratory Studies of Thermoconvective Phenomena in High-Level Waste Disposal and Development of Empirical Heat Transfer Correlations for Repository Licensing," University of Delaware (FY's 84 and 85), Colorado State University (FY 86), experiments on thermohydrological phenomena have been designed successfully by applying the principle of dynamic similarity (5-9). The experiments have been designed so that the dimensionless groups that apply to full scale repositories can be bracketed in the experiments. Examination of the ranges of these groups has shown that heat transfer in a repository is likely to range from pure conduction to a regime of mixed conduction and buoyancy-driven convection. A major result of the work done so far is that the average temperature of the simulated emplaced waste may, under some circumstances, attain a minimum value as function of the aspect ratio (length/height) of the test section (5). Mathematical simulations of a repository whose results are based on numerical analysis necessarily involve establishment of a simulated repository with a fixed aspect ratio. In a real repository, the aspect ratio is difficult to define, but it is likely to be very large, and any predicted average waste temperatures based on idealized repositories with small or moderate aspect ratios should be examined carefully for spurious aspect ratio effects. The experiments in the thermohydrological interactions projects at the University of Delaware and the Colorado State University are designed to provide an empirical sensitivity study of thermohydrological interactions to variations in porosity and fracture patterns. The final results of the experiments are expected to provide some information of the degree of resolution of geologic systems which is needed for adequate predictions of repository-related phenomena.

The successful application of the principle of dynamic similarity in the thermohydrological interactions projects at the University of Delaware and the Colorado State University and the rough experimental design in the ANL leaching and migration project raise the question of what the practical limits are on applying the principle of dynamic similarity to other HLW repository-related phenomena besides thermohydrological interactions. To answer this question, NRC has formulated some tasks to be performed by a contractor who has yet to be selected. These tasks involve a progression of feasibility studies and demonstrations to show just what are the practical limitations on laboratory-simulated HLW repository-related phenomena.

Engineered Systems

In addition to the set of projects that integrate experiments and modeling to explore ways to predict the performance of the natural barrier system of a repository of HLW, under the NRC HLW research program a set of projects is being conducted to test the adequacy of models of the performance of the individual components of the engineered barrier system: the waste packages, packing materials around the waste packages, the waste form, and backfill materials in repository tunnels. Some natural barrier system projects mentioned above also consider aspects of the engineered barrier system. Moreover, with several of the projects on the engineered barrier system, consideration is given to the interaction between that part of the engineered barrier system being studied and the surrounding natural environment.

Underground Facility

The work of the LBL coupled processes project (40) and the LBL geochemistry project (70) and "Modification of Backfill Materials," ANL (71-72), has studied the performance of backfill and packing materials, usually clays. Through this work, coupled processes have been predicted to be of significance in the behavior of packing and backfill clays at temperatures typical of those expected in HLW repositories by using an Onsager formalism to predict the coupling. Transport effects that were thought to have been secondary in comparison to water movement, such as thermal osmosis, have been predicted to dominate radionuclide migration through clays in some cases. Another finding of the research is that although there are models of most of the individual phenomena that can occur in clay packing and backfill materials in HLW repositories, and there are models of some of the couplings, there is no model of all of the couplings. Furthermore, several of these models have not been validated. Suggestions have been made to NRC for validating these models and determining if a comprehensive coupled model is needed.

Under the LBL geochemistry project and ANL's packing material project, aspects of the migration of contaminants through and the hydrothermal alteration of packing materials around waste packages have been considered. Water movement in altered packing materials also has been considered in the thermohydrological interactions projects at the University of Delaware and the Colorado State University (8). Experiments on diffusion of contaminants through unaltered, essentially impermeable clay packing materials have been done under the LBL geochemistry project (70). The experiments were designed on the basis of dynamic similarity principles using a model involving diffusion and convection. This work showed that in addition to molecular diffusion, surface diffusion is important to the movement of radionuclides in clay packing materials and in fact resulted in movement many times faster than had been expected. Chemical effects were also believed to be important, but the experiments were not designed to identify them. Suggestions have been made to NRC for redesigning the experiments to identify chemical effects and to test models of these effects.

The hydrothermal alteration and degradation of clay packing materials was examined under ANL's packing material project (71-72). The ANL experiments showed that in the heating environments that clays may experience in HLW repositories, it is possible that the saturated, essentially impermeable, clay considered in the LBL geochemistry project can dry out and become very permeable. This observation also was made by investigators working under the University of Arizona's rock mass sealing project at the University of Arizona. In that situation, water and radionuclides could move rapidly through a resaturated packing material altered by the influence of the heat given off by the waste packing. The thermohydrological interaction in permeable packing materials is being examined under the thermohydrological interactions projects at the University of Delaware and the Colorado State University.

Waste Package Overpack Experiments

In order to obtain an understanding of the degradation of HLW overpacks, the NRC HLW research program is supporting efforts on corrosion in the projects "Long Term Performance of Materials Used for High-Level Waste Packaging" (73-76), at Battelle Columbus Laboratories (BCL); "Pitting Corrosion Chemistry" (77), at Brookhaven National Laboratory (BNL); and "Statistics of Package Failure by Pitting" (78-80), at the National Bureau of Standards (NBS). Stress corrosion cracking also has been identified as a mechanism by which metallic containers of HLW can fail. There are no existing models of stress corrosion cracking that would be applicable to predicting HLW repository performance. An experimental program to assure that overpack materials and design, the overpack manufacturing process, and the waste package environment expected within the repository are selected such that stress corrosion cracking does not take place appears to be a feasible solution to the stress-corrosion-cracking problem. An alternative source of information on stress corrosion cracking that may of value to NRC is the bilateral agreement that NRC has negotiated with the Swiss national radioactive waste cooperative, which is performing tests on stress corrosion cracking.

