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EXTRAPOLATION OF SHORT-TERM TEST DATA FOR ASSESSMENT OF LONG-TERM SEAL PERFORMANCE

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ABSTRACT

Conventional seal performance tests are likely to be of short duration relative to the period for which HLW repository seal performance may be required. Providing reasonable assurance about the acceptable performance of repository seal performance will necessitate extrapolating results of short-term tests. Various strategies are reviewed that have been proposed and partially implemented for demonstrating the feasibility of long-term sealing.

The most promising strategy for providing reasonable assurance about long-term performance predictions combines extended monitoring of in-situ seals with parallel laboratory seal performance investigations, backed up by theoretical analyses and predictions of potential seal/rock/fluid interactions. In-situ and laboratory investigations can determine environmental parameters that influence seal performance. Extended testing can best be conducted by initiating testing as early as practicable during performance confirmation, and planning for continued monitoring up to permanent closure. Supplementary model validation can be achieved by seal-performance oriented characterizations of cementitious materials, ancient and modern, emplaced and aged in environments reasonably similar to those at an eventual Yucca Mountain repository. Analog studies are most promising for predicting long term performance of clay-type sealants.

The emplacement of high quality (high density, low permeability, low porosity) sealants, as nearly as possible chemically and physically compatible with the host rock, is likely to be a substantial factor enhancing credibility in long term performance.

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1.0 INTRODUCTION

This document presents an overview of procedures and strategies that can be implemented in order to predict the long-term performance of HLW repository seals. Because such seals may be required to function for periods far exceeding the typical design life of engineered structures, unusual difficulties will be encountered in demonstrating conclusively that longevity requirements can be met. A number of strategies have been proposed to demonstrate extreme longevity requirements. The present document summarizes such strategies, with specific application to repository seals. It is important to recognize that the question of predicting long-term performance pervades the HLW program. Strategies for validating such predictions are likely to be developed in a number of disciplines, such as waste form and waste package materials sciences, hydrology, geochemistry, geology, tectonics and rock mechanics. Similar longevity studies aimed specifically at sealing performance predictions clearly would benefit from efforts at integrating relevant information from numerous sources. A comprehensive integration along those lines would be well beyond the scope of this document. Nevertheless, such a comprehensive integration, focused on details particularly relevant to long-term sealing, is likely to be a significant contribution to assessing the state of the art, and to lead to an explicit identification of information needs that still need to be addressed.

Strategies for determining the durability of cementitious materials, especially concrete, are well developed and are receiving increasing attention. The growing concerns about concrete deterioration problems are particularly well illustrated by the growing, if not exploding, number of publications on the subject. To quote an eminent authority (Neville, 1987), ". . .it is tempting to ask why, after all these years of research, there are still so many problems with the durability of concrete." Similarly, at least equally authoritative investigators Mather and Mather (1987) observe that "An unsolved problem is assessment of the nature and severity of the exposure, so that requirements can be graduated according to severity. . . Most of the raw material of knowledge to do this exists, some in relatively quite refined states. But the manner in which this knowledge is used in an attempt to make it an effective tool for makers and users of concrete is primitive."

Notwithstanding these major durability concerns, the longevity and durability of many concrete and cement type structures is well documented. Ancient mortars and concretes have withstood millennia (e.g., Malinowski, 1982; Roy and Langton, 1982; Roy and Langton, 1983; Roy and Langton, 1989). Old "modern" concrete pipe has lasted for well over a century, and continues to perform satisfactorily (Bealey and Duffy, 1987). Ascertaining the products, preparation and emplacement, and environmental conditions that determine whether a concrete or cementitious material will be durable or not will be a significant step forward in providing reasonable assurance that seal systems designed on the basis of such a rational approach will continue to perform satisfactorily for the necessary time. Arguments based on ancient materials, modern materials aged for decades, and supporting theoretical models will be strengthened considerably if they are supplemented by experimental verification. The regulatory time frame provides an opportunity to establish experimental credibility on two time scales. Experiments on the scale of years can be completed by the submission of the License Application. This time frame makes it feasible to demonstrate extrapolation of conventional short-term tests (weeks to months) by one order of magnitude, to several years. Monitoring seal systems installed from early in the performance confirmation program up to permanent closure would make it possible to verify predictions for a duration increased by an additional order of magnitude.

While considerable evidence can be obtained from laboratory aging, characterization and testing, it must be deemed highly desirable to complement monitoring of samples prepared under tightly controlled conditions and aged under tightly controlled conditions with in-situ monitoring, preferably of relatively large, if not full-scale, seal systems. Laboratory testing provides data for model validation primarily. Monitoring of seals emplaced in situ will provide complementary assurance that no unexpected variables have been overlooked in the design of the laboratory program. Particularly in a host environment of relatively chemically active volcanic tuffs, in-situ monitoring of cementitious seal components must be deemed highly desirable. The case for long-term monitoring is reinforced by repeated observations of deterioration in concrete structures initiating after 20 to 30 years (e.g., Mindess and Young, 1981, p. 141; Dolar-Mantuani, 1983, p.81)—i.e., after an aging period well within the duration of the performance confirmation program. Also reinforcing the case for monitoring in-situ performance of relatively large, preferably full-scale, seal systems is the well-established difference between laboratory-scale and field-scale behavior, whether it be of concrete (e.g., Abdun-Nur, 1978; Newman, 1987), clay (e.g., Daniel, 1984; Dunn, 1986), or host rock (e.g. Bredehoeft et al., 1978: Hoek and Brown, 1980).

