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OVERVIEW OF ORNL/NRC PROGRAMS ADDRESSING DURABILITY OF CONCRETE STRUCTURES*

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ABSTRACT

The role of reinforced concrete relative to its applications as either safety-related structures in nuclear power plants or engineered barriers of low-level radioactive waste disposal facilities is described. Factors that can affect the long-term durability of reinforced concrete are identified. Overviews are presented of the Structural Aging Program, which is addressing the aging management of safety-related concrete structures in nuclear power plants, and the Permeability Test Methods and Data Program, which is identifying pertinent data and information for use in performance assessments of engineered barriers for low-level radioactive waste disposal.

1. INTRODUCTION

History tells us that concrete is a durable material. However, a number of factors acting singularly or in combination can compromise its performance in a structure: (1) faulty design; (2) use of unsuitable materials; (3) improper workmanship; (4) exposure to aggressive environments; (5) excessive structural loads; and (6) accident conditions. Furthermore, aging of concrete structures occurs with the passage of time and has the potential, if its effects are not controlled, to increase the risk to public health and safety. Many factors complicate the analysis of aging effects on the residual life of concrete structures. Uncertainties arise due to (1) differences in design codes and standards for components of different vintage; (2) lack of past measurements and records; (3) limitations in the applicability of time-dependent models for quantifying the contribution of aging to structure failure; and (4) inadequacy of detection, inspection, surveillance, and maintenance methods or programs [1].

Concrete in many structures can suffer undesirable degrees of change with time because of improper specifications, a violation of specification, or environmental or aging effects. Over the life of the structure, changes in properties of the structure's constituent materials in all likelihood will occur as a result of aging or environmental stressor effects. The longevity, or long-term performance, of reinforced concrete structures is primarily a function of their durability or ability to withstand potential degradation effects. Primary mechanisms which can produce premature deterioration of reinforced-concrete structures include those that can impact either the concrete or steel-reinforcing materials. Degradation of concrete can be caused by adverse performance of either its cement-paste matrix or aggregate materials under chemical or physical attack. Chemical attack of concrete may occur in several forms: efflorescence or leaching, sulfate attack, salt crystallization, attack by acids and bases, and alkali-aggregate reactions. Physical attack mechanisms for concrete include freeze/thaw cycling, thermal exposure/thermal cycling, irradiation, abrasion/erosion/cavitation, and fatigue or vibration. Degradation of mild steel reinforcing materials can occur as a result of corrosion, irradiation, elevated temperature, or fatigue effects. Steel prestressing materials are susceptible to the same degradation mechanisms as mild steel reinforcement, plus the loss of prestressing force due primarily to tendon relaxation, and concrete creep and shrinkage. References [2] and [3] provide more detailed discussions of the potential degradation mechanisms.

2. BACKGROUND

Within the nuclear power industry, the aging of structures, as well as that of components and systems, has recently become the subject of significant research. This interest is prompted by the need to quantify the effects of aging to support current or future condition assessments of safety-related concrete structures in light-water reactor (LWR) plants, and to quantify the effects of aging in terms of potential loss of component integrity or function of the concrete structures being considered for use as engineered barriers in low-level radioactive waste disposal sites.

A myriad of concrete structures are contained as a part of an LWR facility to provide vital foundation, support, containment, and shielding functions. The names and configurations of the safety-related concrete structures vary somewhat from plant to plant depending on the nuclear steam supply system vendor, architect-engineer firm, and owner preference. Examples of some of the safety-related concrete structures include the primary containment, reactor building, water intake structure, containment foundation, auxiliary building, reactor vessel pedestal, biological shield wall, and fuel/equipment storage pool. A general description of these structures is provided in Refs. [2] and [3]. In the next few years, several of the commercial nuclear power plants will reach the end of their nominal 40-year operating license period. Guidelines and criteria are required for use in assessing the remaining structural margins (residual life) of the safety-related concrete structures. These assessments will be part of the standardized review guidelines used in the evaluation process associated with requests by utilities to continue the service of nuclear power plants beyond their initial operating license period.

