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CONTRACTOR REPORT

STRUCTURAL AGING ASSESSMENT METHODOLOGY FOR CONCRETE STRUCTURES IN NUCLEAR POWER PLANTS

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EXECUTIVE SUMMARY

The Structural Aging (SAG) Program, sponsored by the Nuclear Regulatory Commission (NRC) and conducted by the Oak Ridge National Laboratory, has the overall objective of providing the NRC with an improved basis for evaluating nuclear power plant structures for continued service. Basic components of the program include development of a structural materials property data base, establishment of structural component assessment/ repair methodologies, and formulation of a quantitative methodology for continued service determinations. This document addresses the second of the Program components and has the objective of providing a logical basis for identifying the most critical light-water reactor (LWR) concrete structural elements as well as the degradation factors which can impact their performance. To accomplish this objective, the scope of work and this report are divided into three primary sections entitled: "Concrete Component Description/Classification System," "Determination of Degradation Factor Significance," and "Structural Aging Assessment Methodology." These sections address the types/elements of Category I structures, degradation factors influencing the life of concrete structures, and the methodology for ranking structures, respectively.

The first section identifies typical safety-related concrete structures at LWR facilities, including subelements thereof, and materials of construction. Safety-related structures are of obvious importance to the long-term performance and safety of LWR plants. The relative importance of subelements, safety significance of each Category I structure, and influences of environmental exposure are then presented in terms of a numerical rating system. The importance of a subelement to a specific structure is related to its impact on the ability of the structure to meet its functional and performance requirements. The ranking system established for subelements of a structure is based on a 1-10 scale, with 10 being highest. The safety significance of an LWR structure is related to its functional and performance requirements with respect to meeting 10CFR regulations. The safety significance ranking of a structure is based on the quantity and criticality of safety functions performed. Each structure is ranked on a scale of 1-10, with 10 being highest. The influence of environmental exposure is evaluated in terms of physical location of the structure and the predicted or observed aggressiveness of its local environment. The environmental exposure rating system is based on a 1 to 10 scale, with 10 being most aggressive.

The second section addresses potential degradation or aging factors which could affect the Category I concrete structures during their lifetime. The degradation factors considered in this report are those which have been observed and documented for a variety of civil works structures, including in some cases LWR plants. The significance of the degradation factors is then evaluated for particular structures/subelements in terms of: their effect on overall structural integrity, environmental conditions present, and materials of construction. The effect of a degradation factor on structural integrity includes its rate of attack, inspectability/early identification, repairability, and ultimate impact on the structure. Because of the variability in likelihood of occurrence of degradation to concrete structures in U.S. LWR plants due to design differences, material utilization, geographical locations, etc, the grading system for degradation factors is stated in terms of a range of possible values. A specific value for each plant is selected from the range based on site-specific characteristics. The resulting value for individual degradation factors (between 1 and 10) is then combined into a single value for each subelement of the evaluated structure for input into the methodology computations.

A usage of the Structural Aging Assessment Methodology to identify critical LWR concrete structures in three different nuclear power plant types is presented in the third section. The methodology is based on the simple combination of values for subelement importance, safety significance, environmental exposure, and degradation influence. For each subelement of a Category I structure, a numerical rank is computed by application of weighting factors and summing "subelement importance," "safety significance," and the average of "environmental exposure" and "degradation factor significance" values. This

computation results in a single rank for each subelement; using the sum of ranks for individual subelements, the final rank for the structure may be obtained. A listing of critical subelements and structures is then generated using a computer-based matrix format. Three example plants are assessed to demonstrate the procedural aspects of the methodology and to display the calculation of ranks for critical LWR structures and related subelements.

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ABSTRACT

One of the essential activities in meeting the objectives of Task S.3 (Structural Component Assessment/Repair Technology) in the Nuclear Regulatory Commission's Structural Aging Program is to develop a methodology for classifying concrete structures in nuclear power plants in terms of their safety significance. Associated with this activity is an assessment of the vulnerability of these structures to aging effects. The intent of such a methodology is to assist NRC staff in the definition, classification, and evaluation of concrete structures in existing nuclear power plants and to assess impacts of aging on the serviceability and integrity of such structures.

An Aging Assessment Methodology was developed which utilizes numerical ranking and relative weighting procedures to evaluate and categorize concrete structures in nuclear power plants by the importance of their subelemental parts, safety significance, environmental exposure, and influence of degradation factors. The impact of structural integrity evaluations and repair methods has been included in the makeup of the methodology. Utilization of the aging assessment methodology is illustrated through its application to three LWR facilities: (1) pressurized-water reactor plant with a "large-dry" metal containment, situated in the midwestern U.S.; (2) boiling-water reactor plant, with a conventionally reinforced concrete Mark II containment, located in the eastern U.S.; and (3) pressurized-water reactor plant, with a "large-dry" prestressed concrete containment, located in the midwestern U.S.

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1. INTRODUCTION

1.1 Background

Within the nuclear power industry, the aging of plant structures and components has become the subject of significant research in the last few years. This interest is prompted by the need to quantify the effects of aging in terms of potential loss of component integrity or function and to support current or future condition assessments of critical components. Since certain concrete structures play a vital role in the safe operation of nuclear power plants, guidelines and criteria for use in evaluating the remaining integrity (residual life) of each structure are needed. Standardized review guidelines for near-term evaluation of operating license renewal applications (LRAs) may be required as early as the first half of the 1990's when utilities are planning to submit initial requests.

In its role of regulating the safe use of commercial energy, the U.S. Nuclear Regulatory Commission (USNRC) has instituted several programs aimed at providing criteria to demonstrate the continued safe and reliable performance of nuclear power plants during any protracted license renewal period, i.e., ensuring that no age-related degradation alters the performance of components, systems, and structures significant to safety and reliability. One such program is the Structural Aging Program[1.1] initiated at the Oak Ridge

National Laboratory to provide the USNRC with potential structural safety issues and acceptance criteria for use in nuclear power plant evaluations for continued service.

1.2 Objective and Scope

Task S.3 of the Structural Aging Program, entitled "Structural Component Assessment/Repair Technology," has the following objectives: (1) development of a systematic methodology for quantitatively assessing the presence, magnitude, and significance of any environmental stressors or aging factors which could impact the durability of safety-related concrete components in nuclear power plants; and (2) providing recommended inservice inspection or sampling procedures which can be utilized to develop the required data both for evaluating the current structural condition as well as trending the performance of these components for use in continued service assessments. The initial activity under this task, "Light-Water Reactor Concrete Component Classification," has the objective of identifying critical safety-related concrete structural elements in light-water reactor plants as well as the degradation factors which can impact the performance of these components.

In meeting the objective of this study, an aging assessment methodology for concrete structures was developed which consists of a procedure for categorizing and ranking the safety-related concrete structures in terms of their safety significance, environmental exposure, and subelement function. An evaluation was made of the significance of different degradation mechanisms which can impact the ability of these subelements to meet their functional and performance requirements. Finally, the structural aging assessment methodology (i.e., component classification system) was applied to three representative nuclear power plants.

1.3 Approach

A number of goals were identified prior to development of the Aging Assessment Methodology for Category I concrete structures. They included the need to be comprehensive in terms of what is important to structural aging, to be user-friendly and efficient, to cover known degradation factors and their implications to LWR structures, and to allow repeatable (consistent) results to be obtained by several different users. The methodology that evolved from these goals was founded on several criteria: (1) importance of subelements to overall importance of the Category I structure, (2) safety significance of the structure as a whole, (3) influence of applied environment, and (4) probability of occurrence and end result of degradation.

The Structural Aging Assessment Methodology developed was based on a numerical ranking system that included each of the four criteria noted above. Basic components of the methodology include: (1) identification of all Category I structures and subelements (e.g., foundation, wall, etc.), (2) assignment of values ranging from 1 to 10 to each of the above four criteria for each subelement, and (3) entering the values assigned into a formula which combines the values using weighting factors to prioritize aging importance. The end result is a listing of Category I concrete structures and subelements, ranked in terms of importance to aging and longevity of the LWR facility. Table 1.1 presents an overview of the approach used by the Structural Aging Assessment Methodology to evaluate (i.e., numerically rank) Category I concrete structures in LWR facilities. Section 4.0 provides procedural guidelines on use of the methodology.

Reference

1.1 D. J. Naus et al., *Structural Aging (SAG) Program Five-Year Plan: FY 1988-1992*, ORNL/NRC/LTR-89/1, Martin Marietta Energy Systems, Inc., Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 1989.

Table 1.1. Approach to the Assessment of Aging in LWR Concrete Structures[a]

Step	Activity
1.	Identification of Category I structures and their subelements
2.	Rating of importance of each subelement to its parent structure
3.	Evaluation and ranking of the safety significance of the Category I structure (common to all subelements)
4.	Evaluation and rating of the severity of the environmental exposure of each subelement
5.	Identification of potential and existing degradation factors and evaluating their influence on Category I structure performance
6.	Computation of the rank of each subelement in terms of importance to aging (based on Steps 2 through 5)
7.	Computation of the rank of each Category I structure (on the basis of Steps 2 through 6)

[a]A more comprehensive flow chart of the methodology is contained in Fig. 4.1.

2. CONCRETE COMPONENT DESCRIPTION/CLASSIFICATION SYSTEM

All commercial nuclear power plants in the United States contain concrete structures whose performance and function are necessary for protection of the safety of plant operating personnel and the general public. The basic laws that regulate the design (and construction) of nuclear power plants are contained in Title 10 of the *Code of Federal Regulations*,[2.1] which is clarified by Regulatory Guides (e.g., R.G. 1.29[2.2]), NUREG reports, Standard Review Plans (e.g., Concrete and Steel Internal Structures of Steel or Concrete Containments[2.3]), etc. In addition, R.G. 1.29 and Part 100 to Title 10 of the *Code of Federal Regulations (10CFR)* state that nuclear power plant structures important to safety must be designed to withstand the effects of earthquakes without loss of function or threat to public safety. These "safety-related" structures are designated as seismic Category I. Seismic Category I structures typically include those classified by the American Society of Mechanical Engineers and the American Nuclear Society in Safety Classes 1, 2, and 3, i.e., safety related.

2.1 Materials of Construction

Nuclear safety-related concrete structures are composed of several constituents which, in concert, perform multiple functions, i.e., load-carrying capacity, radiation shielding, and leak tightness. Primarily, these constituents include the following material systems: concrete, conventional steel reinforcement, prestressing steel, steel liner plate, and embedment steel.

2.1.1 Concrete

The concrete typically used in nuclear safety-related structures consists of Type II portland cement, fine aggregates (e.g, sand), water, various admixtures for improving properties or performance of the concrete, and either normal weight or heavyweight coarse aggregate. Type II portland cement was used because of its improved sulfate resistance and reduced heat of hydration relative to the general purpose Type I portland cement. Both the water and fine and coarse aggregates are normally acquired from local sources and are subjected to material characterization testing prior to use. Various admixtures have been used to improve air entrainment (enhanced durability), improve workability (enhanced placement and compaction), modify hardening or setting characteristics, aid in curing, reduce evolution of heat, or provide other property improvements.[2.4] Coarse aggregate consists of gravel, crushed gravel, or crushed stone conforming to ANSI/ASTM C 33.[2.5] For those concrete structures in nuclear power plants which provide primary (biological) radiation shielding, heavyweight or dense aggregate materials, such as barites, limonites, magnetites, ilmenites, etc, have been used to reduce the section thickness requirements needed for attenuation.

The defined elements are then proportioned via mixing to develop portland cement concrete that has specific properties. Depending on the characteristics of the structure, the concrete mix may be adjusted to provide increased strength, higher durability, or better workability for placement. The hardened concrete typically provides the compressive load-carrying capacity for the structure. Reinforced concrete, in one form or another, has been used in the construction of all LWR plants. Specified concrete unconfined compressive strengths have ranged from 13 to 55 MPa, with 28 MPa being most common.

2.1.2 Conventional Steel Reinforcement

Most of the mild, or conventional, reinforcing steels[2.6] used in nuclear power plants to provide primary tensile and shear load resistance/transfer consists of plain carbon steel

bar stock with deformations (lugs or protrusions) on the surface. These bars typically conform with ASTM A 615[2.7] or A 706[2.8] specifications (older vintage plants may contain bars conforming to ASTM A 432[2.9] or A 305[2.10] specifications which have been superseded by the above). The minimum yield strength of this material ranges from 270 MPa to 415 MPa, with the 415 MPa material being most common. Conventional reinforcing steel also encompasses welded wire fabric (ASTM A 185[2.11] and A 497[2.12]), deformed wire (ASTM A 496[2.13]), bar and rod mats (ASTM A 184[2.14]), and all accessory steel components used in positioning/placing the reinforcement, e.g., seats, ties, etc.

2.1.3 Prestressing Steel

A post-tensioned prestressing system consists of prestressing tendons which are installed, tensioned, and then anchored to the hardened concrete forming the structure. A number of concrete containment structures utilize prestressing steel tendons to provide primary resistance to tensile loadings. Three major categories of prestressing systems exist depending on the type of tendon utilized: wire, strand, or bar. These systems typically conform to ASTM specifications A 421,[2.15] A 416[2.16] and A 722,[2.17] and have minimum ultimate strengths ranging from 1035 MPa to 1860 MPa. The tendons are installed within preplaced ducts in the containment structure and are post-tensioned from one or both ends after the concrete has achieved sufficient strength. After tensioning, the tendons are anchored by buttonheads, wedges, or nuts. Corrosion protection is provided by filling the ducts with wax or corrosion-inhibiting grease (unbonded), or portland cement grout (bonded) following tendon tensioning. Supplemental conventional reinforcing is also used to minimize shrinkage or temperature effects and to provide local load-carrying capacity or transfer. With the exception of Robinson 2 (bar tendons) and Three Mile Island 2 (strand tendons), plants that have post-tensioned containments utilize unbonded tendons. Bellefonte and Ginna each have grouted tendons (rock anchors) to which tendons are attached. Although post-tensioning has been primarily used in containment structures to reduce size/thickness of members, certain LWR facilities have used post-tensioning in other safety-related structures, e.g., shield walls and fuel pools.

2.1.4 Liner Plate

Leak tightness of reinforced and post-tensioned concrete containment vessels is provided by steel liner plate. A typical liner is composed of steel plate stock less than 13 mm thick, joined by welding, and anchored to the concrete by studs (Nelson studs or similar conforming to ASTM A 108[2.18]), structural steel shapes, or other steel products. The "dry well" portions of BWR containments and PWR containments are typically lined with carbon steel (ANSI/ASTM A 36[2.6] or A 516[2.19]). The linings of the "wet well" of BWR concrete containments and the liner of LWR fuel pool structures typically consists of stainless steel (ANSI/ASTM A 276 Type 304[2.20] is common). Certain LWR facilities also have used carbon steel clad with stainless steel weld metal for liner members. Although the liner's primary function is to provide a leaktight barrier for containment of radiation, it acts as part of the formwork during concrete placement and is used for supporting internal piping/equipment.

2.1.5 Embedment Steel

Anchorage to concrete is required for heavy machinery, structural members, piping, ductwork, cable trays, towers, and many other types of structures. Anchorage design had to meet certain requirements such as ease of installation, load capacity, susceptibility to vibration, preload retention, temperature range, corrosion resistance, postinstallation or preinstallation, and ease of inspection or stiffness.[2.21] In meeting its function, loads that the anchor must transfer to the concrete vary over a wide combination of tension, bending, shear, and compression. Examples of types of anchors available include embedded bolts

(ANSI/ASTM A 307,[2.22] A 325,[2.23] or A 490[2.24]), grouted bolts, embedded studs, self-drilled expansion anchors, or wedge anchors. Embedded steel, typically ANSI/ASTM A 36,[2.6] may also be constructed of structural plates or shapes installed during concrete placement.

2.2 Category I Concrete Structures

Category I (safety-related) structures are those essential to the function of the safety class systems and components, or that house, support, or protect safety class systems or components, and whose failure could lead to loss of function of the safety class system and components housed, supported, or protected. Design and construction requirements for Category I structures of early LWR designs were specified in American Concrete Institute (ACI) Standard 318 "Building Code Requirements for Reinforced Concrete,"[2.25] as supplemented by regulatory guides and by the NRC Standard Review Plan.[2.26] Current design and construction requirements for concrete structures which perform safety-related functions at nuclear power plants are contained in ACI 349.[2.27] The procedures and requirements in this document are endorsed by *U.S. Nuclear Regulatory Guide 1.142*[2.28] as providing an adequate basis for complying with *General Design Criteria for Nuclear Plants* (Appendix A to 10CFR50) for structures other than reactor vessels and containments. Current requirements for concrete reactor vessels and containments are presented in ACI 359.[2.29] Supplemental load combination criteria are presented in Sect. 3.8.1 of the NRC Standard Review Plan.[2.26]

In the following sections, concrete structures that are uniformly safety-related at all nuclear power plants of that type as well as auxiliary concrete structures which may or may not be safety-related depending on plant unique design, licensing, or operating criteria are addressed. Table 2.1 lists typical safety-related concrete structures in LWR plants. The description of safety-related concrete structures that follows is based on a review of numerous plant docket files, safety analysis reports, and other industry information sources. In order to make the study results as generally applicable as possible, concrete structures that were considered to be "plant specific," or unique, may not have been directly addressed. However, these "plant specific" structures may be considered, or bounded, by comparison to similar structures and environments that have been included in the concrete component classification system. Additionally, the names of certain structures may vary from plant to plant depending on the nuclear steam supply system vendor, architect-engineering firm, and owner preference. Identification of structures that may be referred to by more than one name can be approached in the same manner as for "plant specific" structures.

2.2.1 Typical Plant Structures

2.2.1.1 Boiling-Water Reactors. Typical safety-related concrete structures contained in boiling-water reactor plants can be grouped into four general categories: primary containments, containment internal structures, secondary containments/reactor buildings, and fuel/equipment storage pools.