2.0 REGULATORY FRAMEWORK

The NRC regulatory requirements with respect to repository sealing are stated in the following sections of 10CFR60.

60.112 Overall System Performance Objective for the Geologic Repository After Permanent Closure

60.134 Design of Seals for Shafts and Boreholes

(a) General Design Criterion

(b) Selection of Materials and Placement Methods

60.142 Design Testing

Paragraph 60.101(a)(2) recognizes the difficulty in providing proof of performance over periods of hundreds or even thousands of years, and identifies methods that can be used to provide reasonable assurance that long-term criteria and objectives will be satisfied.

Regulatory guidance about sealing requirements has been provided in a number of NRC documents. Two technical positions deal specifically with repository sealing, and hence are primary guidance documents: the Generic Technical Position Borehole and Shaft Sealing of High-level Nuclear Waste Repositories (NRC, 1986) and the Draft Technical Position on Post-Closure Seals in an Unsaturated Medium (NRC, 1988).

Complementary guidance with respect to repository sealing is provided in a number of related guidance documents, notably the following.

1. GTP on Design Information Needs in the Site Characterization Plan (NRC, 1985a). Section 3.4 of this GTP briefly identifies the salient design features of shaft and borehole seals that need to be identified in the SCP.

2. GTP on In-Situ Testing during Site Characterization for High-Level Nuclear Waste Repositories (NRC, 1985b). In-Situ seal testing during site characterization is discussed in Sections 2, 5.4 and, especially, 5.4(7) of this GTP.

3. Draft Issue-Oriented Site Technical Position (ISTP) for Nevada Nuclear Waste Storage Investigations (NNWSI) (NRC, 1984). Sealing issues for NNWSI are identified in Sections 4.3.3. and 4.6 of this ISTP.

4. Regulatory Guide 4.17: Standard Format and Content of Site Characterization Plans for High-Level Waste Geologic Repositories (NRC, 1987b). Section 6.4 of the Regulatory Guide identifies specific design information about Sealing of Shafts, Boreholes and Underground Openings that is to be provided in the Site Characterization Plan.

5. Draft Technical Review Plan for NRC Staff Review of DOE's Site Characterization Plans (NRC, 1987a). Section 4.3.21 of this document is the Review Guide for Borehole and Shaft Seals. This Review Guide includes criteria for the compatibility of materials for borehole and shaft seals with the host rock, for the adequacy of installation of borehole and shaft seals, for preliminary performance assessment, for long-term stability, and for performance confirmation testing.

6. Draft GTP "Guidance for Determination of Anticipated Processes and Events and Unanticipated Processes and Events" (NRC, 1988). This Draft GTP has particular relevance within the context of long-term performance. Although intended for the repository performance as a whole, and certainly not limited to or even intended primarily for sealing considerations, the guidance provided in this GTP is directly applicable to long term seal system performance, and will assist in identifying processes and events that need to be considered when predicting long term seal performance.

7. Draft TP on Tectonic Models in the Assessment of Performance of High-Level Radioactive Waste Repositories (NRC, 1989). This TP is important within the context of predicting long term seal performance and seal performance requirements first because it addresses a specific concern that may affect sealing, i.e. future tectonics at the site, and second because it amplifies and clarifies regulatory requirements for long term prediction models.

3.0 YUCCA MOUNTAIN REPOSITORY SEALING

Current sealing design concepts for the proposed Yucca Mountain repository are described in Section 6.2.8 of the Consultation Draft Site Characterization Plan (CDSCP) (DOE, 1988). Section 8.3.3 of the CDSCP describes the site characterization seal program. An analysis of seal characteristics is given in Section 6.4.3, and a seal performance assessment program in Section 8.3.5.11. Seal designs are also given in Sections 5.1 through 5.3 of the Site Characterization Plan Conceptual Design Report (SCPCDR) (MacDougall et al., 1987).

Seals will be placed in shafts, ramps, drifts, and boreholes. Shaft seals will include several massive concrete plugs, some to be installed at or near the surface, others at depth. Ramp seals may consist of numerous dams along the ramps, or of a single repository seal (DOE, 1988, p. 8.3.3.2-6). Many different types of seals that might possibly be used in the underground facility have been identified (DOE, 1988, pp. 8.3.3.1-4/5, p. 8.3.3.2-6). The sealing strategy for shafts, ramps and especially the underground facility emphasizes the likely use of a combination of barriers (dams, bulkheads, fracture grouting) and drains (channels, sumps). Clay and cementitious seal materials are mentioned.