Reinforced concrete structures are being considered for use as engineered barriers in low-level radioactive waste disposal applications. These structures will most likely be constructed using concrete and reinforcing steel materials that are currently available. Design methods also would essentially be adaptations of those that have been developed for structures currently being constructed [4]. However, unlike today's reinforced concrete structures, which are intended to remain in service for 40 to 100 years, these structures may need to provide structural support for 300 years and provide recognition as an intruder barrier for 500 years. The reinforced concrete may also be used, if justified, to provide resistance to fluid flow and mass transport of radionuclides for long periods of time. Although the construction materials and design methods are similar to those used for conventional civil engineering structures, historical field data on long-term performance of reinforced concrete exposed to various below-grade environments for use in performance assessments of the low-level radioactive waste disposal facilities are lacking.

3. DURABILITY OF REINFORCED CONCRETE STRUCTURES

Two programs are currently being conducted at Oak Ridge National Laboratory under United States Nuclear Regulatory Commission (USNRC) sponsorship that address the durability of reinforced concrete structures. The Structural Aging (SAG) Program is investigating aging management of safety-related concrete structures in nuclear power plants. The Permeability Test Methods and Data Program is identifying pertinent data and information for use in performance assessments of engineered barriers for low-level radioactive waste disposal.

3.1 Structural Aging Program

Incidences of structural degradation related to concrete components in nuclear power plants [5] indicate that there is a need for improved surveillance, inspection/testing, and maintenance to enhance the technical bases for assurances of continued safe operation of nuclear power plants. The SAG Program has the overall objective of preparing documentation that will provide USNRC license reviewers with (1) identification and evaluation of potential structural degradation processes; (2) issues to be addressed under nuclear power plant continued service reviews, as well as criteria, and their bases for resolution of these issues; (3) identification and evaluation of relevant in-service inspection or structural assessment programs; and (4) methodologies required to perform current assessments and reliability-based life predictions of safety-related concrete structures. To accomplish this objective, activities are conducted under three task areas: (1) materials property data base; (2) structural component assessment/repair technologies; and (3) quantitative methodology for continued service determinations.

3.1.1 Materials Property Data Base

The primary objective of this task is to develop a reference source [Structural Materials Information Center (SMIC)] containing data and information on the time variation of material properties under the influence of pertinent environmental stressors and aging factors. Presentation formats developed for the SMIC include a *Structural Materials Handbook* and a *Structural Materials Electronic Data Base* [6]. When issued, the *Structural Materials Handbook* will be an expandable, hard-copy reference document containing complete sets of data and information for each material entry. Included will be performance and analysis information useful for structural assessments and safety margin evaluations, e.g., performance values for mechanical, thermal, physical, and other properties presented as tables, graphs, and mathematical equations. The *Structural Materials*

Electronic Data Base is an electronically accessible version of the handbook. The electronic data base is being developed on an IBM-compatible personal computer and employs two software programs: Mat.DB[7] and EnPlot [8]. Mat.DB is a menu-driven program for data base management that employs window overlays to access data searching and editing features. EnPlot incorporates pop-up menus for creating and editing graphs. To date, 145 material data bases (129 concrete, 12 metallic reinforcement, 1 prestressing steel, 2 structural steel, and 1 rubber material) have been developed. Concrete material property data files are available presenting the effects on specific performance characteristics of age, curing conditions, thermal exposure, radiation exposure, sulfate exposure, and acid exposure. Also included are data files containing results either obtained by testing concrete core samples obtained from U.S. nuclear power facilities or prisms cast in conjunction with fabrication of several United Kingdom power plants. Reference [5] presents more details on data base files contained in SMIC.

A second objective of this task is to evaluate methods for predicting the service life or performance of existing reinforced concrete structures. Degradation processes (corrosion of steel reinforcement, sulfate attack, etc.), which can potentially impact the performance of these structures, were reviewed based on likelihood of occurrence, manifestations, and detectability. Models identified for each of these processes were evaluated. A major conclusion of the study was that theoretical models need to be developed, rather than relying solely on empirical models. Predictions from theoretical models are more reliable, far less data are needed, and they would have wider application. Purely stochastic models have limited application because of the lack of data to determine statistical parameters. Deterministic and stochastic models should be combined to give realistic predictions of the service life of an engineering material. More details are available in Ref. [9].