Primary Containment. Currently, there are twelve boiling-water reactor (BWR) plants that utilize either reinforced (2 Mark I, 6 Mark II, 2 Mark III) or prestressed (2 Mark II) concrete primary containments. Leak tightness of each of these containments is provided by a steel liner attached to the inside surface of the concrete containment structure. Boiling-water reactor containments, because of provisions for pressure suppression, typically have "normally dry" sections (dry well) and "flooded" sections (wet well) which are interconnected via piping or vents (see Figs. 2.1-2.3). Requirements for BWR con-

tainments include the following:

1. Provide an "essentially" leak tight barrier against the uncontrolled release of radioactivity to the environment for all postulated design basis accident conditions;
2. Accommodate the calculated pressure and temperature conditions resulting from a loss-of-coolant accident;
3. Withstand periodic integrated leak-rate testing at the peak calculated accident pressure which may be at levels up to and including the containment design pressure; and
4. Permit appropriate periodic inspection of all important components and surfaces and the periodic testing of the leak tightness of containment penetrations.

In addition, the containment vessel can provide structural support for the nuclear steam supply system and other internal equipment. The containment foundation, typically a basemat, provides the primary support and transfer of load to the earth below.

Containment Internal Structures. Each of three BWR plant types (Mark I, Mark II, and Mark III) incorporate a number of reinforced concrete containment internal structures. These structures may perform singular or several functions including the following:

1. Radiation shielding;
2. Human accessibility provisions;
3. Nuclear steam supply system and other equipment anchorage/support/protection;
4. Resistance to jet, pipe whip, and other loadings produced by emergency conditions;
5. Boundary of wet wells and pool structures, allow communication between dry well and wet well (Mark II and III);
6. Lateral stability for containment;
7. Transfer of containment loads to underlying foundation; and
8. Transfer of fuel to reactor (Mark III).

As many of these functions are interrelated with the required containment functions, these structures are considered safety-related.

Secondary Containments/Reactor Buildings. Many BWR plants have reinforced concrete structures which serve as secondary containment and provide support and shielding for the primary containment. These structures typically are safety-related because they: provide additional radiation shielding; provide resistance to environmental/operational loadings; and house safety-related mechanical equipment, spent fuel, and the primary metal or concrete containment. Although these structures may be massive in cross-section in order to meet shielding or load-bearing requirements, they generally have smaller elemental thicknesses than primary containments because of reduced exposure under postulated accident loadings. Typically, these structures are maintained at a slight negative pressure for collection and treatment of any airborne radioactive material that might escape from operating conditions.

The secondary containments of Mark I plants (Fig. 2.1) are typically composed of beam, floor, and wall structural elements. A concrete reactor shield wall encircles the metal bulb-shaped containment to form the dry well. The shield wall is relatively massive in section to meet radiation shielding requirements. The containment shell provides primary shielding in Mark I plants with concrete containments.

The secondary containments of Mark II plants are fabricated using the same structural elements as the Mark I plants. Although these elements share similar functions to those in Mark I plants, because of the truncated cone-shape of the containment (Fig. 2.2), the structural elements must meet different design parameters.

Fuel/Equipment Storage Pools. The spent- and new-fuel storage pools, and the pools for reactor internals storage, typically have a four wall-with-bottom slab configuration. The walls and slab are composed of reinforced concrete members lined on the interior surface with stainless steel. Cross-sections of these members are generally large because they must support a large pool of water and heavy fuel/component loads, including high density fuel storage considerations. The fuel storage pool in Mark III plants is located within the primary containment.

2.2.1.2 Pressurized-Water Reactors. Typical safety-related concrete structures in pressurized-water reactor plants can be grouped into four general categories: primary containments, containment internal structures, secondary containments/reactor buildings, and fuel/equipment storage pools.

Primary Containments. Currently, there are 63 pressurized-water reactor (PWR) plants that utilize either reinforced (21 plants) or prestressed (42 plants) concrete primary containments. In meeting the same functional and performance requirements as noted for BWR containments in Section 2.2.1.1, the concrete containments in PWR plants are one of three different functional designs (Fig. 2.4-2.6): subatmospheric (reinforced concrete), ice condenser (reinforced concrete), and large/dry (reinforced and prestressed concrete). The primary differences between these containment designs relate to volume requirements, provisions for accident loadings/pressures, and containment internal structures layout.

The PWR containment structure generally consists of a concrete basemat foundation, vertical cylindrical walls, and dome. The basemat may consist of a simple mat foundation on fill, natural cut or bedrock, or may be a pile/pile cap arrangement. Most of the plants have utilized the simple mat on fill design. Interior containment surfaces are lined with a thin carbon steel liner to prevent leakage. Two of the PWR plants (Bellefonte and Ginna) have rock anchor systems to which the post-tensioning tendons are attached.

Containment Internal Structures. The containment internal structures in PWR plants tend to be more massive in nature than the internal structures in BWR plants because they typically support the reactor pressure vessel, steam generators, and other large equipment and tanks. In addition, these structures provide shielding of radiation emitted by the nuclear steam supply system (NSSS). Some of the specific functions which these structures (typically floor slabs, walls, and columns) are required to perform include:

1. Provision of human accessibility,
2. Support and separation of various plant equipment,
3. Resistance to emergency loading conditions,
4. Transfer of containment loads to containment foundation,
5. Missile protection, and
6. Channeling/routing steam and air through ice condensers (PWR ice condenser containments).

Containment-internal structures are typically constructed of conventionally reinforced concrete.

Secondary Containments/Reactor Buildings. Pressurized-water reactor plants that utilize a metallic primary containment (large dry and ice condenser designs) are usually contained in reinforced concrete "enclosure" or "shield" buildings. This secondary containment consists of a vertical cylinder wall with shallow dome (Fig. 2.5) and is often supported by the containment basemat. In addition to withstanding environmental effects, the secondary containment provides radiation shielding and particulate collection and ensures that the free standing metallic primary containment is protected from the natural environment.

Fuel/Equipment Storage Pools. The spent- and new-fuel storage pools for PWR plants are typically located in an auxiliary building proximate to the containment. These reinforced concrete wall and slab structures are generally massive in cross-section to support a large pool of water and the fuel elements, and are lined on the water side with stainless steel. The pools are connected to the reactor/refueling cavity (inside containment) via a transfer channel which is also a safety-related structure since it must provide radiation shielding and support for the fuel transport mechanism and fuel.

2.2.2 Auxiliary Structures

Auxiliary (or other) structures are considered to be those concrete structures in a nuclear power plant which may or may not perform safety-related functions, depending on the plant-unique or site-specific design and licensing or operating criteria. These structures typically house important plant equipment or control-room facilities or provide additional

radiation shielding/containment to meet 10CFR requirements. They may be located immediately adjacent to the secondary containment (auxiliary building, diesel generator building, etc.) or be separated on site (intake structures, offgas stacks, etc). Although these reinforced concrete structures may take many different physical configurations in meeting their functional and performance requirements, they typically fall into two broad categories: (1) common structures and (2) plant-unique structures.

2.2.2.1 Common Structures. Common building structures are typically configured in a rectangular box shape, and consist of reinforced concrete floor slabs, walls, and mat foundation. These subelements are typically of lighter construction (thinner sections with reduced conventional reinforcing) than the plant containment structures. They may also be composite with structural steel framing and contain shear walls for vertical and horizontal load resistance. Primary functions of these structures are to provide an enclosure for equipment important to plant safety and to provide secondary radiation containment.

2.2.2.2 Plant-Unique Structures. Plant-unique concrete structures include components such as intake canal liners, offgas stacks, and emergency cooling pathways. Although these structures are typically constructed of conventional reinforced concrete, their configuration and methods of construction differ from that of general building construction because the structures must meet specific design loading conditions dictated by their function as well as that of potential extreme environmental conditions (e.g., earthquake, flood, tornado, etc.). In addition, these structures may be required to resist the effects of the natural environment, and may be exposed to cooling water (river, ocean, lake). Typically, the plant-unique structures contribute to plant safety by serving to dissipate heat and radiation, or to protect other safety-related components.

2.2.3 Subelement Division of Structures and Application of Importance Factors

2.2.3.1 Subelement Division of Structures. Each Category I concrete structure is comprised of a number of subelements (e.g., walls, slabs, columns, etc.) that are fabricated using the material constituents discussed in Sect. 2.1. Because of the complexity of many Category I structures, their subelement division was based on geometric differences, structural behavior/performance characteristics, and environmental exposure. Tables 2.2 and 2.3 provide the subelement division of Category I concrete structures for typical BWR and PWR plants, respectively.

2.2.3.2 Assessment of Importance Factors. The performance, or importance, of the subelements of a Category I structure is difficult to assess quantitatively. Factors related to structural behavior, response to environmental effects, site-specific requirements, etc., must be considered. Additionally, the physical boundaries of each subelement must be defined. A qualitative, or "relative," importance among subelements may be established, however, and associated importance factors assigned. The primary purpose for these importance factors stems from the structural contribution of the subelement. For simplicity, assignment of importance factors is on a 1 to 10 scale, with 10 being most important.

Tables 2.2 and 2.3 present the resulting assignment of importance factors to the subelements of Category I concrete structures that are typically contained in BWR and PWR plants, respectively. The intent of distinguishing the relative importance of subelements, and their structural contribution, is to factor into the assessment the importance of their long-term performance. By identifying those subelements that are more critical, prioritized inspections and appropriate resource allocations can be established. The following paragraph summarizes the assignment of importance factors in Tables 2.2 and 2.3.

The primary load-carrying component for each structure is typically the foundation, which must distribute the plant loadings to the underlying soil or rock. Most foundation elements of building/structures, therefore, have been assigned an importance factor of 10. Vertical elements (walls, columns), which transmit loads to the foundation, provide radiation shielding, and resist potential environmental-induced loadings, were assigned relative importance factors between 6 and 9. Slabs which support much of the equipment,

piping, and personnel loads, and transfer them to load bearing walls or columns were assigned relative importance factors between 5 and 8. Other miscellaneous subelements which perform a reduced structural function (or other localized benefit to integrity) were considered of lower importance and assigned factors between 1 and 6.

2.3 Classification and Ranking of Structures by Safety Significance

The definition of "safety-related," or Category I concrete structures comes from the aforementioned 10CFR50 and 10CFR100 requirements and associated regulatory guides. Plant structures necessary to assure the integrity of the reactor coolant pressure boundary, to shut down the reactor and maintain it in a safe condition, and to mitigate the consequences of offsite radiation release (beyond 10CFR100 limits) during an accident are generally considered "safety-related." Structures whose failure could cause, or increase the severity of, a loss of coolant accident (LOCA), or other design basis accident (DBA), are also considered to be safety-related. Design of these structures is also required to include the effects of a safe shutdown earthquake, such that the particular structure continues its function during such an event. During the design and construction phase of nuclear power plants, U.S. NRC Regulatory Guides 1.26 (Ref. 2.30) and 1.29 (Ref. 2.2) are used to identify and define the seismic Category I plant structures.

Using the above definitions of "safety-related" and "Category I" structures, nine specific safety significance functions have been identified and are listed in Table 2.4. In meeting their functional and performance requirements, a structure may be required to accomplish more than one of the functions listed in the table. A listing of each safety function is also provided in Table 2.4. Although the "structural support" requirements may be similar, the relative safety significance is different based on the function/criticality of the supported/shielded equipment.

2.3.1 Safety Significance Function Descriptions

2.3.1.1 Prevention of Uncontrolled Liquid or Airborne Radiation Releases. Certain structures (such as the primary containment) are required by 10CFR50 to prevent the uncontrolled release of radioactive fission products to the environment during all phases of plant operation. This requirement is paramount to the safety of the general public and plant operating staff. Satisfaction of this requirement necessitates that the structure have the ability to withstand large operating and environmental events (impact, tornado, earthquake, pipe whip, etc.) without allowing leakage. With respect to primary or secondary containment structures, this infers that through-section cracking or loss-of-containment function is unacceptable for any causation or practical load combination.

2.3.1.2 Radiation Attenuation and Shielding. In addition to preventing release of the radioactive fission products, concrete structures in LWR facilities are utilized to attenuate gamma, neutron and other irradiation that occurs during normal operation as well as that which may occur under postulated accident conditions. Due to the potentially large radiation fields that could occur during a DBA, the concrete shield structures must have relatively thick cross-sections to meet the allowable radiation exposure limitations of 10CFR100. Concrete structures in LWR plants which provide shielding include the primary or biological shield walls and containment vessel.

2.3.1.3 Structural Support for Nuclear Steam Supply System and Containment Internal Equipment. In order to operate properly, the nuclear steam supply system and associated components required for the safe production of nuclear power require adequate structural support and constraint, i.e., limit deflections and distortions. Reinforced concrete has been used for this function because of its economy, design versatility, durability, and compatibility with the containment foundation. Typical nuclear steam supply system components which these structures support or constrain include the reactor pressure vessel, steam generators, coolant pumps, and connected piping.

2.3.1.4 Structural Support for Redundant Safety-Related Equipment and Components. Nuclear power plants contain redundant backup safety systems which are required to operate under "upset" or "emergency" plant conditions. These systems include various equipment (pumps, blowers, etc.) and components which are required to function on demand, usually to provide water supply to the reactor vessel or mitigate the effects of accidents. Structural support for these systems is necessary, and is provided by reinforced concrete floor slabs, columns, and walls within the auxiliary or other site buildings. Examples of structures in this category are those that support the safety injection system (PWR), core spray system (BWR), and residual heat removal system (PWR, BWR).

2.3.1.5 Structural Support for Ultimate Heat Sink Equipment and Components. The ultimate heat sink systems (cooling water intake and conveyance) are typically located outside of the main power block buildings of nuclear power plants. However, these components must remain functional during all plant conditions, including earthquake events, to support primary plant safety systems. Reinforced concrete is typically utilized for providing support and anchorage of this equipment or for the (structural) components themselves. Examples of ultimate heat sink structures include service and cooling water component support structures, emergency water intake structures and piping, and dams.

2.3.1.6 Support for New/Spent Fuel Pools and Other Pool Loads. All light-water reactor plants have stainless steel lined, reinforced concrete pools for short- or long-term underwater storage of spent fuel rod assemblies and other components. Because of the radiation shielding and load support requirements that these structures must provide under both normal and postulated accident conditions, the structures are relatively massive in section. Similar requirements also exist for the concrete wet wells in BWR plants.

2.3.1.7 Protection of Safety-Related Equipment/Components from Natural or Harmful Environments. Exposure of safety-related components to the natural environment could result in enhanced degradation rates, missile impacts, or other physical damage. Protection is typically provided via design and construction of a reinforced concrete structure which may also serve other safety functions. Similarly, missile barriers and other structures are constructed inside of nuclear facilities to protect necessary equipment from missile damage, fire effects, and chemical exposure.

2.3.1.8 Separation or "Communication" Function. Several LWR containment types rely on the performance of concrete structures to separate or guide the pressure-suppression (steam/air) containment function during a LOCA or similar event. Specifically, these structures consist of the divider barrier (PWR - ice condenser), drywell and weir walls (BWR - Mark III), and diaphragm floor (BWR - Mark II). These structures must meet design leaktight requirements (divider wall during LOCA) or maintain dedicated communication via vents or downcomers between the dry well and wet well during all plant conditions. The structures must be designed for various loading conditions, including missile impact, jet impingement, and earthquakes.

2.3.1.9 Failure Could Damage Safety-Related Component. Those concrete structures, whether safety-related or not, whose "failure" could result in damage to safety-related components, or could cause a loss-of-coolant accident, were also typically considered Category I or safety-related by the Architect-Engineer. The design and construction of Category I structures typically accommodates a wide range of loading combinations to prevent failure. As most Category I structures are located proximate to other safety-related equipment/components, they share this particular factor.

2.3.2 Safety Significance Ranking System

The relative importance of a structure's performance to the overall safety of the specific nuclear generating plant has both qualitative and quantitative aspects. That is, certain safety functions are qualitatively more important than others because of their performance requirements for both normal and emergency operations. Similarly, those structures which perform numerous safety functions are generally more important to overall

plant safety from a quantitative viewpoint. Characterization of the Category I concrete structures on the basis of safety significance must consider both of these issues.

The ranking system which was developed utilizes a 0-10 scale (10 having the highest safety significance) to order the Category I concrete structures in terms of the quantity and importance of safety significance functions they satisfy from Table 2.4. Table 2.5 provides a listing of the safety significance ranking criteria for the even-numbered elements (values) of the system. The following paragraphs provide guidance in the selection of even-numbered safety significance rankings for a Category I structure.

"0" Ranking. As all Category I structures perform a minimum of at least one safety-related function, a ranking of "0" is not possible. The "0" ranking is included to accommodate non-safety-related structures should it be desired to include them in the overall classification methodology.

"2" Ranking. Category I structures whose safety significance is specifically limited to their failure consequence alone are considered to have a ranking of "2." The basis for this ranking is that these structures provide a single safety function. Performance of these structures will degrade only under "severe" environmental effects which have a low probability of occurrence.

"4" Ranking. Category I structures which perform a minimum of one safety function (other than "failure consequence") are considered in this ranking. These structures typically provide either environmental protection, structural support, or shielding functions for a confined area or specific safety-related plant component.

"6" Ranking. Category I structures which perform at least two safety functions simultaneously during all plant operating conditions are included in this ranking. These structures typically perform a containment function, shield or contain radioactivity, or provide for anchorage of equipment.

"8" Ranking. Category I structures which perform at least three safety functions simultaneously and which are required for all plant operating conditions are included in this ranking. These structures are typically required for primary containment or shielding, support of NSSS components, or spent fuel management, and are critical to safe plant operation.

"10" Ranking. Structures which perform four or more safety functions, including those required by 10CFR50, are considered to have the highest safety significance ranking. The LWR primary containment is considered to have this ranking.

In order to apply the safety significance ranking system to the subelements in a nuclear power plant, several important criteria need to be considered. They include the following:

1. The qualitative differences (relative importance among the safety functions described in Section 2.3.1) must be considered through the application of weighting factors. Functions required by 10CFR50, related to NSSS operation, or necessary for normal, abnormal, and emergency plant status, need to be weighted more heavily than other functions.
2. The safety significance of certain "primary" structures is heavily influenced by performance of its subelements, e.g., prestressed concrete containments rely on the performance of the post-tensioning system. The ranking of each primary structure, therefore, must include the cumulative contribution of safety significance of each of its subelements.

2.4 Classification of Structures by Environmental Exposure

Since the durability of concrete structures can be dependent on the environments in which these structures are required to operate, the effects of environmental exposure need to be included in any concrete component assessment methodology which is developed. In addition, a procedure needs to be established which will indicate the relative severity of the

environment in which a concrete component is required to meet its functional and performance requirements.