4.0 PREDICTING LONG-TERM SEAL PERFORMANCE BASED ON SHORT-TERM TESTS

4.1 Description of Problem

Tests for determining the various performance characteristics of seals, seal materials and seal systems typically are of very short duration when compared against the time period for which sealing performance may be required. The problem is not exclusive to sealing, but rather is a characteristic and fundamental problem for virtually all aspects of HLW repositories, particularly when considering the waste isolation time frame. While a number of methodologies have been proposed and developed specifically for strategies aimed at predicting the long-term performance of seals and, while those are the ones on which the present document focuses, it needs to be recognized that the long-term prediction problem is pervasive throughout HLW repository investigations. As a result, sealing oriented studies should benefit from numerous parallel investigations that are being pursued in the HLW waste programs with regard to predicting long-term behavior of many components of the repository system.

An initial information need for seal performance predictions is that of the future environment in which seals will have to function. Here, again, rather than detailed and comprehensive predictions generated specifically for the purpose of defining the seal environment as a function of time, it is likely that much of this information can be obtained from closely related analyses conducted for overall repository performance predictions.

4.2 Characterization and Testing of Aged Sealing Materials or Seals

A number of strategies may be, and have been, implemented to test seals or sealing materials that have aged as a result of having been emplaced in situ for years, for decades, or for millennia. The feasibility or practicality of such an approach clearly depends on the availability of relevant materials that have been emplaced in a relevant environment. Recognizing that an exact or even a fairly close matching of emplaced materials, history and host environment with the corresponding factors for HLW repositories is unlikely, considerable insights can be derived from such investigations. Of critical concern in such investigations is the question of biased sampling. Clearly, only preserved materials can be sampled, characterized, and tested. However, severely altered or deteriorated materials may be available, as well as the very well preserved materials that appear to be more commonly tested. It would seem highly desirable for studies of ancient or recent materials to identify explicitly the sampling approach used and, in particular, to evaluate the representativeness of the materials characterized.

Rhoderick (1981) examined a 63 year-old cement grout cored from a foundation. Based on X-ray diffraction (XRD)and scanning electron microscopy (SEM), Rhoderick determined that the grout had a normal composition and microstructure, after having been continuously below the water table for about 63 years.

Much more comprehensive and systematic investigations have been performed on cement-based ancient building materials (Roy et al., 1979; Roy, 1980; Grutzeck et al., 1980; Sarkar et al., 1982; Roy and Langton, 1982; Roy and Langton, 1983; Langton and Roy, 1984), including characterizations of ancient concretes in tuff-like environments (Roy and Langton, 1989). Their investigations have tended to focus on the determination of structure and composition of the materials. Although relations between hydrological characteristics and structural or compositional changes have been postulated to exist and have been implemented in longevity studies (Coons and Alcorn, 1989), more direct experimental determinations of such relations would be highly desirable.

A fairly comprehensive suite of characteristics and properties for a cementitious plug sample recovered some 17+ years after emplacement in a borehole includes determination of plug, host rock and contact region mineralogy, compressive strength and permeability, porosity and density, and chemical composition (Roy, 1980; Buck and Burkes, 1979).

Given the feasibility of estimating the original mixes of the ancient cementitious materials, it would be helpful to reconstruct such materials, and to determine their original properties of primary significance for HLW repository sealing. This includes hydraulic properties such as hydraulic conductivity and porosity, chemical (surface) characteristics, in particular sorptivity with respect to various radionuclides, and thermomechanical properties. If instigated sufficiently early, e.g. during the initiation of performance confirmation, the change in properties as a function of natural ageing in simulated repository conditions could be investigated up to the time of permanent repository closure (and, in principle, beyond). Investigations of this type have been performed on a very limited scale within the context of some repository programs (e.g. Rhoderick and Buck, 1981; Buck et al, 1981).

The extent to which the original composition and construction of ancient cementitious materials can be defined is not certain. For example, Coons et al. (1987, p. 12) take the position that "raw materials and ancient production practices are largely unknown". In order to establish a longevity demonstration based on a strategy of testing aged and ancient materials, it clearly is necessary to reduce uncertainties of this type to the greatest extent possible.

It has been proposed that the extreme durability of at least some ancient cementitious and concrete materials is due to exceptionally high quality emplacement and curing procedures (Malinowski, 1982) which may be difficult to duplicate today. It is equally well recognized that many of the presently encountered concrete durability problems are caused by unacceptably poor quality "workmanship" (ranging from design, to mixing and placing, through curing) [e.g., Newman, 1987; Mather and Mather, 1987; Neville, 1987; Welfare, 1987]. Predictions of the future performance of cementitious sealants based on investigations of ancient materials need to take account of variables related to workmanship. Similarly, they should be included in experimental and theoretical analyses and subsequent predictions based on techniques of materials science. Finally, the seal designer, specifier, contractor and inspector will need to assure that the seal materials, when emplaced, are indeed the materials for which longevity has been studied and predicted.