In a related activity, a collation of survey data and a durability assessment review of reinforced concrete structures contained as a part of several nuclear power stations located in the United Kingdom has been completed [10]. The survey data were input into models developed for prediction of onset of corrosion of steel reinforcement due to either carbonation or chloride ingress. Predicted maximum age for steel reinforcement corrosion activation due to either carbonation or chloride ingress at selected locations in the plants ranged from 31 to >140 years and 43 to >140 years, respectively. Visual surveys of the plants indicated that the interior structures were sound with no corrosion, whereas the external concrete in many instances exhibited a few localized areas of cracking and spalling.

3.1.2 Structural Component Assessment/Repair Technology

The objectives of this task are to (1) develop a systematic methodology which can be used to make quantitative assessments of the significance of any environmental stressors or aging factors which could adversely impact the durability of safety-related concrete structures in nuclear power plants and (2) provide recommended in-service inspection or sampling procedures to develop data to evaluate the current condition as well as trend the performance of concrete components. Techniques for concrete repair or mitigation of deteriorating influences are also addressed.

LWR Critical Concrete Component Classification. A methodology has been developed which provides a logical basis for identifying critical concrete structural elements in a nuclear power plant and the pertinent potential degradation factors [11]. Numerical rating systems were used to establish structural subelement relative importance, the subelement's safety significance, and influences of environmental exposure. Determination of a structure's relative ranking is based on the weighted contributions of the (1) structural importance of subelements; (2) safety significance; (3) environmental exposure; and (4) degradation factor significance.

NDE/Sampling Inspection Technology. Direct and indirect methods used to detect concrete material degradation have been assessed [12]. Direct methods involve a visual inspection of the structure, material removal/testing/analysis, or a combination of the above. Indirect methods measure a concrete property and use established correlation curves to estimate the strength, elastic behavior, or degradation. Contained in the assessment are (1) reviews of the capabilities, accuracies, and limitations of available concrete inspection techniques; (2) descriptions of inspection methodologies for indicating concrete condition; (3) recommendations on application of testing methods; and (4) descriptions of developing methods for indicating concrete degradation, e.g., magnetic (leakage flux and nuclear magnetic resonance), electrical (capacitance, polarization resistance, and half-cell potential using impulse radar), ultraviolet radiation, and finite-element analysis methods.

As noted, indirect testing methods for concrete structures require correlation curves developed from a small number of destructive and nondestructive tests conducted in tandem at noncritical locations. If destructive tests cannot be performed to develop these curves, assessment of in-place strength must be based on published results. Correlation curves, other statistical data, and parameters required to estimate compressive strength from subsequent nondestructive tests were developed for commonly used nondestructive testing techniques by applying monovariant linear regression analyses to published data, i.e., break-off, pullout, rebound hammer, ultrasonic pulse velocity, and probe penetration [13].

Remedial/Preventative Measures. An overview of the European perspective on concrete repair has been conducted [14]. Specific topics covered included (1) descriptions of repair materials/procedures utilized, (2) criteria for procedure selection, (3) assessment of the procedure effectiveness, and (4) future direction of concrete repairs. Although there are no European standards governing repair of concrete, there are several documents that provide guidelines, with the most widely developed regulations having been prepared by the German Committee on Reinforced Concrete [15]. Damage occurring as a result of carbonation or chloride presence are the most important sources of concrete distress in Europe. For carbonation, the emphasis has been placed on anti-carbonation surface treatments, protective properties of patch materials, and the durability/compatibility of these materials. For chloride attack, efforts are underway to provide an improved understanding of the corrosion mechanisms, the mechanism of incipient anode development, and the use of cathodic protection to overcome the problem.

A complementary activity has reviewed North American practices for concrete repair and covered deterioration modes, repair methodologies and materials, techniques for repair evaluation, and case histories [16]. Information addressing repair of reinforced concrete in nuclear power plants was assembled through a questionnaire sent to U.S. utilities requesting information on inspection procedures, deterioration mechanisms and manifestations, repair actions undertaken, and repair performance history. Responses provided by 29 sites representing 41 units indicate that (1) inspection of the concrete structures is generally done only in compliance with integrated leak-rate testing and post-tensioning system surveillance requirements; (2) the performance of the concrete structures has been good, with cracking, spalling, and staining being the primary forms of degradation; and (3) most of the repair activities were associated with problems during construction (cracks, spalls, and delaminations), with the repairs performed on an as-needed basis, and post-repair evaluations done using visual methods.