2.4.1 Characteristic Environment Descriptions

Category I concrete structures in nuclear power plants may be exposed to one or more environments during normal plant operation. Table 2.6 lists seven environmental exposure categories that may interact with exposed surfaces of these structures. A short description of each of these categories follows.

2.4.1.1 Subterranean. Depending on geographical location, concrete structures built below the existing grade of soil/rock may be exposed to a variety of conditions. Effects of groundwater, surrounding soils, and environmental events (floods, freezing/thawing, wetting/drying, etc.) may be either passive in nature or aggressive. Long-term exposure to these effects can result in degradation of the concrete and steel reinforcement. Typical Category I structures which are located partially or fully below grade include the foundation and lower walls of the primary containment and reactor buildings, and structures required for conveyance of cooling water to and from the heat sink.

2.4.1.2 Natural Environment (Direct Exposure). Natural environmental exposure may subject reinforced concrete structures to a number of mechanisms that can result in degradation, e.g., carbonation, wet/dry cycling, freeze/thaw cycling, chemical attack, ocean salt spray, acid rain, electrical effects, etc. The rate of attack of these mechanisms is highly dependent on the imposed environmental conditions, geographical location and quality of construction materials. In addition, the adequacy of the design and quality of construction affects the durability of these structures. Category I concrete structures which may be directly exposed to natural environmental conditions include primary containments, enclosure/shield buildings, and other auxiliary structures (e.g., offgas stack).

2.4.1.3 Natural Environment (Indirect Exposure). Indirect exposure to the natural environment is defined as the exposure condition where natural temperature conditions and precipitation (via spray, fog, etc.) are present, but direct exposure to other conditions is restricted or shielded. As the exposure conditions are somewhat shielded, the potential for certain mechanisms to degrade the reinforced concrete is reduced as well as the rate of attack. However, shielded conditions can increase the impact of certain degradation mechanisms, e.g., carbonation. This exposure condition is common among certain auxiliary structures whose internal environments are uncontrolled, e.g., pipe tunnel interior surfaces.

2.4.1.4 Continuous Fluid Exposure. Continuous fluid exposure conditions may be present for those Category I concrete structures used for ultimate heat sink or safety-related water intake and conveyance. These structures include intake/discharge buildings, hyperbolic cooling towers (interior surfaces), emergency intakes, water wells, dams, and canal liner structures. Typically, the fluid consists of water from the plant cooling source (lake, river, etc.) which may be screened or chemically treated. This water may also contain microorganisms, solids, or chemicals potentially harmful to exposed concrete constituents or reinforcing steel. If the flow/velocity of this fluid is great enough, erosion or scouring of concrete may also occur. Continuous water exposure may also lead to wet/dry cycling, or leaching, which may affect the exposed concrete matrix. Also, corrosion cell formation may be promoted by this exposure. Critical exposure areas include lower portions of the concrete structures and surfaces proximate to the waterline.

2.4.1.5 Fluid/Pressure Retaining. Category I concrete structures which are required to perform a fluid or pressure retaining (leaktight) function are normally lined with carbon or stainless steel plate. Although the concrete proximate to the liner does not come into direct contact with the fluid, it may still be exposed to characteristics of the enclosed fluid or environment, e.g., via temperature gradients, bearing loads, and radiation fields. Examples of Category I structures that can be subjected to this environmental exposure condition include the concrete containment, primary reactor (biological) shield wall, spent fuel pool, and other pool structures.

2.4.1.6 Inside Primary Containment. Concrete structures located within the primary containment may be exposed to a number of conditions, including high humidity (to 100% relative), high temperature (to 65°C or locally higher),[2.31] and large radiation fields. Possible secondary effects include chemical exposure or spills, wear/abrasion/impact from heavy loads movement, and fatigue/vibration loads. Local areas where intensified conditions may exist include surfaces proximate to the reactor or hot piping/penetrations, next to the reactor coolant pressure boundary components, or near locations of fluid buildup (e.g., sumps). Enhanced thermal conditions may also occur within sealed concrete structures (lined with plate), such as in BWR shield walls. Because of the contributions of humidity, temperature and radiation, this environment is termed to be quite aggressive.

2.4.1.7 Controlled Interior Environment. Controlled interior environments are defined as environments which are modified or altered through the use of heating, ventilation, air conditioning, and dehumidification. These alterations result in "controlled" levels of humidity and temperature. Many Category I buildings have controlled interior conditions such that exposure of concrete to aggressive conditions is minimized. The risk of chemical spills is generally not reduced by the control alterations. However, the resulting environment is considered to be significantly less aggressive than others.

2.4.2 Environmental Exposure Rating System

The rating system developed to include environmental exposure conditions in the Category I concrete structures classification system was based on several considerations: (1) historical environment data, (2) exposure conditions for all surfaces of the structure, (3) accessibility to the structure's exposed surfaces for inspection, and (4) quantity/severity of the specific environmental conditions to which it is exposed. The rating system was developed by comparing each of the environments to one another and identifying the relative significance of the potential aging or degradation effects that may be produced by each on the concrete structures (materials). The numerical ratings, based on a 0-10 scale (10 = most severe), that resulted for each of the characteristic environmental exposure conditions discussed in the previous section, are presented in Table 2.6. The ratings are supported by general industry data[2.32-2.36] regarding structural performance and failure in a variety of environments. These data, if characterized by the difference in exposure, indicate that underground conditions are typically the most aggressive and controlled environments the most benign with respect to degradation of concrete structures. The ratings provided in the table for each exposure condition are average ratings. The actual assignment of a specific rating may vary somewhat from plant to plant to accommodate local site conditions. Structures exposed to two or more environments may be assigned either the maximum rating or an average value (see Section 4 also). The following paragraphs provide a description of each exposure and the basis for assignment of its relative importance rating.

The subterranean environment was found to be most severe. The subterranean environment may be characterized (worst case) as having aggressive groundwater or soil conditions, excessive hydrostatic conditions, and surfaces of the structure which are difficult to inspect for environmental effects. Ongoing degradation may occur unnoticed until widespread structural damage has resulted. Any structure exposed to a subterranean environment should be rated between the values of 8 and 10.

The direct natural environment was considered to be less severe than subterranean conditions but in certain geographical areas, acid rain, freeze/thaw conditions, etc, may impact the durability of concrete structures. Comparing this environment to the subterranean environment generally resulted in a rating of 6.

The indirect natural environment was considered to be generally less severe than direct exposure for most conditions, except for the effects of carbonation and possibly chemical attack. As such, it was generally given a lower rating of 4.

Continuous fluid exposure, as compared to the direct and indirect natural environment, was considered to be relatively more severe and generally given a rating of 7. The reasoning for this is the increased potential for aggressive chemical exposure, freeze/thaw damage, and other degradation factors. An additional consideration is that exposure of concrete to flowing fluids may lead to leaching of the concrete cement paste matrix and premature degradation.

The fluid or pressure retaining environment experienced by the concrete is somewhat moderated by the presence of a metallic liner. However, thermal effects and radiation exposure may still occur. The presence of the liner also restricts any inspection of the exposed concrete. Thus, a rating of 5 was assigned to this environment.

Environments inside of primary containment were considered to be severe because of humidity, temperature, and radiation conditions that exist. Certain structures located in the containment will be more notably affected by these conditions, especially those proximate to the reactor coolant pressure boundary. From a qualitative viewpoint, the effects of the environment inside containment were judged to be comparable to the natural environment and thus were weighted nearly equally. A rating of 7 was considered appropriate. However, this rating may be adjusted for notably enhanced exposures (e.g., under the reactor vessel) or where affected by application of protective coatings.

Because of conditions associated with the controlled-interior environment of many plant buildings, the relative rating aspect of this condition was judged to be quite low. Degradation of concrete from this environment has not been widely documented. A general rating of 2 was assigned to this environment. Specific conditions known to be more locally severe may be given a higher rating.

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Table 2.1. Typical Safety-Related Concrete Structures in LWR Plants

Primary containment
Containment dome/roof
Containment foundation/basemat
Slabs and walls
Containment internal structures
Slabs and walls
Reactor vessel support structure (or pedestal)
Crane support structures
Reactor shield wall (biological)
Ice condenser dividing wall (ice condenser plants)
NSSS equipment supports/vault structures
Weir and vent walls (Mark III)
Pool structures (Mark III)
Diaphragm floor (Mark II)
Drywell/wetwell slabs and walls (Mark III)
Secondary Containment/Reactor Buildings
Slabs, columns, and walls
Foundation
Sacrificial shield wall (metallic containments)
Fuel/Equipment Storage Pools
Walls, slabs, and canals
Auxiliary building
Fuel storage building
Control room (or building)
Diesel generator building
Piping or electrical cable ducts or tunnels
Radioactive waste storage building
Stacks
Intake structures (inc. concrete water intake piping and canal embankments)
Pumping stations
Cooling towers
Plant discharge structures
Emergency cooling water structures
Dams
Water wells
Turbine building

Table 2.2. Subelement Division of Category I Concrete Structures: Boiling Water Reactor

	Importance Factor
A. Primary Containment	
Concrete Containment	
1. Basemat Foundation	10
2. Drywell Pedestal	10
3. Vertical Walls (Mark I)	8
4. Steel Liner	4
5. Suppression Chamber (Mark I)	8
6. Chamber Steel Liner (Mark I)	4
7. Vertical Walls (Mark II)	8
8. Vertical Walls (Truncated Cone - Mark II)	8
9. Concrete Dome (Mark III)	8
10. Polar Crane Support (Mark III)	10
Steel Containment	
1. Basemat Foundation	10
B. Containment Internal Structures	
1. Bottom Slab (Steel Mark I and Pre-Mark Containments	10
2. Reactor Pedestal/Support Structure	9
3. Biological (Reactor) Shield Wall	6
4. Floor Slabs	6
5. Walls	7
6. Columns	7
7. Diaphragm Floor (Mark II)	7
8. NSSS Equipment Pedestals/Supports	5
9. Upper and Fuel Pool Slabs (Mark III)	5
10. Drywell Wall (Mark III)	6
11. Weir/Vent Wall (Mark III)	7
12. Crane Support Structure (Mark III)	5

Table 2.2. (cont.)

	Importance Factor
C. Secondary Containments/Reactor Buildings	
1. Basemat Foundation (if isolated from containment basemat)	10
2. Walls	8
3. Slabs	6
4. Columns	7
5. Equipment Supports/Pedestals	4
6. Sacrificial Shield Wall (Metal Containments)	6
7. Spent/New Fuel Pool Walls/Slabs	6
8. Drywell Foundation (Mark I)	9
D. Other Structures (Category I)	
1. Foundations[a]	10
2. Walls[a]	8
3. Slabs[a]	6
4. Cable Ducts	5
5. Pipe Tunnels	5
6. Stacks	5
7. Concrete Intake Piping	6
8. Cooling Tower Basins	5
9. Dams	6
10. Intake Crib Structures	6
11. Embankments	4
12. Tanks	5
13. Water Wells	4

[a]Components of other site buildings such as Auxiliary, Turbine, Control, and Diesel Generator Buildings.

Table 2.3. Subelement Division of Category I Concrete Structures: Pressurized Water Reactor

	Importance Factor
A. Primary Containment	
Concrete Containment	
1. Basemat Foundation	10
2. Tendon Access Galleries	3
3. Vertical Walls (and Buttresses)	8
4. Ring Girder (PCCV)	9
5. Dome	8
Steel Containment	
1. Basemat Foundation	10
B. Containment Internal Structures	
1. Bottom Floor (Metal Containments)	10
2. Floor Slabs	6
3. Walls	7
4. Columns	6
5. NSSS Equipment Pedestals/Supports	5
6. Primary Shield Wall (Reactor Cavity)	8
7. Reactor Coolant Vault Walls	7
8. Beams	5
9. Crane Support Structures	4
10. Ice Condenser Divider Wall and Slab	5
11. Refueling Pool and Canal Walls	6
C. Secondary Containment Buildings (metal containments)	
1. Foundation	10
2. Walls	8
3. Slabs	6
D. Other Structures (Category I)	
1. Foundations[a]	10
2. Walls[a]	8
3. Slabs[a]	6
4. Cable Ducts	5
5. Pipe Tunnels	5
6. Stacks	5
7. Concrete Intake Piping	6
8. Hyperbolic Cooling Towers	5
9. Dams	6
10. Intake Crib Structures	6
11. Embankments	4
12. Tanks	5
13. Water Wells	4

[a]Components of other site buildings such as Auxiliary, Turbine, Control, and Diesel Generator Buildings.

Table 2.4. Safety Significance Functions

1. Prevention of uncontrolled release of liquid or airborne radiation to the environment (all plant conditions)
2. Radiation attenuation and shielding for all plant operating conditions and postulated events
3. Structural support for power production NSSS and containment internal equipment and components
4. Structural support for plant equipment whose function is safety-related but which is redundant, serving a "back-up" role
5. Structural support for "ultimate heat sink" equipment and components
6. Support for new-spent fuel assemblies and other pool loads
7. Protection of "active" safety systems and components from natural or harmful environmental effects
8. Separation or "communication" function (inside containment)
9. Prevention of failure

Table 2.5. Safety Significance Ranking Criteria[a]

	Safety Significance Criteria	Ranking
1.	Non-Category I structures	0
2.	Category I structures whose relation to safety is due to their failure consequence alone	2
3.	Category I structures performing one safety function in addition to "failure consequence" (typically related to environmental protection, etc.)	4
4.	Category I structures performing two safety functions of greater importance than "failure consequence" (i.e., secondary containment, radiation shielding, etc.)	6
5.	Category I structures performing at least three safety functions of greater importance and which are required for primary containment, support of NSSS components, etc.	8
6.	Category I structures performing four or more safety functions simultaneously (i.e., the primary containment pressure boundary)	10

[a]Safety functions are defined in Table 2.4. Intermediate values between those noted above may be used based on actual safety function of the structure.

Table 2.6. Environmental Exposure Categories and Ratings

	Exposure condition	Rating
1.	Subterranean (below grade)	10
2.	Natural environment (direct exposure)	6
3.	Natural environment (indirect exposure)	4
4.	Continuous fluid exposure (without liner)	7
5.	Fluid/pressure retaining (liner provided)	5
6.	Inside primary containment	7
7.	Controlled interior environment (secondary containment, auxiliary building, etc.)	2

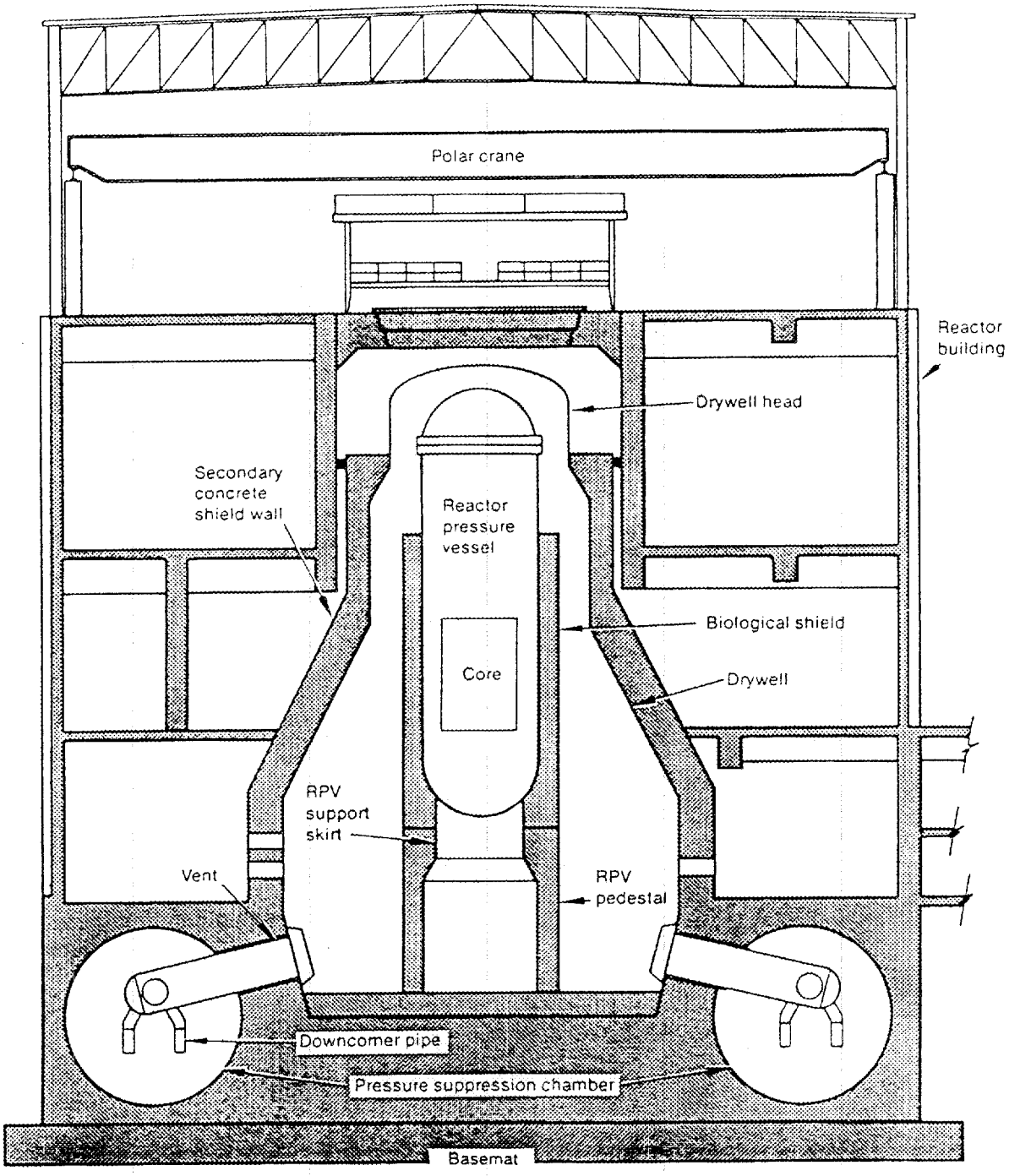

Fig. 2.1. BWR Mark I type metal containment enclosed in a reactor building. Source: *Residual Life Assessment of Major Light Water Reactor Components – Overview*, NUREG/CR-4731, Vol. 2, EG&G Idaho, Inc., Idaho National Engineering Laboratory, Idaho Falls, November 1989.