4.3 Monitoring Aging of Materials

Several investigations demonstrate the key information provided by experimental study of the aging of concrete materials. For example, Martialay (1987) tested air permeability of concrete over a 20 year period. The permeability for this concrete under the test conditions increased by an order of magnitude in 10 years. Beyond that time (i.e., over the 10 to 20 year decade), the permeability increase was far less. Tests of this type on sealants emplaced in a repository environment, initiated during site characterization and continued through permanent closure, would provide considerable hard data about the prospective long-term performance of seals.

Buck et al. (1981) and Rhoderick and Buck (1981) monitored structure, composition and some physical properties of cement grout designed for borehole sealing over a four-year period.* Samples

*Indications are given in the reports that specimens continue to be stored and are to be examined and tested in the future. The author is not aware of more recent reports of tests on these samples.

were stored wet, under partially simulated in situ conditions, and dry. Characterizations included visual inspection, XRD and SEM examination, and physical tests (uniaxial strength). While the scope of this program appears to be quite limited, valuable insight has been gained into the aging of these cement grouts under different environmental conditions. A systematic test program of this type, broadened to include more comprehensive simulation of in-situ conditions (e.g., emplacement in host rock, representative moisture content with water of representative chemistry) as well as more complete characterization testing (hydrological, chemical, thermo-mechanical) would be of considerable assistance in evaluating long-term performance.

Clearly, it would be desirable to conduct such continuing tests in parallel with detailed characterizations in order to elucidate the causes of changes, if any. While credibility arguments favor conduct of such tests in situ, laboratory storage may facilitate aging under more tightly controlled environmental conditions. Consideration should be given to testing materials that have been emplaced in repository-like environments several to many decades ago, as well as to testing materials emplaced specifically for seal testing purposes, or for repository construction reasons, in addition to testing of ancient materials.

4.3.1 Monitoring Engineered Materials Previously Emplaced in Repository-Like Environments

It is virtually certain that many concrete structures have been emplaced in tuffs broadly similar to those in which repository seals are to be emplaced. Such concrete structures may include tunnel liners, shaft liners, dams, sewer pipe or mine structures. It is probable that such structures have been in place for periods ranging from a few to many decades. For at least some of them, records should be available specifying installed mixes. Similarly, it should be possible to define for many such structures the environmental history to which they have been subjected. Detailed characterization and seal performance testing of the materials in such structures, including the emplaced materials and the host rock, as well as groundwater and the interface region between host and structure, would provide considerable insight into the time-dependent changes that could be expected in sealing systems.

In order to derive the full benefit of such investigations, it is essential that they integrate the information needs for all disciplines that may be required to provide input in longevity determinations, as well as in performance determinations. Guidance for such studies is provided by publications on similar investigations as cited previously.

The seals emplaced at the Nevada Test Site as part of the weapons testing program may well be prime candidates both for characterization and testing aged engineered cementitious materials and possibly for continued monitoring of aging materials. A brief description of some seals, including fracture grouting, is given by D'Appolonia (1979, Section 5.1). Although no details about host rock are provided, it is implied that numerous seals have been installed over a wide range of depths. This strongly suggests that some seals might have been installed in tuffs. Cemented shaft and/or borehole casings similarly might provide opportunities for characterizing, testing, and future monitoring of cement or concrete performance in a tuff environment. A broader range of structures could be considered (e.g., tunnel or shaft liners, concrete pipe, or even concrete foundations). Recognizing the difference in environments, such structures and materials nevertheless provide opportunities for evaluating interactions between cementitious materials and potential seal host rocks over periods that may have ranged up to many decades. Results may also be useful in validating or calibrating theoretical models developed for predicting such interactions. Moreover, it should be feasible to repeat such characterizations in the future. This would allow the acquisition of a data base over a duration well in excess of a century, from the time of emplacement of the structures up to the time of repository closing. Availability of a data base over such a duration will reduce the time over which extrapolations need to be made by several orders of magnitude.

4.3.2 Long-Term Monitoring of Seal Materials, Seals, and Seal Systems

A variety of strategies have been proposed and pursued for demonstrating long term performance of seals. These include accelerated aging, investigations of old and ancient materials, aging calculations based on chemical thermodynamics and kinetics, dissolution and precipitation calculations, and natural analog studies. Particularly when used in combination, such strategies will assist considerably in providing reasonable assurance that long-term sealing is feasible. The lack of direct physical validation of the performance of the sealing systems to be implemented will leave residual uncertainty.

The time frame over which necessary extrapolations need to be made can be reduced greatly by conducting seal performance testing over a time period up to permanent closure. If such experiments were to be initiated during site characterization, their completion would provide observations over nearly a century. Extrapolation by a factor of 10 of this time frame would cover the most critical period for seal performance. Extrapolation by a factor of 100 would cover the entire duration for which seal performance might be required. While such extrapolations may not be considered particularly reliable in a strict scientific methodology, they are not uncommon in engineering practice. Extrapolations by 10 or 100 are certain to be more credible than extrapolations over time periods which are 1,000 to 10,000 times longer than currently possible on the basis of most sealing experiments performed to date.