Although uniform corrosion has been cited as the major mode of degradation of metallic overpacks, recent work, carried out under the BCL waste package project, has shown that local corrosion may be significant (75). BCL experimentally tested the conventional model of pitting corrosion which is based on the assumption that all chemical effects and therefore all the corrosion of the pit surface takes place only at the bottom of the pit. The BCL experiments showed, however, that the side walls of the pit are not inert, as was assumed in the model, and that pits tend to grow broader in carbon steels than had been expected. Consideration is now being given to ways to model side wall corrosion, since the breadth of a penetrating pit is important estimating the surface area of the waste form exposed to leaching ground water subsequent to failure of the overpack and, therefore, important to estimation of the "source term" used for determining compliance with the EPA HLW standard.

The effect of the ages of pits on pit growth rates was studied under the BNL pitting corrosion project (77). Models initially used in this project were based on a network of equivalent electrical resistances in order to predict electrochemical effects. Experiments done by BNL have shown that the models were oversimplified and new ways are being devised to make the models more realistic. Under the NBS pitting corrosion project (73-76), statistical analyses of data taken during corrosion experiments are being done to see if one can identify the onset of corrosion from observations made of electrochemical "events" prior to the onset of corrosion. Also considered in this project are questions about the importance to performance of individual pits, especially ones that form early, and the characterization of ensembles of pits.

The NRC HLW research projects on corrosion also have considered environmental effects on corrosion. The effect of groundwater chemistry has been given considerable attention. However, more needs to be done and the effect of elevated temperatures has been given only very limited attention. An open question that needs to be answered is: How does the total waste package environment (host rock, backfill, packing, groundwater, and heat) affect corrosion processes? Several integrated modeling and experimental efforts under the overall title "geocorrosion" will be initiated in FY 87 to examine this question.

Waste Form Experiments

The major work done in the NRC HLW research program on the degradation of waste forms has been done in "Glass Analogue Study," at ANL (81-82), and under the BCL waste package project (73) and the LBL geochemistry project (57). There were other NRC HLW research projects on waste forms which preceded these three in the late 1970's but ANL's glass analogue project, BCL's waste package project, and LBL's geochemistry project began by addressing issues that those projects had raised but not resolved.

Waste Form: HLW Glass

Experimental tests of "fresh" (unaged) borosilicate glass and comparisons with model predictions have been done under the BCL waste package project (73). Currently available models of leaching and dissolution of radionuclides from glass appear to be adequate when applied at temperatures near 25 degrees C. At higher temperatures, the models become less reliable. Workers at BCL have established ways to calculate the effect of groundwater chemistry on leaching and dissolution of "fresh" glass, but the models are crude and could be improved. However, due to budgetary constraints, no additional work will be done to improve the models of leaching and dissolution of HLW glass to account for higher temperatures or to improve estimations of groundwater chemical effects.

Under ANL's glass analogue project, the long-term aging of natural glasses in geologic systems was examined as a model of the expected degradation of the borosilicate glass to be used in HLW disposal (81-82). Workers at ANL were able to show that the aging of natural glasses provides a good indicator of the expected degradation of man-made HLW glass waste forms in a repository environment. The subsequent question of what the radionuclide leaching properties of degraded ("aged") HLW glass are was examined by LBL under the LBL geochemistry project (57). However, due to budgetary constraints, this line of research ended before quantitative results became available. Even though there are missing data for this reason, the information obtained, along with the glass leaching model described above, will be useful in helping NRC to assess models of radionuclide release used by DOE.

Waste Form: Spent Fuel

Because most of the inventory of a repository of

HLW may be spent fuel rather than the byproduct of reprocessing spent fuel, the NRC HLW research program has supported work, through the BCL waste package project, on the degradation of spent fuel cladding and the leaching and dissolution of spent fuel (73). Work done under the BCL waste package project has indicated that the extension of models of leaching and dissolution applied to glass to predicting the leaching and dissolution of spent fuel appears to be a valid step. However, the degradation of spent fuel cladding and the effects of the products of this degradation on packing material performance and the leaching and dissolution of spent fuel are not well understood. The NRC HLW research program is supporting efforts under the BCL waste package project to resolve these issues.

CONCLUSIONS

The NRC HLW research program has made significant progress in assembling the information that will be needed by the NRC staff in making licensing decisions about HLW disposal. The program has progressed far enough that NRC now has a fairly good idea of which phenomena are important to HLW repository performance and which are not. Through its HLW research program and through bilateral agreements with other countries, NRC has attained a good understanding of many of the important phenomena affecting the performance of HLW repositories. However, as indicated throughout this paper, there are unresolved issues associated with many of these phenomena and some phenomena that can be understood only by additional research.

Because NRC expects that DOE will support many of claims of compliance with regulatory criteria by using mathematical models, NRC is very concerned about the validity of those models. Most of NRC's HLW research projects have had an impact on NRC's attempts to resolve questions on the validity of assumptions supporting models used to predict HLW repository performance. With the progress that these projects have made, NRC has reached a point in its HLW research program where the issue of validity of models, as opposed to the validity of individual assumptions supporting them, will receive much more direct attention than it has in the past. In its efforts to plan for such work, NRC held a workshop on the validity of mathematical models applied to HLW disposal and is using the findings of this workshop (83) as an information resource for formulating new HLW research projects that validate or refute mathematical models that are expected to be used to support or audit DOE's claims of compliance with NRC's regulatory criteria pertaining to HLW disposal.

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