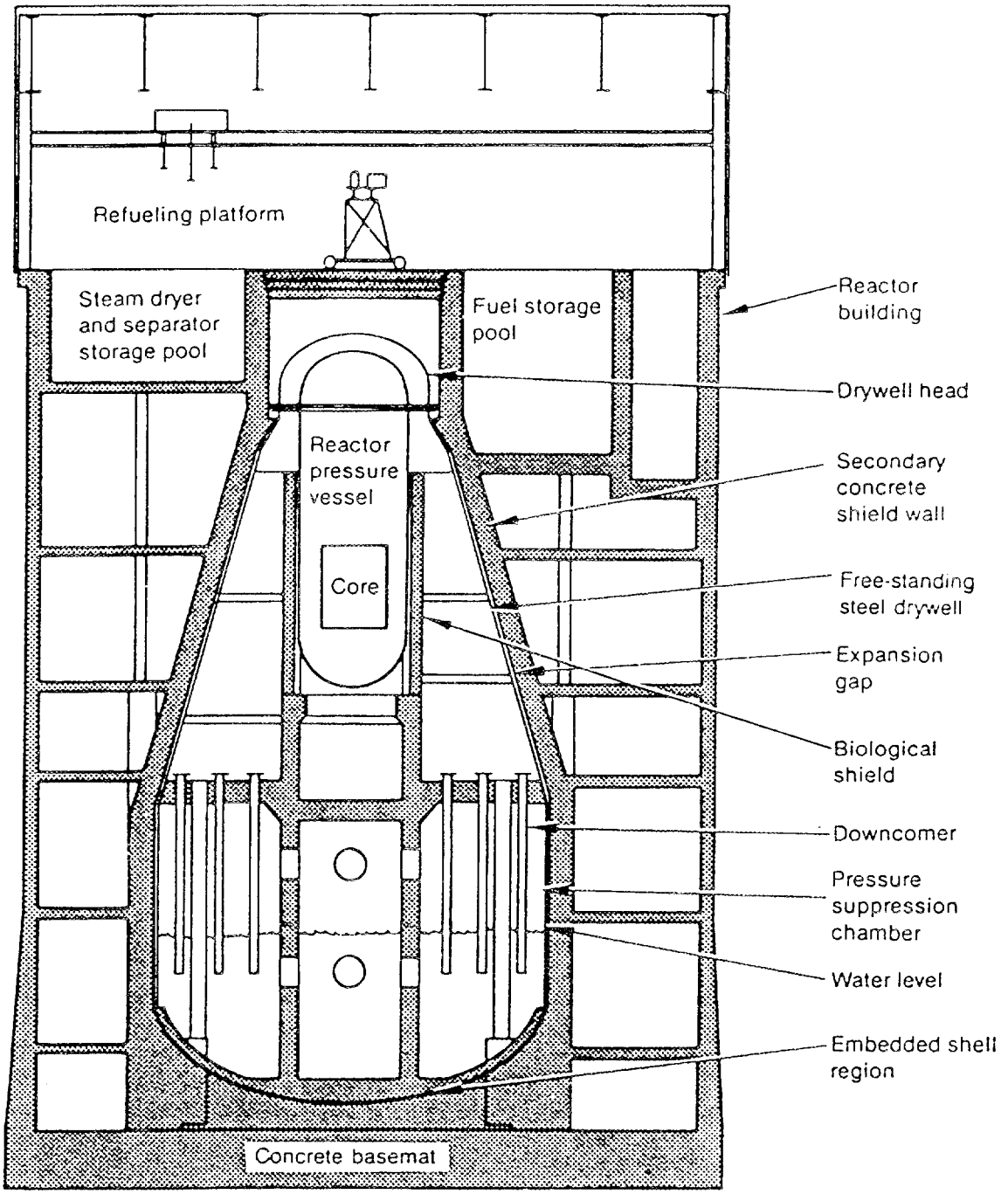

Fig. 2.2. BWR Mark II type metal containment enclosed in a reactor building. Source: *Residual Life Assessment of Major Light Water Reactor Components – Overview*, NUREG/CR-4731, Vol. 2, EG&G Idaho, Inc., Idaho National Engineering Laboratory, Idaho Falls, November 1989.

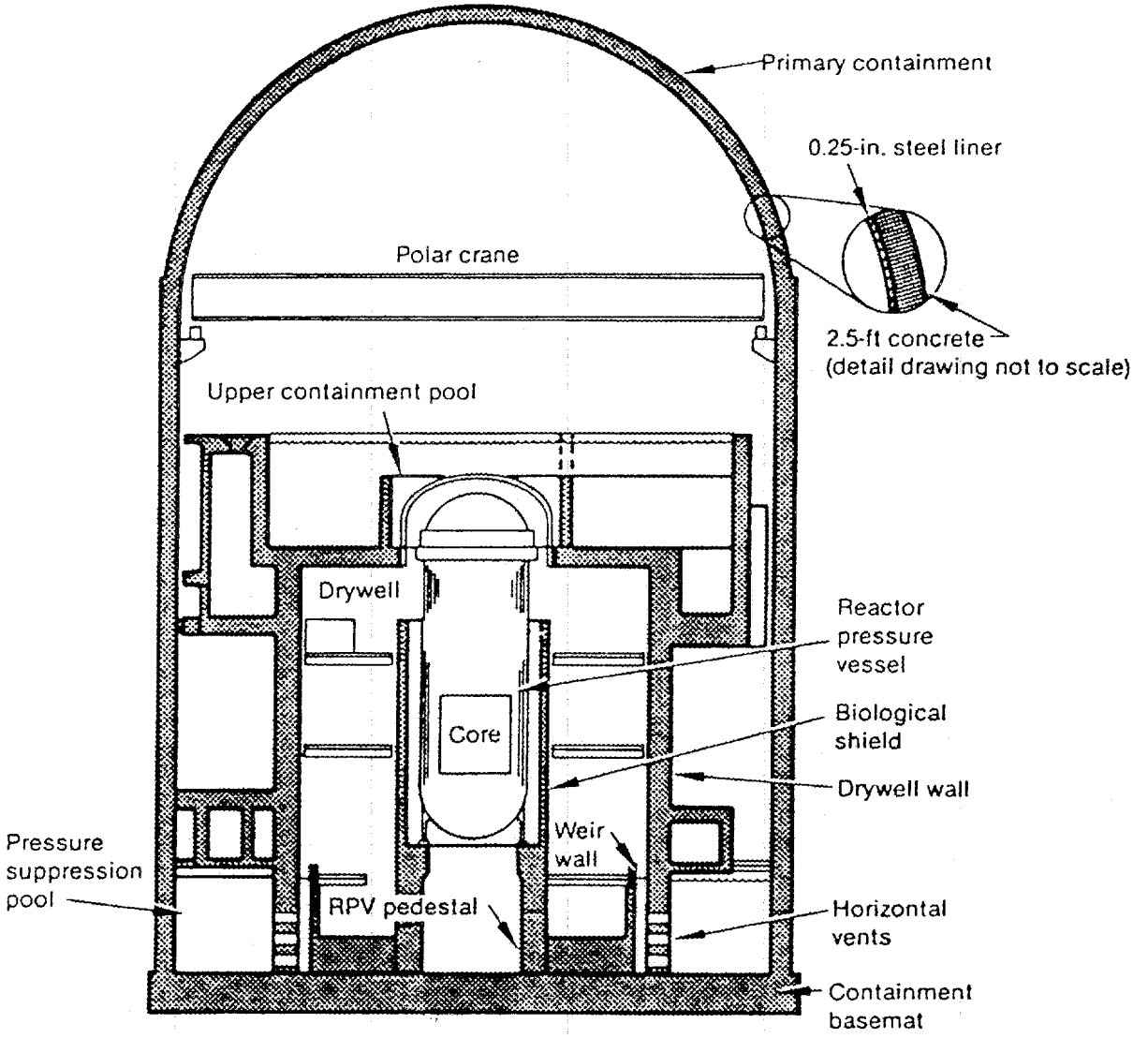

Fig. 2.3. BWR Mark III type reinforced concrete containment. Source: *Residual Life Assessment of Major Light Water Reactor Components – Overview*, NUREG/CR-4731, Vol. 2, EG&G Idaho, Inc., Idaho National Engineering Laboratory, Idaho Falls, November 1989.

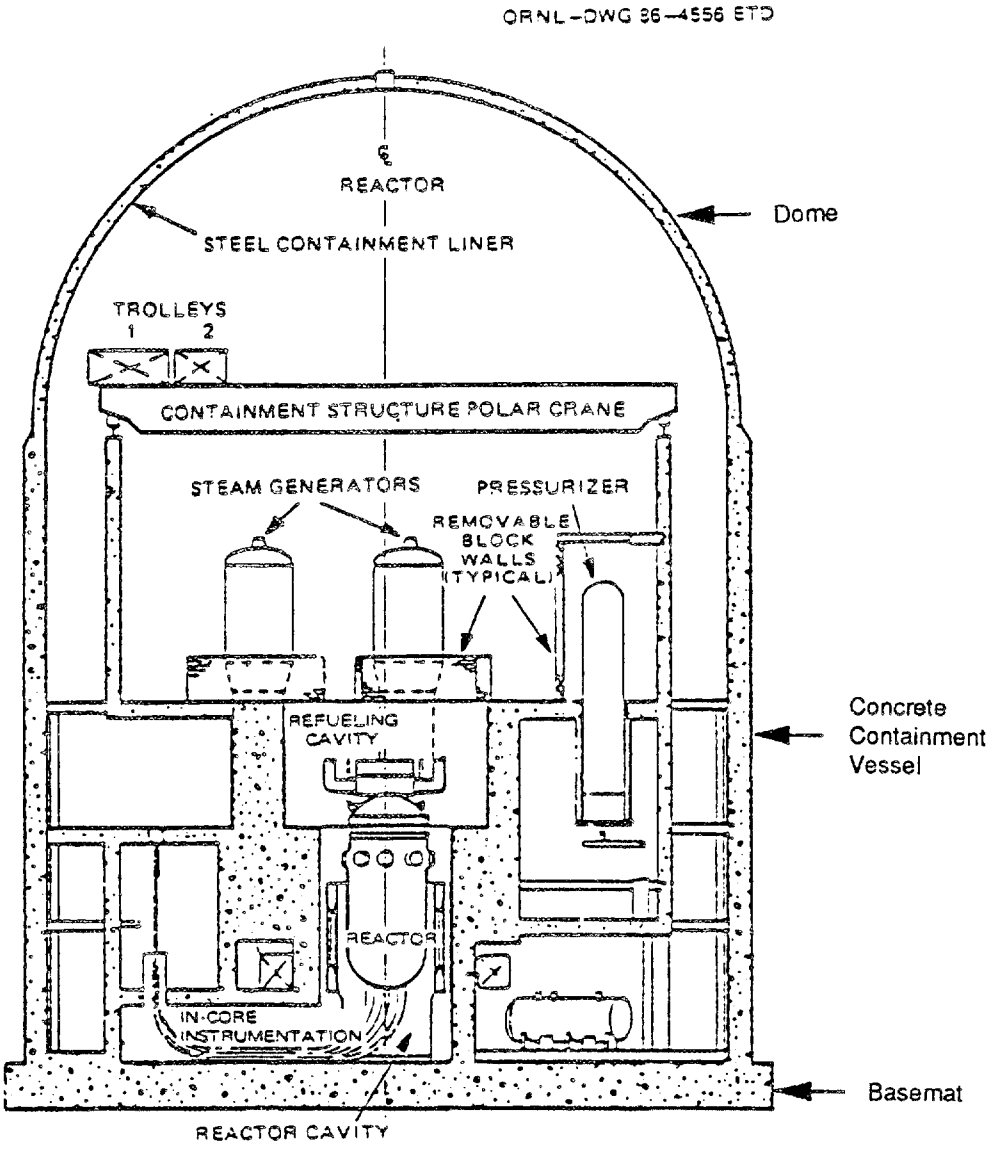

Fig. 2.4. PWR subatmospheric type reinforced concrete containment. Source: *Containment Performance Working Group Report,* Draft Report for Comment, NUREG-1037, U.S. Nuclear Regulatory Commission, Washington, D.C., May 1985.

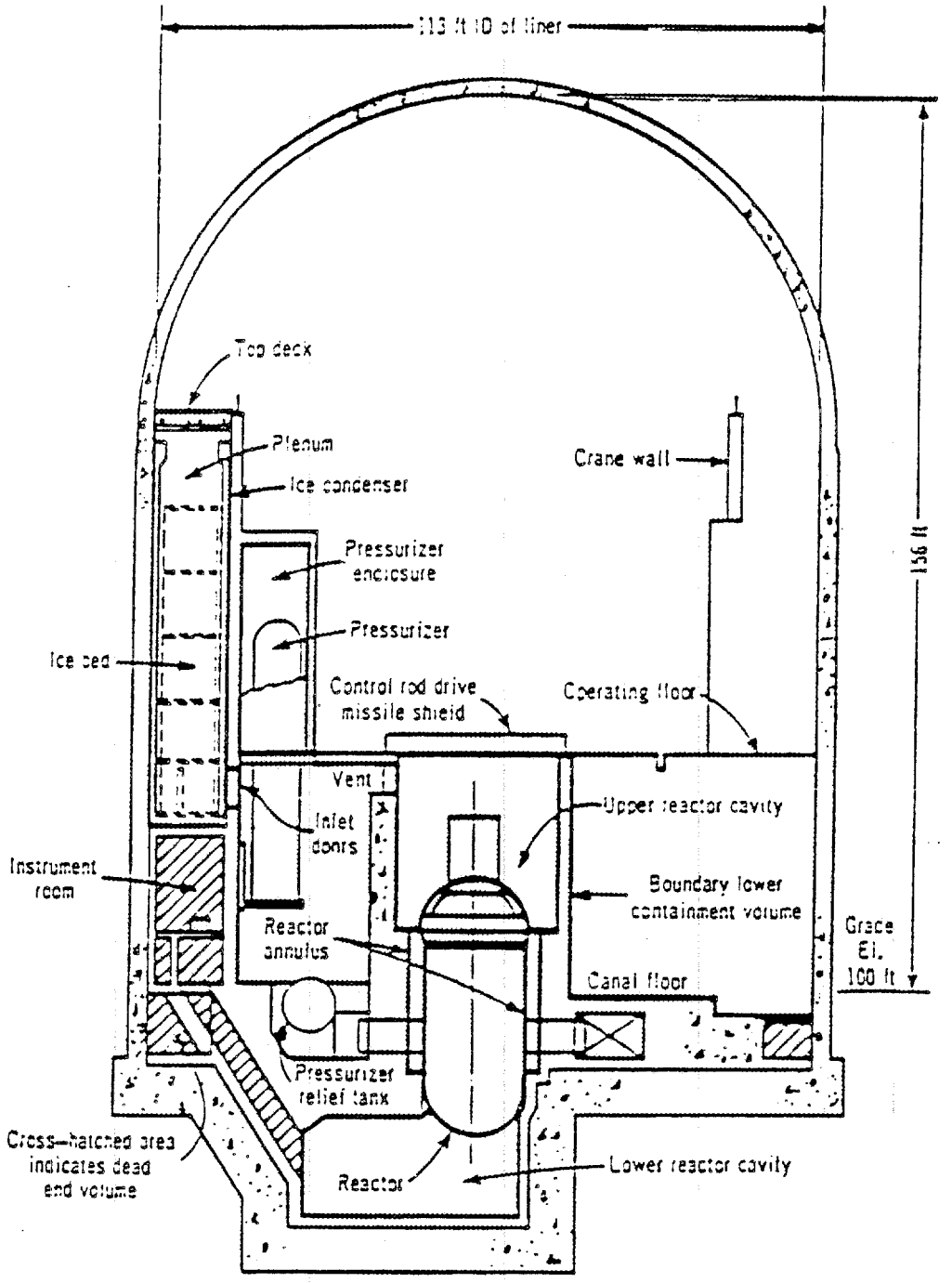

Fig. 2.5. PWR ice condenser type reinforced containment. Source: "Structural Analysis and Design of Nuclear Plant Facilities," *ASCE Manual and Report on Engineering Practice – No. 58*, 1980.