The most obvious approach to an in-situ seal performance monitoring program would consist of repeated, although not necessarily frequent, characterization of seals emplaced during site characterization. Seals to be monitored could be emplaced within or near the exploratory shaft facility. Initial flow testing could provide early demonstration of the feasibility of short term sealing—i.e., results available by the time of license application. Various installation or aging conditions would be desirable, and could include "natural" conditions, artificial accelerated dry and saturated conditions. If such a range of installations could be maintained up to permanent closure, it would provide an extensive data base for model validation.

While basic seal performance monitoring (e.g., flow testing) is an essential objective of such tests, at least equally important is the acquisition of the necessary data to validate long-term prediction models. This would require comprehensive characterization of the seal system, in terms of the information needs for various disciplines (geochemistry, hydrology, mechanics). Invasive sample extraction on multiple occasions will be required, indicating the need for sufficiently large and/or numerous seal installations to permit such sampling without compromising future continuation of the monitoring efforts.

Clearly, it would be highly desirable to complement extended insitu monitoring with parallel laboratory monitoring and testing of seal systems, i.e. seal materials emplaced in host rock samples. Laboratory testing permits a broader range of variables. Accelerated laboratory aging, in conjunction with extended insitu monitoring, could provide the necessary data to assess the validity of accelerated tests for predicting long-term behavior.

While monitoring the performance of materials designed for sealing purposes is the preferred approach, other options will present themselves in practice. In particular, exploratory shaft liners in contact with a range of host tuffs will be available for occasional characterization. Although it can be expected that good quality specifications and construction records will be available for these liners, it may be noted that comprehensive and detailed characterization of all materials used could be of considerable help in future aging studies. (A common problem in analyses of concretes and grout plugs that were installed decades ago is the lack of detailed information about the originally installed products and installation procedures).

4.4 Accelerated Aging

Accelerated aging or curing of concrete compression test specimens is accepted standard practice, at least over short periods. However, the relevant standard (ASTM C 684, Section 4.2) itself extensively qualifies the use of accelerated curing, clearly indicating questionable aspects of such procedures.

Commonly used aging procedures involve accelerating reactions by raising the temperature and pressure of the reacting materials. Strong reservations have been expressed about such accelerating procedures (e.g., Lambert, 1980; Meyer and Howard, 1983, p. 123; Mott, Hay and Anderson, 1984, p. 123; Abdun-Nur, 1987), because of the risk of introducing reactions which do not occur at expected operating conditions. Recognizing the risks associated with accelerating aging, this procedure nevertheless deserves further attention. First, if the accelerating environment is controlled to a relatively limited range, it may provide correct accelerations—i.e., speed up the intended reactions without introducing extraneous reactions. While the rate of acceleration may be limited, and hence not reduce the necessary test time dramatically, such accelerated tests will provide data representative for longer periods than can be achieved otherwise. Second, accelerated tests can provide model validation results. In particular, they can be useful in assessing the adequacy of model predictions with respect to reaction types and reaction rates.

In order to obtain the full potential benefit of accelerated aging experiments, it would be highly desirable that they integrate a complete suite of characterization tests and performance tests. The former include structure and composition, the latter permeability, porosity, sorption, and strength.

4.5 Natural Analogs

Validation of long-term predictions by means of natural analogs has been pursued extensively within various HLW repository programs. As may be expected, within the sealing context, natural analogs have been invoked primarily to justify "natural" engineered barriers such as certain clays, in particular, bentonite (e.g., Pusch and Bergstrom, 1980; Smith and McCarel, 1980; Hodges et al., 1980, Kelsall et al., 1982, Section 3.1.2.3; Cameron, 1982; Meyer and Howard, 1983; Pusch, 1983). Notwithstanding the basic selection of bentonite type sealants because of their demonstrated stability in many natural environments, stability under specific repository operational conditions is not assured, and needs to be demonstrated (e.g., Roy and Burns, 1982; Meyer and Howard, 1983, Ch. 4 and, in particular, Section 4.2.2.4). The widespread occurrence of smectite within and below the Yucca Mountain repository horizon (Bish et al., 1984) strongly suggests that assessment of long-term chemical stability of bentonite seals could largely be derived from the geochemical repository program.

4.6 Theoretical Modeling as an Extrapolation Strategy from Short-Term Testing to Long-Term Seal Performance

Given the impossibility of conducting tests over a period even approximating that for which repository sealing is required, theoretical extrapolations of experimental results and empirical data are essential and integral aspects of demonstrating long-term seal performance. Several approaches may be applied.