An assessment has been completed of the corrosion of metals embedded in or in contact with concrete [17]. Topics covered included discussions of the electrochemical process, types of corrosion (uniform, bi-metallic, fretting, etc.), conditions that affect corrosion rate (temperature, electrolyte conductivity, etc.), effect of concrete environment, detection of corrosion (visual, half-cell potential measurements, magnetic perturbation, etc.), and remedial measures (corrosion inhibitors, chloride removal, dielectric isolation, etc.). The potential for occurrence of stray electrical current-induced corrosion in nuclear power plants and use of cathodic protection systems to mitigate corrosion are also discussed.

An approach for develoment of a systematic damage rating system to assess repair requirements for reinforced concrete structures in nuclear power plants has been outlined [18]. The approach is similar to that for the critical concrete component classification methodology [11] except that instead of using four factors to develop a rating (repair prioritization number), two factors are considered: the environmental exposure and damage state. Criteria are being developed to relate these two factors to repair requirements, i.e., no further action, testing and evaluation required, or remedial action required.

3.1.3 Quantitative Methodology for Continued Service Determinations

The objective of this task is to develop a methodology to facilitate quantitative assessments of current and future structural reliability and performance of concrete structures in nuclear power plants. Time-dependent reliability analysis provides a framework for condition assessments of existing structures and for determining whether in-service inspection/maintenance is required to maintain reliability and performance at the desired level. The methodology integrates information on degradation and damage accumulation, environmental factors, and load history into a decision tool that provides a quantitative measure of structural reliability and performance under projected service conditions based on an assessment of a new or existing structure. A more detailed discussion of the methodology relative to that presented below is presented in Ref. [19].

The strength of structural members and components can be described statistically by data gathered in research over the past decade to develop improved bases for structural design of new reinforced concrete structures [20, 21]. Time-dependent changes in concrete strength due to aging phenomena were not considered in developing these statistics, and they are not directly applicable to the evaluation of existing, possibly degraded, structures with a given service history [22]. To account for aging effects, the concrete structural resistance can be modeled as

$$R(t) = R_o \, g(t), \tag{1}$$

in which R_o is the initial random resistance and g(t) is a time-dependent degradation function defining the fraction of initial strength remaining at time t. Conceptually, a function g(t) can be associated with each environmental stressor.

Structural loads are random in both time of occurrence and intensity. If the load intensity varies slowly during a load event, its effect on the structure is essentially static. Also, durations of significant loads are usually short, occupying only a small fraction of the total life of a structure. Therefore, structural loads can be modeled as a sequence of pulses, whose occurrence is described by a Poisson process with mean occurrence rate, λ, and duration, τ. The pulse intensities S_j are assumed to be identically distributed and statistically independent random variables described by the cumulative distribution function $F_s(x)$. Many loads for which nuclear power plant structures are designed can be modeled by such processes [23].

The reliability function, L(t), is defined as the probability that the structure survives during the interval of time (0,t). If n events occur within time interval (0,t), the reliability function for a structural component can be represented as

$$L(t) = P\left[R(t_1) > S_1 \cap R(t_2) > S_2 \cap \cdots \cap R(t_n) > S_n\right]. \tag{2}$$

Taking into account randomness in number of loads, as well as times at which they occur, and in the initial strength, and assuming that g(t) is deterministic, the reliability function becomes

$$L(t) = \int_0^\infty \exp\left[-\lambda t\left[1 - \frac{1}{t}\int_0^t F_s\,(r \bullet g(t))dt\right]\right] f_{R_o}\,(r)dr, \tag{3}$$

in which $f_{R_o}(r)$ is the probability density function of the initial strength R_o [19, 24]. The limit state probability, or probability of failure during (0,t), is

$$F(t) = 1 - L\,(t). \tag{4}$$

The hazard function, or failure rate, h(t), is the probability of failure within time interval (t,t+dt) given that the component has survived up to time t, and can be expressed as

$$h(t) = -\frac{d}{dt} \ln L(t). \tag{5}$$

When structural failure occurs due to aging, h(t) increases with time.