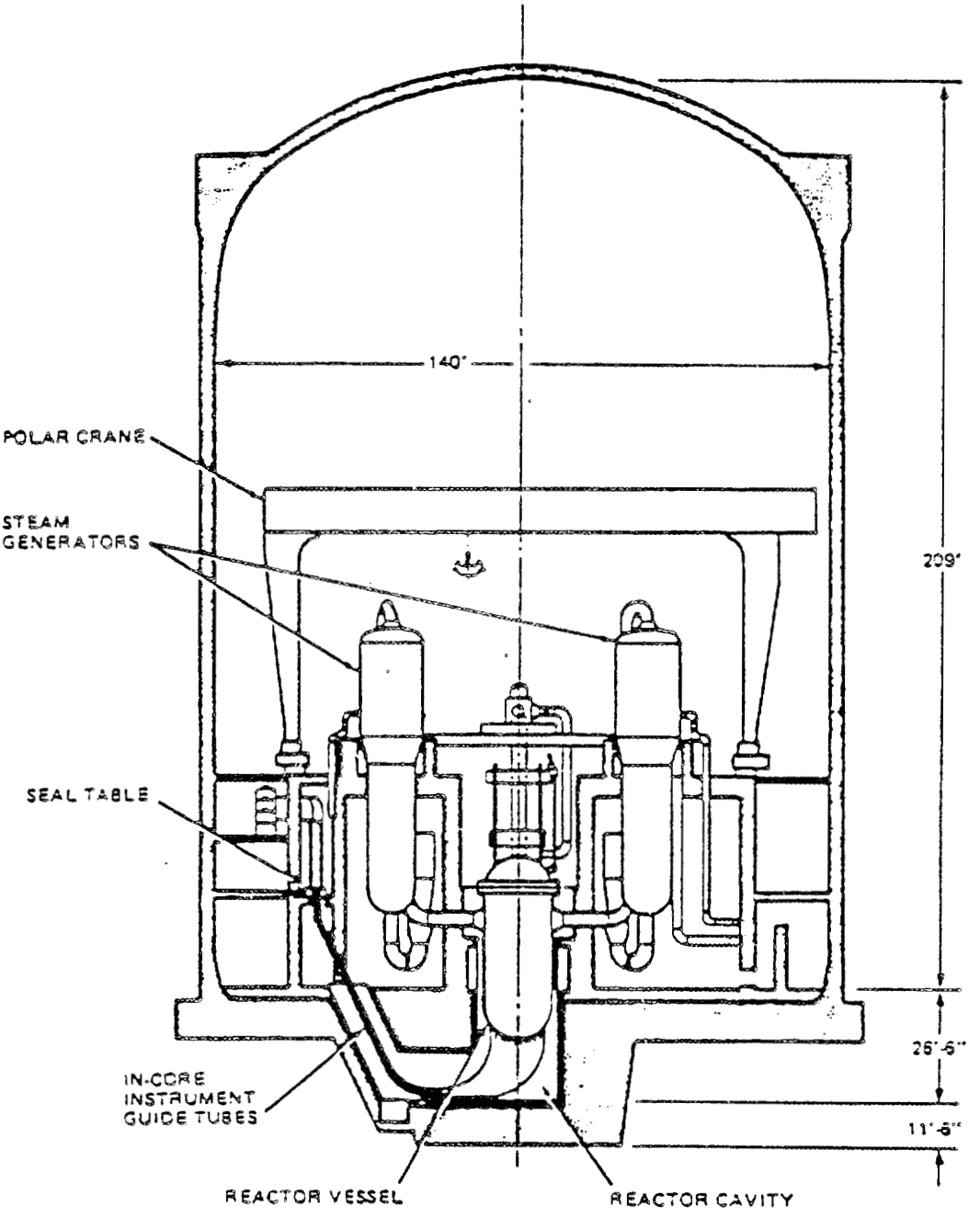

Fig. 2.6. PWR large dry type prestressed concrete containment. Source: *Containment Performance Working Group Report*, Draft Report for Comment, NUREG-1037, U.S. Nuclear Regulatory Commission, Washington, D.C., May 1985.

3. DETERMINATION OF DEGRADATION FACTOR SIGNIFICANCE

The longevity, or long-term performance, of Category I concrete structures is primarily a function of the durability or propensity of these structures to withstand the potential effects of degradation. Thus, any prioritization system developed for such structures with respect to aging must include any and all forms of degradation which can occur. The degradation factors that have been observed in the nuclear power industry, as well as in general civil engineering structures, are described in this section including methods for assessing the presence/severity of the factors. Also, a grading system is presented which can be used to assign relative values to each of the degradation factors affecting the critical LWR concrete structures.

3.1 Degradation Factor Description

Table 3.1 presents a summary of the primary age-related degradation factors that can affect the concrete, mild steel reinforcing, prestressing, and liner/structural steel systems in nuclear power plant Category I concrete structures.[1] A description of these factors and characteristics such as rate of attack and threshold values are presented in the following paragraphs. A number of critical areas where degradation may adversely impact the performance or function of these material systems is provided in Table 3.2.

3.1.1 Concrete Material Systems

If concrete is properly designed for the environment to which it will be exposed, produced using good quality control principles, and proper construction methods are utilized, it is capable of maintenance-free performance for decades. However, concrete is potentially vulnerable to attack under a variety of different exposures. Degradation of concrete can be caused by adverse performance of either its cement-paste matrix or aggregate constituents under either chemical or physical attack.

3.1.1.1 Chemical Attack. Chemical attack is the alteration of the concrete through chemical reaction with either the cement paste or the coarse aggregate. Generally, the attack occurs on the exposed surface region of the concrete (cover concrete), but with the presence of cracks or prolonged exposure, chemical attack can affect entire structural elements (cross sections). The rate of chemical attack on concrete is a function of the pH of the aggressive fluid and the concrete permeability, alkalinity, and reactivity. Figure 3.1 presents a summary of the types of chemical reactions responsible for concrete deterioration and the detrimental effects which can occur. Chemical attack may occur in several different forms as highlighted in the following sections.

Efflorescence and Leaching. Efflorescence occurs on the surface of concrete following the percolation of a fluid (e.g., water) through the material, either intermittently or continuously, or when an exposed surface is alternately wetted and dried. Efflorescence results from the dissolution of salts contained in the cement matrix, which are leached out of the concrete and crystallized upon subsequent evaporation of fluid or interaction with carbon dioxide in the atmosphere. As such, efflorescence is primarily an aesthetic problem rather than a durability problem but may indicate that alterations to the cement paste are taking place in the concrete.

Leaching is a form of mild chemical attack which alters the cement paste matrix by hydrolyzing or dissolving calcium-containing products. The rate of leaching is dependent on the permeation of the fluid through the cement matrix, temperature, and reactivity. Extensive leaching causes an increase in porosity and permeability, thus lowering the

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[1] Short-term conditions such as fire exposure, missile impact, flooding, tornado, etc were not considered to be age-related problems.

strength of the concrete[3.1] and making it more vulnerable to hostile environments, e.g., water saturation and freeze/thaw damage, or chloride penetration and corrosion of the reinforcing system. Category I structures most susceptible to leaching are those subjected to rain water, cooling water, or ground water.

Sulfate Attack. Sulfates of sodium, potassium, and magnesium present in alkali soils and waters (rain, groundwater, sea water) have caused significant deterioration in a small population of concrete structures.[3.2] The sulfates react chemically with the hydrated lime and hydrated calcium aluminate in cement paste to form calcium sulfate and calcium sulfoaluminate with considerable associated expansion and disruption (cracking) of the concrete. Sulfate attack can also take the form of progressive loss of strength and loss of mass due to deterioration of cohesiveness of the cement hydration products. The rate of attack is a function of the reactivity of the paste and concentration of the sulphate compounds. Deterioration of subgrade structures in the western U.S. has occurred within five years of construction. A review of research data[3.2,3.3] indicates that sulfate levels of 1200 ppm and higher are aggressive to concrete.

Bases and Acids. Hydrated cement paste is an alkaline material (pH $\geq$ 12.5) and not normally susceptible to attack by alkaline materials. Contact between concrete and high concentrations of alkaline materials (from water treatment or industrial processes), however, can result in deterioration by processes other than direct chemical reaction with hydroxide ions. On the other hand, concrete is vulnerable to acidic solutions which readily attack basic materials. Sulfuric acid and carbonic acid in groundwater and certain plant-internal fluids (boric acid, etc.) are example acids. The cation-exchange reaction between acidic solutions ($HC\ell$, HNO_3, CH_3CO_2H, etc.) and the constituents in portland cement paste give rise to soluble salts of calcium which are removed by leaching and which increase the porosity and permeability of the concrete.[3.4] Table 3.3 presents a listing of the reactivity with concrete of various chemicals commonly found in nuclear power plants and the surrounding environment. The rate of attack is primarily a function of the concentration (pH) of the fluid and the duration of exposure. The potentially acidic ground water exposure on below-grade Category I structures is of primary concern.

Salt Crystallization. Salts can cause damage to concrete through the development of crystal growth pressures that arise through physical causes. Deterioration of this type occurs when concrete is in contact with water containing large quantities of dissolved solids (e.g., $CaSO_4$, $NaC\ell$, Na_2SO_4).[3.5] As the water permeates into the concrete, the salts crystallize in open pores due to evaporation. Repeated evaporation can cause the salt deposits to build up to the point that the stresses generated will crack the concrete. Structures in contact with fluctuating water levels (such as water management structures) or in contact with groundwaters containing salts are susceptible to this type of deterioration.

Alkali-Aggregate Reactions. Expansion and cracking, leading to loss of strength, elasticity, and durability of concrete can result from chemical reactions involving alkali ions (portland cement), hydroxyl ions, and certain siliceous constituents that may be present in aggregates. Generally, three requirements are necessary for alkali-aggregate reactions to occur: sufficient alkali present; availability of moisture; and presence of reactive silica, silicate, or carbonate aggregate material. Deterioration of the concrete results from swelling (hydraulic pressure) of the alkali-silica gel when it comes in contact with water.[3.6] This is termed alkali-silica reaction (ASR). Other alkali-silica reactions involve sand-gravel aggregates contained in river systems in Nebraska, Kansas, certain western states, and sedimentary rock aggregates composed largely of clay minerals. Expansive reactions also occur as a result of alkali-carbonate aggregate reactions (ACR). Both reactions may result in severe cracking and loss of mechanical properties in the structure.

As the influence of alkali-aggregate reaction (AAR) requires the presence of moisture, Category I structures exposed to rain water, ground water, cooling water, or in-containment humidity are most susceptible. Although AAR typically occurs within 10

years of construction, deterioration has not occurred in some structures until 15 to 20 years following installation, and some structures have not exhibited early signs of deterioration until 20 to 25 years after construction. The delay in structures exhibiting deterioration due to AAR indicates that there may be less reactive forms of silica which may eventually cause deterioration.[3.7] Generally, the deterioration takes the form of map (pattern) cracking, popouts, and spalls. Because the degradation is generally visible in its early stages, periodic visual condition surveys may effectively identify the degradation before loss of structural integrity. However, in-place repair requirements due to this reaction may be substantial if the AAR occurs in certain Category I structures (such as inside containment).

3.1.1.2 Physical Attack. Physical attack is the second major cause of deterioration of concrete. Although it is often difficult to separate physical attack from chemical attack of concrete, for purposes of discussion physical attack will include degradation factors that result from environmental or mechanical effects.

Freeze/Thaw Cycling. Concrete, when in a saturated or near-saturated condition, can be susceptible to damage during freezing and thawing cycles caused by hydraulic pressure generated in the capillary cavities of the cement paste as the water freezes. Freeze/thaw cycling is more prevalent in the northern sections of the United States; certain areas witness over 50 cycles per year. Damage to concrete resulting from freeze/thaw cycling can take several forms: scaling, spalling, and pattern cracking (such as D-cracking).[3.8] Concrete slabs which are exposed to freeze/thaw cycles in the presence of deicing chemicals are susceptible to scaling or "flaking off" of the exposed surface. The most common damage that occurs to concrete during freeze/thaw cycling is cracking or spalling due to expansion of the cement paste matrix. Cracking parallel to joints and edges of slabs (D-cracking) can occur when certain porous coarse aggregates have been used in the concrete mix.

Factors controlling the resistance of concrete to freeze/thaw damage include air entrainment (sizing and spacing of air bubbles) as opposed to entrapped air, water/cement ratio, curing, strength, and degree of saturation.[3.9] It is not the total air contained in the cement paste matrix that is the critical factor in producing durable concrete, but having a void spacing of 0.1 to 0.2 mm throughout the hardened cement paste.[3.4] Water/cement ratios should not exceed certain maximums to ensure that the presence of large pores in the hydrated cement paste is minimized, i.e., lower water/cement ratio mixes will result in less water being available for freezing. The concrete should be properly cured prior to frost exposure. Although strength generally is directly proportional to durability, air-entrained concrete, even though of reduced strength,[2] will provide improved resistance to frost action. Even if sufficient entrained air is present in the cement paste matrix to prevent freeze/thaw damage, any porous aggregate particles may be susceptible to freeze/thaw damage.

Many of the structures comprised of concrete at nuclear plants were constructed using air-entrained concrete. However, certain exposed surfaces may still be affected by freeze/thaw damage. Category I structures most susceptible to freeze/thaw damage are those utilized in the intake/conveyance/management of cooling water. These structures, especially at the water line, will have saturation levels in the concrete above the critical level. Other possible locations are exterior surfaces which promote the "ponding" or collection of rain water, or at existing cracks or imperfections. Reference 3.10 contains a chart which identifies those areas in the United States subjected to the greatest number of freeze/thaw cycles (weathering index). LWR facilities in these regions are most susceptible to freeze/thaw damage.

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[2] In medium- and high-strength concretes, each 1 percent increase in air content results in a strength reduction of about 5 percent for mixes having the same water-cement ratio.[3.1]

Freeze/thaw damage is incurred after an extended number of cycles. This is especially true for Category I structures which were primarily designed to accommodate (resist) freeze/thaw activity. This damage is visually inspectable on exposed surfaces. Periodic condition surveys should identify the occurrence of this mechanism before loss of structural integrity occurs. However, certain structures may still be damaged by freeze/thaw damage and require repair.

Thermal Exposure/Thermal Cycling. Elevated temperature and thermal gradients are important to concrete structures in that they affect the concrete's strength (ability to carry loads) and stiffness (structural deformations and loads that develop at constraints). The mechanical property variations result largely because of changes in the moisture content of the concrete constituents and progressive deterioration of the cement paste and aggregate (especially significant where thermal expansion values for cement paste and aggregate are markedly different). Significant deterioration of the concrete strength does not generally occur until the exposure temperature reaches ~400°C at which dehydration of calcium hydroxide occurs.[3.11] Reference 3.12 suggests that concrete exposed to temperatures of 90°C may lose up to 10% of its room-temperature strength and modulus of elasticity values. The response of concrete to elevated-temperature exposure depends on a number of factors, e.g., type and porosity of aggregate, rate of heating, permeability, moisture state, etc. In addition to potential reductions in strength and modulus of elasticity, thermal exposure of concrete can result in cracking or when the rate of heating is high and concrete permeability low, surface spalling can occur. Elevated temperatures also are important in that they affect the volume change and creep of concrete.[3.13] References 3.14 to 3.17 provide additional information on the effects of elevated temperature on concrete materials and structures.

Thermal cycling, even at relatively low temperatures (< 65°C), can have some deleterious effects on concrete's mechanical properties, i.e., compressive, tensile and bond strengths, and modulus of elasticity are reduced. Most reinforced concrete structures are subjected to thermal cycling due to daily temperature fluctuations and are designed accordingly, i.e., inclusion of steel reinforcement. At higher temperatures (200 to 300°C), the first thermal cycle causes the largest percentage of damage, with the extent of damage markedly dependent on aggregate type and is associated with loss of bond between the aggregate and matrix. Temperature variations, or thermal cycles, also can become important if the deformation of the structure resulting from the temperature variations is constrained.

Category I structures are generally limited to maximum temperatures of 65°C by technical specifications (design and operation basis). However, local areas may be heated to temperatures approaching that of the NSSS coolant (345°C)[3.18] at local piping penetrations, improperly ventilated areas, etc. Those structures potentially affected include the in-containment structures near NSSS equipment and containment vessel/shield wall hot piping penetrations.

Excessive thermal exposure is typically characterized by cracking or spalling of the cover concrete at the exposed surfaces. Evaluation of mechanical properties of concrete requires removal of representative samples and use of appropriate laboratory test procedures. If the effect of elevated temperature on the concrete is desired at a location where the concrete is subjected to moderate elevated temperature conditions over an extended period of time, the samples should be tested under representative conditions.

Irradiation. Irradiation in the form of either fast and thermal neutrons emitted by the reactor core or gamma rays produced as a result of capture of neutrons by members (particularly steel) in contact with concrete can affect the concrete. The fast neutrons are mainly responsible for the considerable growth, caused by atomic displacements, that has been measured in certain aggregate (e.g., flint). Gamma rays produce radiolysis of water in cement paste which can affect concrete's creep and shrinkage behavior to a limited extent

and also result in evolution of gas. Prolonged exposure of concrete to irradiation can result in decreases in tensile and compressive strengths and modulus of elasticity. Irradiation has little effect on shielding properties of concrete beyond the effect of moisture loss due to temperature increase.

Approximate threshold levels necessary to create measurable damage in concrete have been reported in limited research studies.[3.19] These levels are 1×10^{19} neutrons/square centimeter for neutron fluence and 10^{10} rads of dose for gamma radiation. Reference 3.20 provides the following data for radiation environments at the outside surface of LWR reactor pressure vessels (plant capacity factor of 80% with 1000 megawatt electric power generation):

	BWR			PWR		
	40 Year (32 EFPY)	60 Year (48 EFPY)	80 Year (64 EFPY)	40 Year (32 EFPY)	60 Year (48 EFPY)	80 Year (64 EFPY)
Neutron Fluence (n/cm^2)						
Slow (E < 1.0 MeV)	3.7×10^{18}	5.6×10^{18}	7.5×10^{18}	2.0×10^{19}	3.0×10^{19}	4.0×10^{19}
Fast (E > 1.0 MeV)	5.1×10^{17}	7.7×10^{17}	1.0×10^{18}	1.0×10^{18}	1.5×10^{18}	2.0×10^{18}
Gamma Total Integrated Dose (rads)	1.6×10^{10}	2.4×10^{10}	3.2×10^{10}	4.7×10^{9}	7.0×10^{9}	9.3×10^{9}

These values indicate that radiation levels approaching those which may damage concrete in the primary shield wall (Category I) may occur after 40 years of operation (32 equivalent full-power years). However, further attenuation of these values may result due to the presence of air gaps, insulation, etc.

Damage to concrete due to excessive irradiation occurs as cracks and spalls at exposed surfaces. Evaluation of the effects of irradiation on the mechanical properties of concrete requires removal and testing of representative samples of material.

Abrasion/Erosion/Cavitation. Progressive loss of material at the concrete surface can occur due to abrasion, erosion, or cavitation. Abrasion generally refers to dry attrition, while erosion is normally used to describe wear by the abrasive action of fluids containing solid particles in suspension. Cavitation relates to the loss of surface material by formation of vapor bubbles and their subsequent collapse, due to sudden change of direction or pressure in rapidly flowing water, on the surface of the structure. Resistance of concrete to abrasion and erosion is dependent on the quality of the concrete (low porosity, high strength) and in particular the aggregate particles used in the mix. While good quality concrete may show good resistance to abrasion and erosion, it may still suffer severe loss of surface material due to cavitation. The best way to guard against the effects of cavitation is to eliminate the cause(s) of cavitation. Reference 3.21 provides additional information on the effects of erosion on concrete structures. With respect to Category I structures, only those providing water intake, conveyance, or management are possibly affected by abrasion, erosion, or cavitation.

Fatigue/Vibration. Concrete structures subjected to fluctuations in loading, temperature, or moisture content (which are not large enough to cause failure in a single application) can be damaged by fatigue. Fatigue damage initiates as microcracks in the cement paste, proximate to the large aggregate particles, reinforcing steel, or stress risers (e.g., defects). Upon continued or reversed load application, these microcracks may propagate to form structurally significant cracks which can expose the concrete and reinforcing steel to hostile environments or produce increased deflections. Ultimate failure

of a concrete structure in fatigue will occur as a result of excessive cracking, excessive deflections, or brittle fracture.