One fundamental approach consists of determining the thermodynamic relations that govern the long-term changes in the seal system—i.e., the interacting seal material(s), host rock, and groundwater (Lambert, 1980; Roy, 1980; D'Appolonia, 1980, Section 2.1.3; Roy 1981; Meyer and Howard, 1983; Myers, 1986; Coons et al., 1987; Pusch et al., 1988; Melchior et al., 1988; Pusch, 1988; Coons and Alcorn, 1989). Thermodynamic predictions of future compositions of sealing systems require the identification of all phases in the system [e.g., concrete (cement paste, aggregates), host rock, and groundwater, or clay, host rock, groundwater], identification of all possible reactions, and calculation of the thermodynamically stable phases based on the free energy of formation of each possible reaction and reaction product. Considerable skepticism has been expressed about the availability of the necessary data (Mott, Hay and Anderson, 1984, p. 124). This does not appear to justify abandoning the approach, particularly in view of progress already made in determining the necessary properties (e.g., Sarkar et al., 1982; Grutzeck, et al., 1980; Roy et al., 1983), but it does point out the daunting scope of the task, well stated by Lambert (1980). A more fundamental problem may well be the question of the applicability of the thermodynamic calculations to a continuously changing system (e.g., in terms of water content, temperature, fluid pressure and total stress).

In order to permit evaluation of the rate at which changes take place and, hence, ultimately, determination of the properties directly relevant to sealing performance as a function of time, the kinetics of the chemical reactions need to be determined. This step is particularly uncertain, especially for products selected specifically to be stable in their operational environment —i.e., subject to very slow changes only. Conversely, it can be argued that less detail or refinement is needed about the kinetics in proportion to the stability of the sealing system at seal emplacement. If reactions are sufficiently slow, their precise rate may be of little consequence.

The final step in the theoretical model predictions is to relate the seal structure phase composition to the sealing performance requirements (Grutzeck et al., 1980; Coons and Alcorn, 1989). The latter include in particular hydrological performance (hydraulic conductivity, porosity), mechanical performance (strength and stiffness), and possible radionuclide retardation properties and thermal properties. At this phase of the modeling also it is essential that the complete seal system be considered —i.e., seal, host rock, and interface, as well as the environmental conditions under which the system is operating.

Phase composition changes within cementitious materials and clay have dominated longevity modeling to date. Experimental evidence clearly indicates that such modeling needs to be complemented by more explicit and direct relations to seal system performance parameters. The considerable strength reductions of Topopah Spring tuff observed by Blacic et al., (1986) after several months of exposure to a range of near-field conditions that may include some seal locations, if accompanied by corresponding stiffness reductions, could substantially enhance loading on even moderately stiff plugs. It is essential, for theoretical models aimed at predicting longevity of seals, to consider the full suite of fundamental processes and events that may initiate changes and to relate them to the final consequences in terms of seal performance parameters.

A second fundamental theoretical approach addresses leaching and precipitation in the seal system. The analysis requires first a prediction of the water flow rate through the seal system, as well as of the temperature and pressure distribution, and knowledge of the water chemistry. Second, dissolution rates of any solution-prone constituents of the seal system components (e.g., cement paste, aggregate, host rock) are determined. Third, reprecipitation from flowing water is determined. Finally, the consequences of the dissolution and precipitation processes with respect to seal performance parameters (e.g., hydraulic conductivity, porosity, stiffness, strength, sorption) are evaluated. Although the detailed modeling of the conditions and processes is complex, even greatly simplified calculations provide considerable insight into long-term seal performance (e.g., Coons and Alcorn, 1989). If highly simplified calculations are conducted for performance assessments, it will be necessary to demonstrate that the conclusions are conservative.

A third basic mechanism of deterioration that needs to be addressed is thermal-mechanical modification of the seal system structure. For example, excessive seal swelling in a rock mass subject to a strongly anisotropic in-situ stress field could readily enhance flow paths via unfavorably oriented discontinuities (e.g., Dowding and Labuz, 1982; Akgun and Daemen, 1986). Similarly, ill-matched thermal expansion of seals and host rock could result in seal-rock separations, or in seal fracturing. Finally, mechanical transport (erosion, piping, channeling) could have deleterious influence on seal structure. In sum, a considerable number of fundamental mechanisms can alter the structure of seals. These need to be identified, and the likelihood of their occurrence needs to be established. If they are considered to be anticipated processes or events, a coherent theoretical formulation will require identification of causes, and an analysis of their development over the duration for which sealing performance is required.

It is clear that acceptance of the theoretical model approach to extrapolating long-term seal performance from short-term test data will require validation. Experimental and empirical validation can be achieved by parallel pursuit of the theoretical approach with complementary experimental and empirical approaches outlined in Sections 4.2 through 4.6 of this document.