These methods have been extended to structures subjected to combinations of structural-load processes and to structural systems [24]. The reliability function has a similar appearance to that in Eq. (3), but the outer integral on resistance increases in dimension in accordance with the number of system components. System reliability is evaluated by Monte Carlo simulation, using an importance sampling technique to enhance the efficiency of the simulation [25, 26]. The effect of degradation in component strength on component and system reliability function using several simple parametric representations of time-dependent strength is presented in Refs. [24, 26]. In the absence of in-service inspection and maintenance, the failure rate, h(t), may increase rapidly after ages of ~60 years, depending on the mode of environmental attack. The methodology can be used to devise appropriate maintenance policies to ensure that L(t) remains above a regulatory target during the service life of interest [27].

3.2 Permeability Test Methods and Data Program

Reinforced concrete structures are being considered for use as engineered barriers in low-level radioactive waste disposal applications. Performance assessments of these structures are most effectively performed through use of historical field data on long-term performance of reinforced concrete exposed to representative below-grade environments. The overall objectives of this program, therefore, are to supplement the existing knowledge base on long-term performance of reinforced concrete and to provide experimental and field data for enhancing the validity of performance assessments.

3.2.1 Reinforced Concrete Use and Current Knowledge State of Performance

Two major functions of reinforced concrete in engineered barriers of low-level radioactive waste disposal facilities may be to retard the release of radionuclides by providing both physical and chemical impediments. The physical barrier is of most value for highly soluble isotopes with relatively short half lives because the reinforced concrete is capable of providing retardation and structural integrity for a period of time sufficient to permit a large measure of the radioactivity to decay. Performance of concrete as a physical barrier is influenced by its transport properties and its mechanical durability, i.e., its ability to function as a physical barrier is likely to be limited by the presence or formation of cracks, which can provide pathways for intrusion of aggressive ions and for flow of groundwater into and through the structure. The chemical barrier provided by the concrete is important because (1) the high concrete pH (> 12) causes a passive iron oxide film to form on the surface of embedded steel to protect the steel from corrosion, and (2) the concrete may provide sorption sites where aqueous concentrations of many long-lived radionuclides are reduced. The effectiveness of the concrete as a chemical barrier is influenced by its ability to maintain an alkaline environment and to provide sites for sorption of radionuclides. Over time, due to leaching of soluble ions [$NaOH$, KOH, $Ca(OH)_2$] by water flowing through the repository, by reactions with sulfate-bearing groundwater, and by internal reactions between repository constituents, the pH of the cementitious materials is anticipated to decrease to a value equal to its host soil or surrounding groundwater.

Prediction of the service life of concrete structures in low-level radioactive waste disposal facilities requires knowledge of the potential mechanisms of deterioration, data on the time-dependent material response to aging and environmental influences, and mathematical models for estimating long-term material behavior, structural response, and transport processes. Knowledge of the potential mechanisms of deterioration is fairly well understood and is based on laboratory research, in-service observations, and field experience with many types of reinforced concrete structures located throughout the world. Materials property data for concretes and related materials are routinely developed using short-term laboratory experiments in which samples of a material are subjected to representative periods of controlled conditioning followed by comparative assessments and testing. Results are used to predict field performance and to guide development of building code requirements intended to ensure long service life. However, this approach does not guarantee long-term durability, particularly when the environments are severe or when the period of performance extends beyond the range of experience. Ideally, numerical modeling of material response in different environments would allow interactions between the basic processes of deterioration and pertinent material parameters. At present, this capability does not exist because mechanistic models lack adequate parameter data bases, especially when synergistic effects are expected, and statistical techniques, such as Monte Carlo, which propagate parameter uncertainties, cannot account for basic uncertainties or lack of understanding in the conceptual model of the waste-disposal facility.

Analytical methods for predicting the behavior of concrete structures are being developed and utilized to estimate the service life of engineered barriers subjected to anticipated exposure conditions [27, 28]. These methods rely on mathematical models and empirical equations derived from experimental data, historical observations, and accelerated-aging test results. Because modern concretes utilize portland cement that has evolved over the last 170 years or so, in-service experience and long-term performance data over a 500-year period of interest are non-existent. Some information is available on the performance of ancient concretes (e.g., lime and gypsum mortars, and hydraulic lime mortars), but these materials were made using cementitious materials that had different formulations and particle sizes than the modern portland cements. Therefore, by necessity, these analytical methods are being extended beyond their range of use, thereby introducing uncertainties in the predicted behavior.