Within LWR facilities, certain Category I concrete structures may be subjected to repetitive or vibration loadings, e.g., supports for NSSS equipment/components and operating pumps/turbines. As a result of the good resistance of concrete to fatigue,[3.22,3.23] and the use of design codes which have limited design stress levels to values below concrete's endurance limit (the fatigue strength of concrete for a life of 10^7 cycles of compression, tension, or flexure loading is approximately 55% of static strength[3.22]), no significant fatigue-related damage has been reported by the nuclear industry. However, there may be instances where locally exposed surfaces of support structures have displayed some effects of vibration loads, e.g., cracks. As the structures age, however, there may be increasing incidences of damage from fatigue at locations where reciprocating equipment is attached to its supporting structure, or at supports for pipes that exhibit flow-induced vibrations.

3.1.2 Mild Steel Reinforcing Systems

3.1.2.1 Corrosion. Although deterioration of concrete may be attributable to the combined effects of more than one cause, corrosion of embedded metal is one of the principal causes. Corrosion of steel in concrete is an electrochemical process. The electrochemical potentials which form the corrosion cells may be generated in two ways: (1) composition cells formed when two dissimilar metals are embedded in concrete, such as steel rebars and aluminum conduit, or when significant variations exist in surface characteristics of the steel, and (2) concentration cells formed due to differences in concentration of dissolved ions in the vicinity of steel, such as alkalies, chlorides, and oxygen.[3.4] As a result, one of two metals (or different parts of the metal when only one metal is present) becomes anodic and the other cathodic. Other potential causes of corrosion include the effects of stray electrical currents or galvanic action with an embedded steel of different metallurgy. The transformation of metallic iron to ferric oxide (rust) is accompanied by an increase in volume which, depending on the state of oxidation, may be as large as 600 percent of the original metal. The volume increase can cause cracking and spalling of the concrete. In addition, corrosion will result in a reduction in effective steel cross-section and capacity. Depending on the source, local embrittlement may also be produced.

In good-quality, well-compacted concretes, reinforcing steel with adequate cover should not be susceptible to corrosion because the highly alkaline conditions present within the concrete (pH > 12) causes a passive iron oxide film to form on the iron surface, i.e., metallic iron will not be available for anodic activity. However, when the concrete pH falls below 11, a porous oxide layer (rust) can form on the reinforcing steel due to corrosion. Carbonation and the presence of chloride ions can destroy the passive iron oxide film. Reduction of the concrete pH can occur as a result of leaching of alkaline substances by water or carbonation, i.e., calcium hydroxide is converted to calcium carbonate (calcite). The penetration of CO_2 from the environment can be accelerated due to the concrete being porous (poor quality) or the presence of microcracks. The penetration of chloride ions can also destroy the passive oxide film on the reinforcing steel, even at high alkalinities (pH > 11.5). For typical concrete mixtures, the threshold chloride content to initiate steel corrosion is about 0.6 to 1.2 kg $C\ell^-/m^3$ (Ref. 3.7). Chlorides may be present due to external sources (deicing salts, etc.) or may be naturally introduced into the concrete via aggregate or mix water transport. Furthermore, when large amounts of chloride are present, concrete tends to hold more moisture, which also increases the risk of steel corrosion by lowering concrete's electrical resistivity. Once the passivity of the steel is destroyed, the electrical resistivity of concrete and availability of oxygen control the rate of corrosion.

The widespread occurrence of reinforcing steel corrosion in general civil works structures has resulted in the issuance of many publications related to its cause, propagation, detection, and damage mitigation, e.g., Ref. 3.9. Because of the potential damage to concrete structures caused by the corrosion of reinforcing steel, this factor is

potentially one of the most significant for all Category I structures. The effects of corrosion may be observed visually following damage (e.g., rust stains, cracking, or spalling of concrete) or assessed nondestructively (see Section 3.2).

3.1.2.2 Elevated Temperature. The properties of mild steel reinforcement used in design are generally a function of the yield stress, which is affected by exposure to elevated temperature. Data for German reinforcing steels[3.24] indicate that for temperatures up to ~200°C, the yield strength is reduced ≤ 10% and that at 500°C, it falls to 50% its reference value, with hot rolled steels performing better than cold twisted or cold drawn steels. The modulus of elasticity exhibits a similar reduction pattern with increasing temperature.

Other data [3.25,3.26] confirm the effects of temperatures above 200°C on reinforcing steel as well as the threshold temperature of 300°C for loss of reinforcing steel bond properties with concrete. As these threshold values are below typical LWR temperature exposures, thermal damage to reinforcing steels should be negligible except for possibly at local areas or structures in close proximity to the NSSS equipment.

3.1.2.3 Irradiation. Neutron irradiation produces changes in the mechanical properties of carbon steel, e.g., an increase in yield strength and a rise in ductile/brittle transition temperature. The changes result from the displacement of atoms from their normal sites by high energy neutrons, causing the formation of interstitials and vacancies. As a consequence, the reduced ductility will increase the possibility of brittle fracture. In LWR facilities, the critical reinforcing steel that may experience irradiation effects is located in the primary shield wall adjacent to the reactor pressure vessel.

References 3.27 and 3.28 suggest that the threshold level of neutron fluence for alteration of reinforcing steel mechanical properties is 1×10^{18} neutrons/square centimeters. As indicated in Ref. 3.20, fluence levels of this magnitude may be present at the reinforcing steel level of the Category I primary shield wall. However, the cover concrete may provide significant attenuation. Further research is necessary to determine ultimate impact of irradiation on reinforcing steel.

3.1.2.4 Fatigue. Fatigue of the mild reinforcing system would be coupled with that of the surrounding concrete. The result of applied repeated loadings, or vibrations, is generally a loss of bond between the steel reinforcement and concrete. For extreme conditions, the strength of the mild steel reinforcing system may be reduced or failures may occur at applied stress levels less than yield. There have been few documented cases of fatigue failures of reinforcing steel in concrete structures and those published occurred at relatively high stress/cycle combinations.[3] Concrete structures in nuclear plants which may be exposed to fatigue or vibration loads include the reactor pedestal or support concrete, refueling structures, and equipment supports. Because of the typically low normal stress levels in reinforcing steel elements in Category I concrete structures, fatigue failure is not likely to occur.

3.1.3 Prestressing Systems

3.1.3.1 Corrosion. Corrosion of prestressing systems can be highly localized or uniform. Most prestressing corrosion-related failures have been the result of localized attack produced by pitting, stress corrosion, hydrogen embrittlement, or a combination of these. Pitting is the electrochemical process that results in locally intensified material loss at the tendon surface, potentially reducing the cross section to the point where it is incapable of supporting load. Stress corrosion cracking results in the fracture of a normally ductile metal or alloy under stress (tensile or residual) while in specific corrosive environments. Hydrogen embrittlement, frequently associated with hydrogen sulfide exposure, occurs

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[3] Reference 3.22 indicates that the lowest stress range known to have caused a fatigue failure of a straight hot-rolled deformed bar embedded in concrete is 145 MPa. The failure occurred after 1.25×10^6 cycles of loading on a beam containing a No. 11, Grade 60 bar when the minimum stress level was 121 MPa.

when hydrogen atoms enter the metal lattice and significantly reduce its ductility. Failure of prestressing tendons can also occur as a result of microbiological-induced corrosion (MIC). Protection of the prestressing systems is provided by filling the ducts containing the post-tensioned tendons either with organic corrosion inhibitors which include microcrystalline waxes such as petrolatums (nongrouted tendons), or portland cement grout (grouted tendons). Regulatory requirements for inspection and replacement have made nongrouted post-tensioned steel tendons the dominant prestressing system used in containments. Fully bonded prestressing tendons were used only at two nuclear power plants (Robinson 2 and Three Mile Island 2), plus two rock anchor installations (Bellefonte and Ginna)

Due to the stress state in the prestressing systems, and the importance of the system to overall structural integrity, the tolerance for corrosion attack is not as great for the prestressing systems as for the mild steel reinforcement. Corrosion is therefore an important factor affecting the service life of LWR prestressing tendons. The prestressing systems, however, are one of the most highly-monitored structural systems in an LWR plant.

3.1.3.2 Elevated Temperature. The effect of elevated temperature on all heat-treated and drawn wires can be significant, and on cooling the wires may not regain their initial strength because the heating destroys the crystal transformations achieved by the heat-treating process. Short-term heating, on the order of 3 to 5 min., even to temperatures as high as 400° C, however, may not harm the prestressing wire's mechanical properties.[3.29] Results of a Belgian study[3.24] involving thirty types of prestressing steels indicate that thermal exposures up to ~200°C do not significantly reduce (< 10%) the tensile strength of prestressing wires or strands. References 3.26 and 3.32 support results of the Belgian study.

Elevated-temperature exposures also affect the relaxation and creep properties of prestressing tendons. Reference 3.30 indicates that losses in a 15.2-mm-diam strand initially stressed to 75% its guaranteed ultimate tensile strength at 40°C will be 5 to 6.4% after 30 years. Relaxation losses of tendons composed of stress-relieved wires have relaxation losses of about the same magnitude as stress-relieved strand, but relaxation of a strand is greater than that of its straight constituent wire because of the combined stress relaxation in the helical wires.[3.31] Creep (length change under constant stress) of stress-relieved wire is negligible up to 50% its tensile strength. Also, the creep effect in steel varies with its chemical composition as well as with mechanical and thermal treatment applied during the manufacturing process. As temperature levels experienced by the prestressing tendons in LWR facilities are below 200°C, the possibility for thermal damage to the prestressing steels under normal operating conditions is reduced to only at local areas.

3.1.3.3 Irradiation. Irradiation of steel affects its mechanical properties because atoms are displaced from their normal sites by high-energy neutrons to form interstitials and vacancies. These defects can propagate or combine and effectively both strengthen the steel and reduce its ductility; or, at higher temperatures, they can recombine and annihilate each other and, for a given neutron dose, reduce the irradiation damage.[3.27] Results obtained from studies[3.27] in which 2.5-mm-diam prestressing wires were stressed to 70% of their tensile strength and irradiated to a total dose of 4×10^{16} neutrons/cm^2 (flux of 2×10^{10} neutrons·cm^2·s) showed that for exposures up to this level, the relaxation behavior of irradiated and unirradiated materials was similar. These flux levels are higher than the level likely to be experienced in a LWR containment vessel.

3.1.3.4 Fatigue. Repeated reversals of stress, or variations in stress, applied to concrete structural elements (beams in particular) can result in fatigue failure in any of the following modes: (1) failure of the concrete due to flexural compression; (2) failure of the concrete due to diagonal tension or shear, (3) failure of the prestressing steel due to flexural, tensile-stress variations; (4) failure of pre-tensioned beams (grouted tendons) due

to loss of bond stress; and (5) failure of the end anchorages of post-tensioned structures.[3.33] The majority of fatigue failures that have been found while testing prestressed concrete beams have resulted from fatigue of the tendons due to stress concentrations that occur in the tendon at a location where a crack occurs. In unbonded post-tensioned construction, the end anchorages could be subjected to some variation in stress under the action of changing external load, but unbonded tendons are not generally used in members subjected to frequent variations in stress. Reference 3.34 presents high-cycle and low-cycle dynamic tensile test requirements for prestressing tendon systems used in concrete containments.

3.1.3.5 Loss of Prestressing Force and End Effects

Loss of Prestressing Force. Primary contributors to loss of the original force level that was applied to the prestressing tendons include (Refs. 3.35 to 3.38): (1) friction, (2) end anchorage deflection (take up end slip), (3) elastic shortening, (4) tendon relaxation, and (5) concrete creep/shrinkage. Of these factors, tendon relaxation and concrete creep/shrinkage are time-dependent factors and thus aging related.

Stress relaxation, defined as loss of stress (force) in the steel when the strain (elongation) does not vary, is related to tendon material properties, initial stress level, exposure temperature, and time. Creep and shrinkage of concrete represent volume changes of the concrete that occur over the life of the structure which can significantly affect the force levels in the tendons. Guidelines for developing surveillance programs acceptable to the USNRC and for providing reasonable assurance (when properly implemented) that the structural integrity of the containment is being maintained are provided in Regulatory Guides.[3.39,3.40] Reference 3.40 is a companion to Ref. 3.39 and provides clarification with respect to determination of prestressing forces and prediction of prestressing force losses over the service life of the structure.

End Effects. As containment tendons, especially strand tendons, are detensioned and retensioned in compliance with inspection or maintenance requirements, localized notching damage can occur. Such notching, if not located and repaired, could result in locations of stress intensification and contribute to the initiation of other potential sources of degradation, e.g., fatigue or corrosion.

3.1.4 Liner Plate and Structural Steel

3.1.4.1 Corrosion. The primary degradation factor for the liner plate and structural steel (both embedded sections and those within containment) is corrosion. Typically, the liner plate and any installed steel are coated, either with a primer or primer-finish coat system, to prevent corrosion. Depending on the component, a corrosion allowance may also have been provided during the design stage. However, local environments may produce aggressive conditions causing material wastage and loss-of-function during the component's lifetime.

The corrosion process which affects these components is similar to that described for conventional reinforcing steel. For liner plates, the influence of local attack is of greatest importance because of its possible affect on leak tightness. Local attack may result from loss of coating integrity, impact, failure of adjoining floor sealant, and other causes. Local attack mechanisms include galvanic corrosion, pitting, crevicing, and corrosion caused by stray electric currents or biological effects. The rate of local attack may also be rapid depending on the aggressiveness of the environment. Rates of general attack have been reported for a BWR metal containment vessel (similar material to liner plate) as being between 0.45 to 1.3 mm/year.[3.41] Through periodic inspection and the maintenance of coatings, the liner plate should perform adequately for its service life. If unattended, the influence of local corrosion on the liner plate may necessitate repairs or replacements.

For structural steel, the most probable corrosion activity will also be localized, in pit or crevice form. Reference 3.42 contains corrosion data for structural carbon steel in numerous environments. For an industrial environment, the atmospheric (general) corro-

sion rate was found to be 0.02 to 0.04 mm/year. This same document reported pitting rates of 0.056 mm/year for low carbon steel placed in polluted seawater. Structural steel embedments are primarily exposed to the surrounding concrete, which is typically protective. However, as indicated in Section 3.1.1, this normally protective environment may become porous or unprotective. Of greatest importance is the possible loss of steel section leading to reduced capacity. Interface locations with concrete are also critical areas due to the permeability of concrete and possible intrusion of aggressive fluids. Should aggressive fluids be present, corrosion rates similar to those of Refs. 3.41 and 3.42 may be expected.

Corrosion of structural steel piles, used in certain containment configurations for transferring foundation loadings to greater depths below grade, is also a possible degradation mechanism. Similar to other containment steel, the concern for piles is from localized corrosion resulting in significant loss of cross-sectional area. One study[3.43] examined corrosion data from 43 piling installations of varying depths (up to 41.5 m) with times of exposure ranging from 7 to 50 years in a wide variety of conditions. The conclusion of this study was that the type and amount of corrosion observed in steel pilings driven in undisturbed soil, regardless of soil characteristics and properties, was not sufficient to significantly affect the piling's performance as load-bearing structures. However, pilings placed in oxygen-enhanced fills, those exposed above grade, or those exposed to seawater or salt spray may be somewhat affected.[3.44]

3.1.4.2 Fatigue. The effects of repeated loads such as polar crane loads, equipment or flow-induced vibrations, and system (such as BWR relief valve testing) or containment leakage tests may possibly detract from the function and performance of liner plate and structural steel members. The influence of repeated loads has been generally addressed at the design stage per national design codes. However, the effects of conditions outside of design predictions and local stress intensification points (material flaws, etc.) may result in fatigue-related problems. With respect to the liner plate, possible fatigue sites include base metal delaminations, weld defects, arc strikes, shape changes near penetrations, structural attachments, and concrete floor interfaces. For structural steel members (liner attachments and anchorages), the locations most susceptible to fatigue include large containment penetration framing (hatches, etc.), and liner anchorages near vibrating load conditions (such as those generated in structural attachments). The fatigue of pile components is considered to be very remote because of the damping provided by the soil and concrete foundation elements.

3.2 Techniques for Detection of Degradation Factor Effects

Debilitation of concrete structures can be a direct result of an individual degradation factor, or the effects of two or more of these factors working in concert. To establish whether or not such an interaction exists involves close evaluation of results obtained during field surveys and inspections, in conjunction with an evaluation of the material systems through sample testing and analysis. Table 3.4 presents a summary and an indication of the relative capability of several methods which are available for the identification of various degradation factor effects noted in the previous section. A brief description of these methods follows. More detailed information on these methods can be obtained from Refs. 3.45 and 3.46.

3.2.1 Concrete Material Systems

Methods which can be used to detect degradation in concrete materials can be grouped into two general categories: direct techniques and indirect techniques.

Direct techniques generally involve a visual examination of the structure, removal/testing/analysis of material, or a combination. Periodic visual examinations of exposed concrete provides a rapid and effective method for identifying and defining areas of distress

(e.g., cracking, spalling, volume change). By locating, marking, identifying by type and orientation, and measuring and recording conditions associated with cracking[4] (seepage, differential movement, edge spalling, etc.), a history that will be of assistance in identifying the cause and establishing whether a crack is active or dormant can be established. In areas exhibiting extensive deterioration, or where a quantitative assessment of the concrete condition is desired, core specimens can be removed for testing and analysis. Through petrographic, chemical, microscopic examination and strength testing of cores, information can be provided on: concrete strength, nature of the air void system, type and relative amounts of aggregate materials, cement content, water-cement ratio (estimate), presence of deleterious substances, and if the concrete has experienced adverse chemical reactions. Concrete coring can also be used to determine the depth of cracks.