4.7 Host- and Environment-Compatible Seals

It has long been recognized (e.g., D'Appolonia, 1979) that one of the most promising approaches to assuring durability and longevity of seals is to provide the greatest possible compatibility between seals and host rock. The objective of such a seal material selection approach is to minimize reactions "which could adversely affect the durability, bond, and host rock in the vicinity of the penetration" (D'Appolonia, 1979, p. III-24). The need is asserted for chemical, electro-chemical and physical compatibility with the host rock. They specify that the seal should not be adversely affected by ambient fluids and gases or pressures and temperatures. Moreover, the seal material should be thermodynamically stable so that its performance can be assured for very long time periods. The potential benefits from such an approach have been demonstrated experimentally by Scheetz and Roy (1985, 1989) for a cementitious grout designed to be chemically compatible with the Topopah Spring tuff. The results also clearly indicate that bulk chemical compatibility is not sufficient to preclude extensive reactions. It was observed that some chemically compatible but less densely welded concrete aggregates suffered considerable dissolution in high temperature experiments.

4.8 Durable Seals

The emplacement of durable seals may greatly enhance confidence in predictions of long-term seal performance. While it may seem tautological to recommend durable seals in order to demonstrate seal longevity, the conceptual theoretical benefits that result from the emplacement of durable seals deserve emphasis in light of the repeated assertions that "limited sealing measures are sufficient to isolate properly the radioactive waste in the [Yucca Mountain] repository. . ." (DOE, 1988, p. 8.3.3.2-24). Demonstration of even limited long-term sealing performance may be far more difficult for seals designed to limited performance specifications if such seals are more susceptible to deterioration as a result of low density, high permeability, low strength, etc., at the time of emplacement.

The installation of high density, low permeability and low porosity seals has a multiplier effect on providing assurance about long term seal performance (Coons and Alcorn, 1989): less contact area is available for reactions between fluids and cement grout components, the slower water travel time reduces the volume of water in which dissolution can place, and less material is removed from the seals. Acceptance of high permeability for seals that are required to be durable, even if at relatively modest performance levels, appears contradictory. This is especially of concern with regard to emplacement of concrete in highly reactive tuffs, for which experimental evidence strongly suggests a high risk of potentially relatively rapid changes in both the aggregate and the cement paste (e.g., Komarneni et al., 1985; Scheetz and Roy, 1989).

Recognizing that some interactions could have beneficial effects by chemically bonding tuff and cement paste (Malek and Roy, 1985), the considerable reactions in a conventional concrete ". . . point to areas of concern" even though ". . . the specimens were not grossly damaged in periods of a few months . . . " (Scheetz and Roy, 1985, p. 942). The matter may have some urgency in light of the probable use of conventional concretes for the exploratory shaft liners (Fernandez et al., 1989, p. 113).

4.9 Long-Term Drainage

If long-term drainage is an allocated performance requirement within the overall seal system performance, reasonable assurance needs to be provided that adequate drainage can be maintained. This is particularly true for a host formation such as the Topopah Spring tuff, with a relatively low virgin hydraulic conductivity and containing highly reactive minerals prone to the formation of smectites and to dissolution (Morrow et al., 1983; Blacic et al., 1986). Further, smectites occur naturally in this unit, possibly in fairly high local concentrations. It can be assumed that the primary responsibility for assessing the long-term hydraulic conductivity of the host rock falls within the responsibility of the hydrology and geo-chemistry programs. To the extent that drainage is affected by overlying or by adjacent seal components, or by nearby structural components (e.g., concrete liners or steel bolts), their influence needs to be investigated and taken into account in predictions of long-term drainage capacities. In this regard, the potential for cementitious materials to cause permeability reductions is raised explicitly by Morrow et al. (1983).

Basic strategies to determine long-term drainage performance by extrapolation from short term tests are likely to parallel those for seals. Experimental results can be obtained through a combination of laboratory and field tests. These may include flow tests at elevated temperatures, pressures, flows, and gradients ("accelerated aging" experiments), with the reservations expressed previously about limitations on accelerated tests. Empirical evidence from historical processes may be obtained from natural infiltration sites, including those where infiltrating waters contact concrete. Integration of experimental and empirical results within a fundamental theoretical model is desirable in order to permit extrapolation of the results to predict long-term performance.

5.0 SUMMARY AND CONCLUSIONS

10 CFR60.101(a)(2) identifies methods that can be used to provide reasonable assurance that long-term criteria and objectives for the performance of a HLW repository will be satisfied. Repository sealing requirements are included among the criteria and objectives. NRC staff guidance is provided in a number of referenced documents, both with regard to sealing requirements and with regard to strategies that can be implemented to demonstrate long performance.

In this document, emphasis is placed on the multidisciplinary aspects of demonstrating long-term performance of seals on the basis of short-term tests. The seal longevity question has much in common with many barrier and repository questions, and needs a similar integrated approach in order to arrive at reasonable assurance about long-term performance. Hydrological performance is likely to be the dominant performance requirement, possibly complemented by retardation performance, in particular sorption. Mechanical performance probably will be required for at least some sealing components. The tests and analyses aimed at extrapolating results from short-term tests to long-term performance need to take account of coupled hydrological and chemical effects. Depending on seal location and ground conditions, thermal and mechanical coupling may also need to be taken into account. Radiological coupling is unlikely to be required for seals. Further, it is possible that the question of potential microbial effects may need to be addressed.