Systematic approaches for assessing the time-dependent performance of low-level radioactive waste disposal concepts are also being developed [29]. These approaches use different analytical methods to predict the behavior of individual disposal-facility barriers over discrete time periods and then update the analysis using predicted results. Due to lack of site-specific exposure information, unspecified design and construction details, inadequate material specifications, and uncertainties in the analytical methods, results from these incremental analyses are being used primarily to evaluate the relative performance of different disposal concepts.

3.2.2 Relationship Between Concrete Durability and Permeability

Concrete's durability, or ability to resist physical or chemical attack and meet its functional and performance requirements, in large measure is an indication of its capacity to resist the deteriorating effects of water. Water is known to be the cause of many types of physical processes of degradation in porous solids and is the vehicle for transport of aggressive ions to produce chemical processes of degradation [30]. The physical/chemical processes associated with water movement through porous solids such as concrete are controlled by the permeability of the solid, i.e., relative ease with which a fluid flows through a porous material. Assuming there are not preferential flow paths such as cracks present, concrete permeability is influenced by the size, distribution and continuity of the void system, and will vary according to proportions of the constituents, degree of cement hydration, cement fineness, aggregate gradation, moisture content, presence of admixtures, etc. No standard test method for determination of concrete permeability currently exists. Simple laboratory tests in which steady-state laminar flow through a porous media is described by Darcy's equation are generally used either to compare the behavior of one cementitious material with another, to understand the effects of different mixing or curing techniques, or to indicate the relative permeability of different sections of the same structure.

3.2.3 Literature Review

In order to supplement the existing knowledge base on long-term performance of concrete materials, and to provide experimental and field data for enhancing the validity of performance assessments of engineered barriers in low-level radioactive waste disposal facilities, a literature search was conducted. Pertinent concrete journals and periodicals, and DIALOG OnDisc, which accessed references available through National Technical Information Service and Applied Science and Technology, were searched. Approximately 1000 potential references were identified and placed into one of four categories for further consideration: (1) concrete permeability tests and data, (2) concrete permeability in general, (3) durability, and (4) no interest. Because of the relationship between concrete's durability and its permeability, 67 references that fell into either category 1 or 2 were examined in detail. For each of these references, summary sheets were prepared that identified the organization performing the work, research objectives, concrete materials utilized, test parameters, experimental procedures, results, and conclusions of the authors. A commentary on each reference was also developed, and if test methods and results were provided, this information was summarized in a table.

3.2.4 Conclusion

Some general conclusions can be derived from this activity. Permeability data are not routinely used in the design of environmental engineering structures or in leaktightness of water-retaining structures. For these structures, low permeability concrete is indirectly achieved by placing maximum limits on the water-cementitious materials ratio and minimum limits on cementitious materials content. Standards organizations, such as American Society for Testing and Materials (ASTM) and American Association of State Highway and Transportation Officials (AASHTO), have adopted numerous test methods for determining the properties of fresh and hardened concrete, but only four methods were identified that relate to concrete permeability. Two of the methods determine the chloride permeability of concrete; one provides guidelines for conducting permeability tests on porous media; and one provides procedures for determining the water permeability of concrete. Comparison of permeability test results for different concretes is difficult because of test parameters associated with the test fluid utilized and test specimen geometry, composition, preparation, curing, conditioning, and age. Results obtained using certain test methods can be used to establish permeability coefficients, but more often than not, test results are only of use in relative assessments comparing one cementitious material to another or to understand the effects of different mixing or curing techniques on permeability. Reference summary sheets, descriptions of test methods that have been utilized to indicate concrete permeability, factors that influence concrete permeability, and data obtained from the literature search are provided in Ref. [31].

4. SUMMARY

Reinforced concrete plays a vital role in the safe operation of nuclear power plants and low-level radioactive waste disposal facilities. Potential regulatory applications of results obtained under the Structural Aging Program include (1) improved predictions of long-term material and structural performance and available safety margins at future times, (2) establishment of limits on exposure to hostile environmental stressors, (3) reduction in total reliance by licensing on inspection and surveillance through development of a methodology that will enable the integrity of structures to be assessed (either pre- or post-accident), and (4) improvements in damage inspection methodology through potential incorporation of results into national standards that could be referenced by standard review plans. The Permeability Test Methods and Data Program has identified data and information on long-term performance of reinforced concrete that will contribute to the knowledge base available for use in conducting performance assessments of engineered barriers of low-level radioactive waste disposal facilities.

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