Indirect techniques measure some property of concrete from which an estimate of the concrete strength, elastic behavior, or the extent of concrete degradation (internal cracks, voids, delaminations, depth of cracking) can be made through correlations that have been developed. Nondestructive test methods include ultrasonic and stress-wave, acoustic impact, radiography and penetrating radar, thermal, surface hardness or rebound, penetration, pullout and breakoff resistance. Electromagnetic devices (cover meters and pachometers) can be used to indicate the depth, position and size of steel reinforcing bars in concrete. In using any methods to predict concrete strength, Ref. 3.47 recommends that this not be done unless comprehensive laboratory correlations of the field materials and mix proportions have been established between the strength parameters to be predicted and the results of in situ/nondestructive tests. Because of the general massive nature of safety-related structures, many of the current nondestructive test methods may need improvement to provide useful information.

3.2.2 Mild Steel Reinforcing Systems

The primary source of distress to which mild steel reinforcement in LWR facilities would be subjected would be corrosive attack. Techniques available for corrosion monitoring and inspection of steel in concrete include: (1) visual inspection (cracking, spalling, and staining of cover concrete), (2) mechanical and ultrasonic testing (delaminated or cracked concrete adjacent to rebars), (3) core sampling (direct examination of rebar for corrosion, distribution of contaminants, concrete resistivity), (4) corrosion potential measurements (rebar passivity), and (5) corrosion probes (rate of corrosion). Degradation due to fatigue or elevated temperature would most likely be reflected through visual examination of the concrete. The removal and testing of material samples would be required to establish the extent (magnitude) of degradation of mild steel reinforcement due to elevated temperature or irradiation exposure.

3.2.3 Steel Prestressing Systems

The condition and functional capability of unbonded prestressing systems in LWR post-tensioned concrete containments is periodically assessed. The present basis for conducting tendon inspections is contained in R.G. 1.35 *Inservice Inspections of Ungrouted Tendons in Prestressed Concrete Containment Structures*.[3.39] Basic components covered in the RG include sample selection, visual inspection, prestress monitoring tests, tendon material tests and inspections, and inspection of filler grease. Since the prestressing systems in nuclear power plants are inspected according to a prescribed schedule, results of the inspections are available for trending the performance of the systems, i.e., relaxation or loss of force, presence of corrosion, water intrusion, etc.

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[4] Cracking of concrete is the primary manifestation that results from the effects of the degradation factors, as well as the effect most readily detectable in a field survey, i.e., visual examination

3.2.4 Liner Plate and Structural Steel

Periodic inspections of exposed liner surfaces and provided coatings are conducted under a surveillance program established in compliance with 10CFR. Section XI, Subsection IWE of the *ASME Boiler and Pressure Vessel Code* (B&PVC)[3.48] provides rules for preservice examination as well as inservice inspection of liners. In addition, a general inspection of the entire containment boundary is required prior to each Type A integrated leakage rate test as specified in Appendix J to 10CFR50.

Structural steel members, and steel portions not backed by concrete in concrete containments, are inspected under a surveillance program established in compliance with 10CFR. The members are inspected in association with a Type A integrated leakage rate test and inspections conducted in compliance with requirements such as provided in Section XI, Subsections IWE and IWL, of the *ASME B&PVC*.

3.3 Degradation Grading System for Nuclear Power Plant Concrete Structures

The effect of degradation on a concrete structure is initially related to the alteration of the structure's constituent materials. As the severity of degradation advances, the integrity, as well as other functional properties, of the structure is reduced. The service life of safety-related concrete structures may be characterized in terms of degradation's effect on the structure's functional and performance requirements, i.e., the remaining life of the structure is dependent on the rate of degradation, or loss of integrity.

3.3.1 Significance Relative to Overall Structural Integrity

Four criteria are considered to have an important role in assessing the significance of the various degradation factors relative to their impact on the performance of concrete structures in nuclear power plants. These criteria include: (1) rate of deterioration, (2) inspectability and early identification (of the degradation factor), (3) repairability (of the degraded structure), and (4) ultimate impact (of applied degradation factor). Table 3.5 summarizes the results of an assessment in which each criterion was evaluated for pertinent factors that can degrade the performance of the concrete, mild steel reinforcing, prestressing, and liner plate/structural steel systems. The relative effects with respect to the four criteria for each material system degradation factor were assigned on the basis of the potential impact on the structure's serviceability or integrity, i.e., high (creates a major limiting condition or has a major adverse effect), moderate (creates a minor effect), or low (creates very low or no effect). A short description of each of the four criteria follows.

3.3.1.1 Rate of Deterioration. Figure 3.2 presents an empirical relationship between degradation and time for reinforced concrete structures, i.e., concrete degradation follows a particular performance-time curve. Early in their service life, concrete materials/structures historically exhibit durable behavior and require little maintenance. However, with passing time and exposure to weathering elements, service loads, and other environmental conditions, degradation can occur. The extent and rate of degradation will depend on several factors, e.g., adequacy of design, quality of construction, concrete constituents, severity of environment, etc. As noted in Fig. 3.2, the rate of degradation generally will increase with time, eventually reaching a point where the structure is no longer satisfactory for its intended use (impairment stage). In assessing the relative effects of the rate of deterioration criterion for the potential degradation factors of each material system in Table 3.5, the time-dependent impact (occurrence and degradation rate) of each of the degradation factors was established on the basis of field and laboratory observations. References 3.49 to 3.53 provide background information that was utilized in the assessments.

3.3.1.2 Inspectability and Early Identification. The ability to inspect and identify a particular degradation mechanism, or a synergistic combination of mechanisms, at an early stage in their development contributes to the long-term serviceability, repairability, and integrity of nuclear power plant concrete structures. In assessing the relative effects of the inspectability and early identification criterion for the potential degradation factors of each material system listed in Table 3.5, the manner in which the degradation factor manifests itself (e.g., ease of identification) was taken into account as well as an assessment of the capability of the appropriate methods available for detection of a particular degradation factor. For structural elements located partially or totally underground, such as foundations, inspectability and early identification of degradation is difficult.

3.3.1.3 Repairability. Repairability, or repair demand, of concrete structures generally falls into one of four categories: (1) restore lost concrete section, (2) repair steel reinforcement damage, (3) restore monolithic/aesthetic effects, and (4) strengthen the composite material interaction. Two distinct points must be considered in assessing the repairability of a concrete structure: its technical and economical feasibility. Experience indicates that essentially any concrete structure can be repaired, but the extent to which the restoration reestablishes the original condition of the structure is subject to considerable debate. Implementation of the appropriate technology in almost all instances will provide a refurbished structure that will continue to meet its functional and performance requirements. Technical feasibility, or the limits of engineering analysis, however, can be economically limited by certain demands of concrete structures. Thus, technical and economical limits were included in the assessment of the relative effects of the repairability criterion for the potential degradation factors of each material system in Table 3.5.

3.3.1.4 Ultimate Impact. In previous sections, the various degradation factors that can impact concrete structures (Table 3.1), potential areas of deterioration in nuclear power plants (Table 3.2), and the manifestation of each degradation factor (Table 3.4) were identified. In assessing the relative effects of the ultimate impact criterion for the potential degradation factors of each material system in Table 3.5, the above was considered as well as the influence of any potential degradation on the safety functions performed by the structure and the physical characteristics of the structure's subelements (column, beam, etc.).

3.3.2 Determination of Degradation Factor Grading Values

A key consideration with respect to the service life of Category I structures is their ability to resist the effects of the various degradation factors, i.e., their durability. A quantitative system for grading the degradation of each Category I structure has been developed based on consideration of the end point or consequent net effects resulting from the specific factor. The basis for this grading system is the historical occurrence of degradation in LWR concrete structures; documented effects in general civil engineering structures; and laboratory, field, and accelerated aging test results.

3.3.2.1 Grading System Components

The influences (effects) of the four criteria in relation to each of the degradation factors that can impact the durability of the concrete, mild steel reinforcing, prestressing, and liner plate/structural steel material systems were presented in Section 3.3.1. These qualitative effects were converted to a numeric (quantitative) degradation factor grading value which includes the influence of each of the four criteria. In developing composite degradation factor grading values, degradation factors with "moderate" or "high" listings under each criterion were assigned appropriately higher values. A range of values was established because of the multitude of characteristics which may affect the occurrence/significance of a degradation factor, i.e., a range of values will accommodate differing characteristics at LWR facilities including environment and material influences, presence of protective coatings, etc. The limits for the range of possible degradation factor grading values was based on a maximum of 10, signifying a degradation factor of potentially major significance, and a minimum of 1, signifying a degradation factor of

potentially minor significance. A range of degradation factor grading values is listed in Table 3.5 and indicates that chemical attack or thermal exposure/thermal cycling of concrete materials and corrosion of the metallic materials are potentially the most significant degradation factors. References 3.11, 3.54, and 3.55 substantiate these results.

Consequent Net Effects. The net effect of degradation in a Category I concrete structure may be a loss of monolithic behavior, damage to the steel reinforcing system, loss of concrete section, or weakening of the structural material. Initially, degradation primarily affects the appearance, behavior, or function of the materials of construction. Propagation of degradation damage without implementation of mitigation, maintenance or repair procedures can result in loss of structural integrity. Degradation factors which promote rapid loss of integrity are most critical.

In order to prioritize the consequent net effect of degradation on a Category I concrete structure, relative importance weight values were assigned to each of the effects noted above using a 0 to 1.0 scale, with 1.0 being the most critical. Table 3.6 presents the relative importance weight value assigned to each of the four consequent net effects of degradation. Assignment of a relative importance weight value was on the basis of a comparative assessment of the potential impact of each consequent net effect on the function of the structure/subelement.

Since the loss of monolithic behavior signifies that the structure no longer is capable of performing its intended function, it was assigned a relative importance weight value of 1.0. This condition is characterized in concrete structures through the occurrence of severe concrete cracking, loss of bond between the concrete and mild steel reinforcement, or loss of a constituent's load-carrying ability.

Significant damage to the mild steel reinforcing system can also result in a loss of monolithic behavior. Because Category I concrete structures must rely on the performance of mild steel reinforcement to meet their performance requirements, this net effect was also assigned a relative importance weight value of 1.0.

The loss of concrete section from a Category I structure can signify the loss of load-carrying capacity and function. If the loss of concrete section is considered to be minor, such as loss of a portion of the mild steel reinforcing cover, a relative importance weight value of 0.7 is assigned. However, if the loss of concrete section is considered to be major, such as a gross loss of concrete net section, a relative importance weight value of 0.8 is assigned.

A reduction in the performance of one or more of the constituent materials of a structure is considered important because it can impact the structure's long-term performance. However, due to the composite nature of a structure, a reduction in the performance of one of its constituent materials will generally not be as significant as that of the other consequent net effects of degradation. A relative importance weight value of 0.6 was assigned to weakening of the structural material.

Subelement Importance Values. In order to prioritize the overall importance of a subelement to the performance of its parent structure, relative importance values were assigned to each subelement using a 1 to 10 scale, with 10 being the most important. Table 3.6 presents the importance values that have been assigned to the pertinent structural subelements, i.e., shell, foundation, floor, beam, column/concrete interior partition wall, and shear wall. Although these values are similar to those presented in Table 2.2, they are not the same. Table 3.6 values are generic in nature and bound all subelements listed in each functional group. The assigned values are based on individual structural behavior and required performance of the subelement in the overall structural system. In establishing subelement importance values, a hierarchy such as presented in Ref. 3.56 was utilized.

Shell members include those which can provide both a structural and pressure-retaining function. An example would be a vertical wall element of the containment vessel. Since shell members are designed to prevent the release of radioactive fission products to the environment under postulated design basis accident conditions as well as protecting

safety class equipment and piping from external events, they are considered to have critical importance and have been assigned an importance value of 10.

Foundation or base slab elements provide the transfer of LWR facility loadings to the supporting medium, i.e., soil, bedrock, piles, or a combination. Since these elements have no redundancy and are not readily inspectable, they have been assigned an importance value of 10.

Floors are typically used to provide the primary means of transferring facility loads to other supporting elements, as well as performing other functions such as radiation shielding. The floor elements have been assigned an importance value of 7.

Beam elements typically are used to provide support for floors, as well as to transfer loadings to other support elements. Beam elements also have been assigned an importance value of 7.

Columns are used to provide intermediate support for floor slabs and primary support for overhead floors when walls are not available or unusually heavy floor loads occur. Columns have been assigned an importance value of 9.

Shear walls are often used to transfer vertical loads from other supporting elements (floors, beams) to the foundation or base slab, as well as restraining horizontal loads applied to the structure. Shear walls have been assigned an importance value of 8.

Consequent Net Effects Prioritization. The prioritization of consequent net effects of degradation on the performance of Category I concrete structures is treated in terms of the structure's generic subelements. To obtain a quantitative indication of the consequent net effects for each of the generic subelements identified previously and listed in Table 3.6, the consequent net effect relative importance weight value (0 to 1 scale) is multiplied by the relative importance value (0 to 10 scale) assigned to the generic subelement, e.g., a shell subelement with respect to minor loss of concrete section has a prioritization of consequent net effects value of 7 (10 * 0.7). Table 3.6 presents the prioritization of consequent net effects of degradation for each generic subelement. The resulting prioritization of consequent net effects value for each generic subelement is based on a 1 to 10 scale, with 10 being most important. A scale of 1 to 10 was used to be consistent with other values presented in the report.

3.3.2.2 Degradation Factor Grading Values. Using the results presented in the previous sections, a system was developed for use in assigning a range of degradation factor grading values to specific degradation factor/subelement combinations. Tables 3.7(a) and 3.7(b) present the resulting ranges of degradation factor grading values for the concrete and metallic constituents, respectively, for subelements of structures found in LWR plants. These tables are based on the significance of each potential degradation factor (Table 3.5) and its consequent net effect on particular subelements (Table 3.6). The methodology used to create Table 3.7 follows:

(1) Select a specific degradation factor and determine its applicability to each subelement. If the factor is determined to be insignificant (e.g., irradiation effects on foundation elements), no range is selected, however, if the factor is found to be potentially significant, its range from Table 3.5 is initially selected (e.g. , corrosion of mild steel reinforcement = 6 - 10),

(2) Classify each subelement (Section 2.0) into one of the six generic subelement types listed in Table 3.6. The specific degradation factor from Step (1) is assessed to determine what the "worst case" consequent net effect is for each subelement (e.g., corrosion of mild steel reinforcement = damage to the steel reinforcing system). The resultant relative importance value is then found in Table 3.6 for the particular subelement under consideration (e.g., beam = 7.0),

(3) Calculate initial Table 3.7 range of degradation factor grading values by multiplying the upper and lower Table 3.5 values [e.g., 10 and 6, from Step (1)] by the Table 3.6 subelement relative importance value [e.g., 7.0, from Step (2)] and divide by 10 (e.g., range of degradation factor grading values = 7 to 4.2), and

(4) Using resulting range, make appropriate adjustments such as: rounding of degradation factor grading values to the closest integer; synthesizing the range to account for specific vs generic subelement differences; modifying values based on experience, review of the LER, age-related data bases; etc.

Selection of an individual degradation factor grading value from the provided ranges in Tables 3.7(a) and 3.7(b) for use in the structural aging assessment methodology requires either a review of plant operation history and environmental data, a condition survey (past or present), or both. These prerequisites are necessary to provide an indication of the past and current presence or probability of degradation at an LWR plant. Should a particular hostile environmental condition (e.g., high sulfate levels in groundwater, exposure to seawater spray, etc.) be present, a degradation factor grading value high in the range presented should be selected. Similarly, if a lower probability of occurrence should be anticipated, a degradation factor grading value low in the range should be selected. Synergism of degradation factors, if present, would be accounted for by the selection of degradation factor grading values high in the range selected for each factor. To assist in the selection of a degradation factor grading value from the ranges presented for the various degradation factors, Table 3.8 contains a listing of typical degradation indicators (characteristics) for the factors which can impact the concrete, mild steel reinforcing, prestressing, and liner plate/structural steel material systems.

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Table 3.1. Degradation Factors That Can Impact the Performance of Category I Concrete Structures

Material System	Degradation Factor
Concrete	Chemical attack Efflorescence and leaching Salt crystallization Alkali-aggregate reactions[a] Sulfate attack Bases and acids Physical attack Freeze/thaw cycling Thermal exposure/thermal cycling Irradiation Abrasion/erosion/cavitation Fatigue/vibration
Mild Steel Reinforcement	Corrosion Elevated temperature Irradiation Fatigue
Prestressing	Corrosion Elevated temperature Irradiation Fatigue Loss of prestressing force
Liner/Structural Steel	Corrosion Fatigue

[a]Includes reactions of cement-aggregate and carbonate aggregate.

Table 3.2. Critical Areas in Nuclear Power Plants Where Concrete Materials May Exhibit Degradation

Material System	Degradation Factor	Potential Areas of Deterioration
Concrete	Chemical Attack	• Subterranean areas • Surfaces exposed to cooling water sources • In-containment floors and slabs • Containment/shield, auxiliary building structures (acid rain, ocean atmosphere, alkali-aggregate reaction)
	Freeze/Thaw Cycling	• External structures where water may collect • Intake/discharge structures, particularly at water line of cooling water source
	Thermal Exposure/Thermal Cycling	• Containment/shield structures (diurnal and seasonal effects) • Areas located near reactor coolant pressure boundary or hot piping systems
	Irradiation	• In-containment structures proximate to reactor coolant pressure boundary • Localized areas of specific containment designs
	Abrasion/Erosion/ Cavitation	• Floor and slab elements • Cooling water intake or discharge structures
	Fatigue/Vibration	• Local areas in containment (e.g., near liner anchors) • Local areas under equipment supports
Mild Steel Reinforcement	Corrosion	• Outer layer of conventional steel reinforcing in all structures
	Irradiation	• In-containment structures proximate to reactor coolant pressure boundary
	Fatigue	• Local areas in structures subjected to repeated equipment loads
Prestressing	Corrosion	• Containment buildings
	Relaxation	• In-containment buildings • Fuel pool structures

Table 3.3. Reactivity of Various Chemicals with Portland Cement Concrete and Reinforcing Steel/Liner Plates*

Material	Reactivity Effect on Concrete	Reactivity Effect on Reinforcing Steel/Liner Plate
Acetone	Liquid loss by penetration (may cause slow disintegration)	None
Acidic Water (less than 6.5 pH)	Disintegrates concrete slowly	May attack rebar and embedments
Boric Acid	Negligible effect unless immersed	Severely corrosive to liner and reinforcing steel
Borated Water (and boron)	Negligible effect unless immersed	Very corrosive at high concentration
Chlorine Gas	Concrete (moist) slowly disintegrates	Highly corrosive
Deicing Salts	Scaling of non-air entrained concrete	Highly corrosive
Diesel Exhaust Gases	May disintegrate moist concrete by action of carbonic, nitric or sulphurous acid; minimal effect on hardened dry concrete	Minimal
Formaldehyde (formic acid)	Disintegrates slowly	Minimal
Hydrochloric Acid	Disintegrates concrete rapidly	Highly corrosive
Hydroxides	At low concentrations, slow disintegration; at high concentrations, greater disintegration	Unknown

Table 3.3 (cont.)