The most promising approach to extrapolation of short-term test data for long-term seal performance prediction is to identify material changes that are likely to occur over the long term, their causes and their consequences in terms of seal performance. As a corollary, it follows that an attractive approach is to promote a seal design in which materials have the least likelihood of being subject to changes in the seal ambient conditions. Durable materials considered for sealing such as cement grouts, concretes, and compacted clays, tend to have increased durability more than proportional to initial sealing performance (e.g., longevity increases more than proportionally to the inverse of the hydraulic conductivity), thus reinforcing the rationale for the desirability of high quality sealing. Conversely, emplacing seals of poorer quality, based on performance assessments that might indicate the adequacy of less stringent seal requirements, is virtually certain to reduce the credibility of predictions of long-term seal performance. Emplacement of seal materials with high permeability, high porosity and less than achievable hydraulic bonding between seals and host rock invites questions about reactions and consequent deteriorations throughout the seal volumes.

Because coupled effects are unavoidable in long-term performance, seals must be considered as a sealing system in which the long-term behaviors of the emplaced seal material, host rock, and groundwater are closely related. Changes in any of these components will affect the other components. Changes in the operational environment may affect all of them.

Several strategies have been proposed and pursued to demonstrate compliance with long term performance requirements. Such methodologies include the study of natural analogs, ancient materials, and structures of industrial age to modern materials and structures, supplemented by theoretical analyses of material stability and of expected repository environments. These can pro vide an extensive combination of empirical, experimental and theoretical results to evaluate long-term performance.

It is concluded from this review that the remaining uncertainty about future seal performance can be reduced further, and most directly, effectively and convincingly by a performance confirmation program aimed at reducing uncertainty at two important milestones: the License Application (10CFR 60.21) and Permanent Closure (10 CFR 60.51). Such a performance confirmation program should be initiated early, in order to assure the availability of initial results by the time of License Application. A firm commitment and plan for continued monitoring, testing and analysis up to the time for the application of a license amendment for permanent closure will provide confidence that experimental data for validation of predictive models will be available covering a period of many decades. A significant potential disadvantage of such a strategy is that it may inhibit the development or application of newer materials or seal configurations. This risk would seem well worthwhile taking into account the considerable assurance that would be obtained from long-term performance monitoring.

The recommended program would include laboratory and field testing, the latter preferably in situ—i.e., in the actual proposed host formation(s) for seals. In-situ testing would include tests on borehole seals and, as a minimum, on small size shaft and drift seals. A sufficient number of seals should be emplaced to allow some seals to age in a virgin environment, and some seals in the likely post-waste emplacement environment. In the latter case, a probable major change in conditions is the potential thermally driven increase in saturation (possibly to full saturation) and pressurized water and vapor flow. These conditions can be readily simulated by standard flow tests. Another extreme condition corresponds to emplacement in a location where seals are dried out by thermal effects. In all cases, plugs emplaced for such long-term performance monitoring should be of sufficient volume to allow occasional material sampling for characterization and testing purposes.

Laboratory monitoring of the aging performance of plugs allows tighter environmental control, and hence less uncertain input for theoretical analyses in terms of initial, boundary and state conditions. Laboratory aging can be performed on seal materials themselves as well as on seal materials emplaced in host rock, thus allowing distinction between changes arising within the material itself from changes associated with seal-rock interactions. Similarly, water composition is more readily controlled and monitored in laboratory experiments.

In field test programs, regular, though not necessarily frequent, characterization of the aging seal system will provide the data needed to validate theoretical models of seal system performance predictions. Such characterizations should include structural, chemical and physical characterization of seal materials, host rock, interface and groundwater. Model development is likely to proceed in parallel with experiments. Models are needed to predict the chemical and physical changes in the seal system components, and to relate these changes to performance parameters such as permeability, porosity, sorption, and strength. Many model developments and validation efforts which will be performed within the context of overall repository performance predictions, particularly with regard to the host rock component of the seal system, can feed directly into the sealing program. An explicit effort intended to ensure that such integration will indeed take place deserves high priority.

Complementary to the recommended direct long-term monitoring approach are various indirect approaches that deserve further consideration. Prominent among these could be characterization and testing of aged concrete structures in the Yucca Mountain environment or in similar environments. In such studies, a concern is that such analog studies are designed to include the system parameters needed in performance analyses. The same comment applies to the use of natural analogs, which, if available for the appropriate materials, processes and settings, could provide data for validation of the predictive method over even longer periods of extrapolation. The proposed use of natural analogs makes the tie-in with the overall repository program particularly obvious. While it may not be clear that a natural analog program devoted exclusively to sealing is needed or justified, transfer of information from any repository natural analog programs to the sealing design and analysis effort would be desirable. Similarly, transfer of information from the sealing effort to natural analog investigations would ensure that sealing issues are addressed in analog studies wherever possible and appropriate.

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