Chemical	Reactivity Effect on Concrete	Reactivity Effect on Reinforcing Steel/Liner Plate
Lubricating Oil	Fatty oils, if present, slowly disintegrate. Liquid loss by penetration.	Minimal
Seawater	Disintegrates concrete with inadequate sulfate resistance	Highly corrosive
Sodium Hydroxide	Not harmful below 20% concentration, disintegrates at concentrations above 20%	Minimal
Sodium Pentaborate	Disintegrates at varying rates depending on concentration	Dependent on concentration
Sulfates	Disintegrates at varying rates with concentration (concretes with low sulfate resistance such as Type I Portland cement concrete)	Harmful at certain concentrations
Sulphuric Acid (sulphurous)	Disintegrates rapidly in concentrations between 10 and 80%	Harmful

*Source: ACI Committee 515, "A Guide for the Use of Waterproofing, Dampproofing, Protective, and Decorative Barrier Systems for Concrete," Table 2.5.2, ACI 515.1R-79, pp. 515.1R-6 to 515.1R-11, *American Concrete Institute Manual of Concrete Practice 1990, Part 5 – Masonry, Precast Concrete*, Special Processes, Detroit, 1990.

Table 3.4a. Summary of Degradation Factors, Primary Manifestations, and Methods Available for Their Detection: Concrete

Degradation Factor	Primary Manifestation	Direct Methods				Indirect Methods		
		Material Sampling/Testing				Ultrasonic	Acoustic Sounding	Penetrating Radar
		Visual Inspection	Petrography	Strength	Chemical/ Microscopic			
Chemical Attack								
Efflorescence/Leaching	Increased Porosity	Good	Good		Good			
Salt Crystallization	Cracking	Good[b]	Good		Good	Good[b]	Good[b]	Fair[b]
Alkali-Aggregate Reactions[a]	Volume Change/Cracking	Good[b]	Good		Good	Good[b]	Good[b]	Fair[b]
Sulfate Attack	Volume Change/Cracking	Good[b]	Good		Good	Good[b]	Good[b]	Fair[b]
Bases and Acids	Increased Porosity/Erosion	Good	Good		Good			
Physical Attack								
Freeze/Thaw Cycling	Cracking/Spalling	Good	Good					
Thermal Exposure/Thermal Cycling	Cracking/Spalling	Good		Good[c]		Fair	Fair	
Irradiation	Volume Change/Cracking		Good	Good[c]				
Abrasion/Erosion/Cavitation	Section Loss	Good						
Fatigue/Vibration	Cracking	Good				Fair	Good	

[a] Includes reactions of cement-aggregate and carbonate aggregate.

[b] After significant deterioration, material sampling/testing techniques would be used to identify the cause.

[c] The strength tests only reveal the effect that elevated temperature or irradiation has after the fact on mechanical properties. Testing must be done under representative conditions to determine effects while under service conditions.

Table 3.4b. Summary of Degradation Factors, Primary Manifestations, and Methods Available for Their Detection: Mild Steel Reinforcement

		Method				
Degradation Factor	Manifestation	Visual Inspection	Half Cell Potential or Polarization	Radiography	Material Sampling	Penetrating Radar
Corrosion	Concrete cracking/spalling, reduced section	Good	Good	Fair	Good	
Elevated Temperature	Decreased yield strength	Poor			Good[a]	
Irradiation	Reduced ductility, increased yield strength	Poor			Good[a]	
Fatigue	Bond loss, fracture	Good		Fair	Good[a]	Poor

[a] Material sampling, e.g., strength testing, only reveals the effects that elevated temperature or irradiation has after the fact on mechanical properties. Testing must be done under representative conditions to determine effects while under service conditions.

Table 3.4c. Summary of Degradation Factors, Primary Manifestations, and Methods Available for Their Detection: Prestressing

		Method		
Degradation Factor	Manifestation	Visual Inspection	Half Cell Potential or Polarization	Material Sampling
Corrosion	Embrittlement, reduced section	Good	Good	Good
Elevated Temperature	Reduced strength, increased relaxation	Poor		Good[a]
Irradiation	Reduced ductility, increased strength	Poor		Good[a]
Fatigue	Concrete cracking, tendon failure	Good		Good

[a] Material sampling, e.g., strength testing, only reveals the effects that elevated temperature or irradiation has after the fact on mechanical properties. Testing must be done under representative conditions to determine effects while under service conditions.

Table 3.5. Relative Weights[a] Assigned to Criteria Affecting Degradation Factor Gradings

Material System	Degradation Factor	Criteria: Rate of Deterioration	Criteria: Inspectability and Early Identification	Criteria: Repairability	Criteria: Ultimate Impact	Range of Degradation Factor Grading Values[b]
Concrete	Chemical attack	Low to high	Low to moderate	Moderate	Low to high	6-10
	Freeze/thaw cycling	Low	Low	Low	Low	2-6
	Thermal exposure/thermal cycling	Moderate	Moderate	High	Moderate	6-10
	Irradiation	Low	Moderate	High	Moderate	4-8
	Abrasion/erosion/cavitation	Low	Low	Low	Low	2-6
	Fatigue/vibration	Low	Moderate	High	Moderate	4-8
Mild Steel Reinforcing	Corrosion	High	Moderate	Moderate	High	6-10
	Elevated temperature	Low	Low	Moderate	Low	2-6
	Irradiation	Low	Low	Moderate	Low	2-6
	Fatigue	Low	Moderate	Low to high	Low to moderate	4-8
Prestressing	Corrosion	High	Moderate	Low to moderate	High	6-10
	Elevated temperature	Low	Low	Low to moderate	Low	2-6
	Irradiation	Low	Low	Low to moderate	Low	2-6
	Fatigue	Low	Moderate	Low to moderate	Low	2-6
	Stress Relaxation	Low	Moderate	Low to Moderate	Moderate	4-8
Liner Plate/ Structural Steel	Corrosion	Moderate	Low	Moderate	High	6-10
	Fatigue	Low to moderate	Moderate	Moderate	Low to moderate	4-8

[a]High = Criterion creates a significant limiting condition or has a major adverse effect which can significantly impact the structure's serviceability or integrity following initiation and may be difficult to identify.
Moderate = Criterion creates a minor impact on structures and requires careful inspection.
Low = Criterion creates either very low or no impact on structures or may be readily observed via inspection.

[b]Degradation factor rgrading values are defined in Section 3.3.2.

Table 3.6. Prioritization[a] of Consequent Net Effects by Generic Subelements

Consequent Net Effect (relative importance weight value)[c]	Subelement (Relative Importance Value)[b]					
	Shell (10)	Foundation (10)	Floor (7)	Beam (7)	Column[d] (9)	Shear Wall (8)
1. Loss of monolithic behavior (1.0)	10.0	10.0	7.0	7.0	9.0	8.0
2. Damage to steel reinforcing system (1.0)	10.0	10.0	7.0	7.0	9.0	8.0
3. Loss of concrete section						
a. Gross loss (0.8)	8.0	8.0	5.6	5.6	7.2	6.5
b. Minor loss (0.7)	7.0	7.0	4.9	4.9	6.3	5.5
4. Weakening of structural material (0.6)	6.0	6.0	4.2	4.2	5.4	5.0

[a]Prioritization of consequent net effects values in table for each subelement represent product of relative importance weight value for particular consequent net effect (0-1) and relative importance value of the particular subelement (0-10).

[b]Number represents relative importance value assigned to corresponding subelement (see Section 3.3.2.1). These values are not the same as the importance factors assigned in Section 2.2.

[c]Consequent net effect values were assigned in Section 3.3.2.1.

[d]Column or interior partition wall (concrete).

Table 3.7a. Range of Values for Degradation Factor Grading in Terms of Subelement Type: Concrete Materials

STRUCTURAL ELEMENT	CONCRETE DEGRADATION FACTORS					
	CHEM. ATTACK	F/T	THERMAL	IRRADIATION	ABRASION	FATIGUE
1. CONTAINMENT VESSEL						
a. FOUNDATION	6–10	–	2–6	0–4	–	0–6
b. TENDON GALLERIES	6–10	–	–	–	–	–
c. VERTICAL WALLS	6–8	2–6	3–9	0–4	0–4	2–8
d. DOME	5–9	2–6	2–6	–	–	0–4
e. SUPPRESSION CHAMBER (BWR)	5–9	–	2–6	0–6	–	0–6
f. POLAR CRANE SUPPORT	2–5	–	2–6	0–4	0–4	4–10
g. RING GIRDER (PWR)	5–8	2–6	2–6	–	–	2–6
2. CONTAINMENT INTERNAL STRUCTURES						
a. BOTTOM SLAB	6–10	–	2–6	0–8	2–6	3–6
b. REACTOR PEDESTAL (BWR)	6–10	–	4–9	2–8	–	4–8
c. PRIMARY REACTOR SHIELD	6–10	–	4–10	5–10	–	4–7
d. FLOOR SLABS	2–7	–	2–7	2–7	0–4	0–4
e. WALLS	4–8	–	2–6	2–8	0–4	2–6
f. COLUMNS	4–8	–	4–8	2–8	0–6	2–6
g. BEAMS	2–6	–	2–6	0–6	–	2–6
h. FUEL POOL SLABS/WALLS	4–8	–	2–8	2–8	0–4	4–8
3. SECONDARY CONTAINMENT STRUCTURE						
a. FOUNDATIONS	6–10	–	0–6	–	–	0–4
b. SLABS	2–6	–	0–4	0–4	0–4	0–4
c. WALLS	4–8	2–6	0–6	0–4	0–4	–
d. COLUMNS	4–8	2–6	0–4	0–6	0–6	–
e. BEAMS	2–4	0–4	0–4	–	–	0–4
4. AUXILIARY STRUCTURES						
a. FOUNDATIONS	6–10	–	0–4	–	0–4	0–4
b. WALLS AND COLUMNS	2–8	0–8	0–4	–	0–6	0–6
c. SLABS/BEAMS/ROOF SLABS	4–9	0–6	0–4	–	2–8	0–6
d. CABLE DUCTS/PIPE TUNNELS	5–9	–	0–4	–	–	–
e. STACKS/COOLING TOWERS	3–7	6–9	0–4	–	0–4	0–4
f. CONCRETE INTAKE PIPING/CRIBS	5–10	–	–	–	4–8	0–4
g. TANKS	2–6	2–6	0–4	–	0–4	0–4
h. MISCELLANEOUS STRUCTURES (WATER MANAGEMENT)	4–8	6–10	0–6	–	4–10	0–4

F/T = FREEZE/THAW DAMAGE

Table 3.7b. Range of Values for Degradation Factor Grading in Terms of Subelement Type: Metallic Materials

STRUCTURAL ELEMENT	METALLIC DEGRADATION FACTORS								
	MILD REINFORCEMENT, LINER PLATE AND STRUCTURAL STEEL				PRESTRESSING REINFORCEMENT				
	CORROSION	THERMAL	IRRADIATION	FATIGUE	CORROSION	THERMAL	IRRADIATION	FATIGUE	RELAXATION
1. CONTAINMENT VESSEL									
a. FOUNDATION	6–10	–	–	–	0–10	0–4	–	0–4	0–4
b. TENDON GALLERIES	6–10	–	–	–	–	–	–	–	–
c. VERTICAL WALLS	6–10	2–6	0–4	3–8	7–10	3–6	0–4	2–6	2–8
d. DOME	6–10	0–4	–	2–6	7–10	0–4	0–4	2–6	2–8
e. SUPPRESSION CHAMBER (BWR)	6–10	2–6	0–4	0–4	–	–	–	–	–
f. POLAR CRANE SUPPORT	6–10	2–6	0–4	2–6	–	–	–	–	–
g. RING GIRDER (PWR)	6–10	0–4	–	0–4	7–10	0–4	0–4	2–6	2–8
2. CONTAINMENT INTERNAL STRUCTURES									
a. BOTTOM SLAB	6–10	2–6	2–6	0–6	–	–	–	–	–
b. REACTOR PEDESTAL (BWR)	4–10	4–8	4–8	4–10	–	–	–	–	–
c. PRIMARY REACTOR SHIELD	4–10	2–6	4–9	2–6	–	–	–	–	–
d. FLOOR SLABS	4–10	2–6	0–4	2–6	–	–	–	–	–
e. WALLS	6–10	2–6	2–6	2–6	7–10	0–6	2–6	0–6	2–8
f. COLUMNS	6–10	2–6	0–4	3–8	–	–	–	–	–
g. BEAMS	4–10	2–6	0–4	2–6	–	–	–	–	–
h. FUEL POOL SLABS/WALLS	6–10	0–4	2–6	4–10	7–10	0–6	2–6	0–6	2–8
3. SECONDARY CONTAINMENT STRUCTURE									
a. FOUNDATIONS	6–10	–	–	–	–	–	–	–	–
b. SLABS	4–10	0–4	–	2–6	–	–	–	–	–
c. WALLS	6–10	0–4	–	0–4	–	–	–	–	–
d. COLUMNS	6–10	0–4	–	0–6	–	–	–	–	–
e. BEAMS	4–10	0–4	–	0–4	–	–	–	–	–
4. AUXILIARY STRUCTURES									
a. FOUNDATIONS	6–10	–	–	0–6	–	–	–	–	–
b. WALLS AND COLUMNS	6–10	2–6	0–4	0–4	–	–	–	–	–
c. SLABS/BEAMS/ROOF SLABS	4–10	0–4	0–4	0–6	–	–	–	–	–
d. CABLE DUCTS/PIPE TUNNELS	6–10	–	–	–	–	–	–	–	–
e. STACKS/COOLING TOWERS	6–10	0–4	–	0–4	–	–	–	–	–
f. CONCRETE INTAKE PIPING/CRIBS	6–10	–	–	–	–	–	–	–	–
g. TANKS	6–10	0–4	–	–	–	–	–	–	–
h. MISCELLANEOUS STRUCTURES (WATER MANAGEMENT)	6–10	–	–	0–4	–	–	–	–	–

Table 3.8. Visible Degradation Indicators: Reinforced Concrete

Material System	Degradation Factor	Indicator
Concrete		
1.	Chemical Attack	Signs of chemical attack usually consist of erosion of the cement paste, leaving exposed aggregates, staining, efflorescence or exudation resulting from chemical reactions or conditions related to reinforcing corrosion. Chemical attack resulting in erosion of paste is most severe, especially for full depth of cover concrete, and should be highly rated. Cement-aggregate reactions generally produce cracking and visible loss of aggregate-cement bond.
2.	Freeze/Thaw Cycling	Signs of freeze/thaw attack include scaling (local flaking or peeling of surface concrete or mortar) and erosion of both the paste and aggregates. This condition may be considered significant when large aggregate popouts occur and when a loss of concrete to depths greater than 13 mm occurs.
3.	Thermal Exposure	Evidence of pattern cracking, especially proximate to heat sources, or volume change are the general result of thermal exposure. Effects such as loss of bond with substrate reinforcing may also be visible. Rating of this factor should be based on crack width comparison to ACI Report 224R-80 (Ref. 3.57).
4.	Irradiation	Evidence of enhanced cracking or internal volume changes, such as around large aggregate, may be observed. Although further testing of mechanical properties may be necessary to characterize this effect, the resulting damage may be evaluated in terms of allowable crack width (in structures which are accessible).
5.	Abrasion/Erosion/ Cavitation	These phenomena initially cause flaking of the exposed concrete surface (cover) and ultimately result in removal or erosion of concrete. This effect should be judged important if the loss of concrete is widespread, or if local losses have reduced the concrete cover by more than 1/2 of original.

Table 3.8. (cont.)

Material System	Degradation Factor	Indicator
6.	Fatigue/Vibration	Fatigue initially manifests as microcracking within the concrete matrix, proximate to rebar, aggregates or defects. Propagation will ultimately be displayed on the surface. Further testing or monitoring is necessary to characterize the cracking observed as fatigue. The ACI Report 224R-80 crack criteria may be used to judge importance, although the observation of any fatigue-related cracks should be considered critical.
Mild (Deformed) Steel Reinforcement		
1.	Corrosion	Corrosion of embedded steel will typically result in the presence of concrete cracks or spalls and rust straining on the structure's surface. Observation of staining or exposed corroded steel, especially over a widespread area of the structure, should indicate that corrosion is a critical factor (for rating purposes). Other testing, such as the half-cell method, may provide more accurate conclusions.
2. 3. 4.	Elevated Temperature Irradiation Fatigue	The presence of these factors is difficult to characterize via visual inspection. Additional testing is required to substantiate their presence.
Prestressing Reinforcement		
1. 2. 3. 4. 5.	Corrosion Elevated Temperature Irradiation Fatigue Loss of prestress force	These effects are not directly visible without disassembly of the end anchorages and tendon removal and require a review of the ISI tendon surveillance or other test records to determine relevancy. The noted presence of water or oxidation inside tendon ducts, or the corrosion of tendon anchorage components, should result in a "high" rating for corrosion. Relaxation and other factors must be judged from mechanical properties tests using representative samples.

Table 3.8. (cont.)

Material System	Degradation Factor	Indicator
Liner Plate/Structural Steel		
1.	Corrosion	The presence of corrosion on these components may include visible pitting, exfoliation, material thinning, intergranular stress corrosion cracking (IGSCC) of stainless steel or other conditions. If the material is coated, ASTM Standard D610-85 (Ref. 3.58) may be used to characterize corrosion presence (anything greater than Grade 8 should be highly rated). For cracking or noted wall thinning, the highest rating shall be used. If corrosion is noted in the liner plate, all structural steel or attachments should be given a high rating.
2.	Fatigue	The presence of fatigue in these components will likely be reflected as a crack or fracture. Areas near attachments, penetrations, and discontinuities should be initially considered. The presence of any cracking or fracture indications should result in the use of the highest rating.

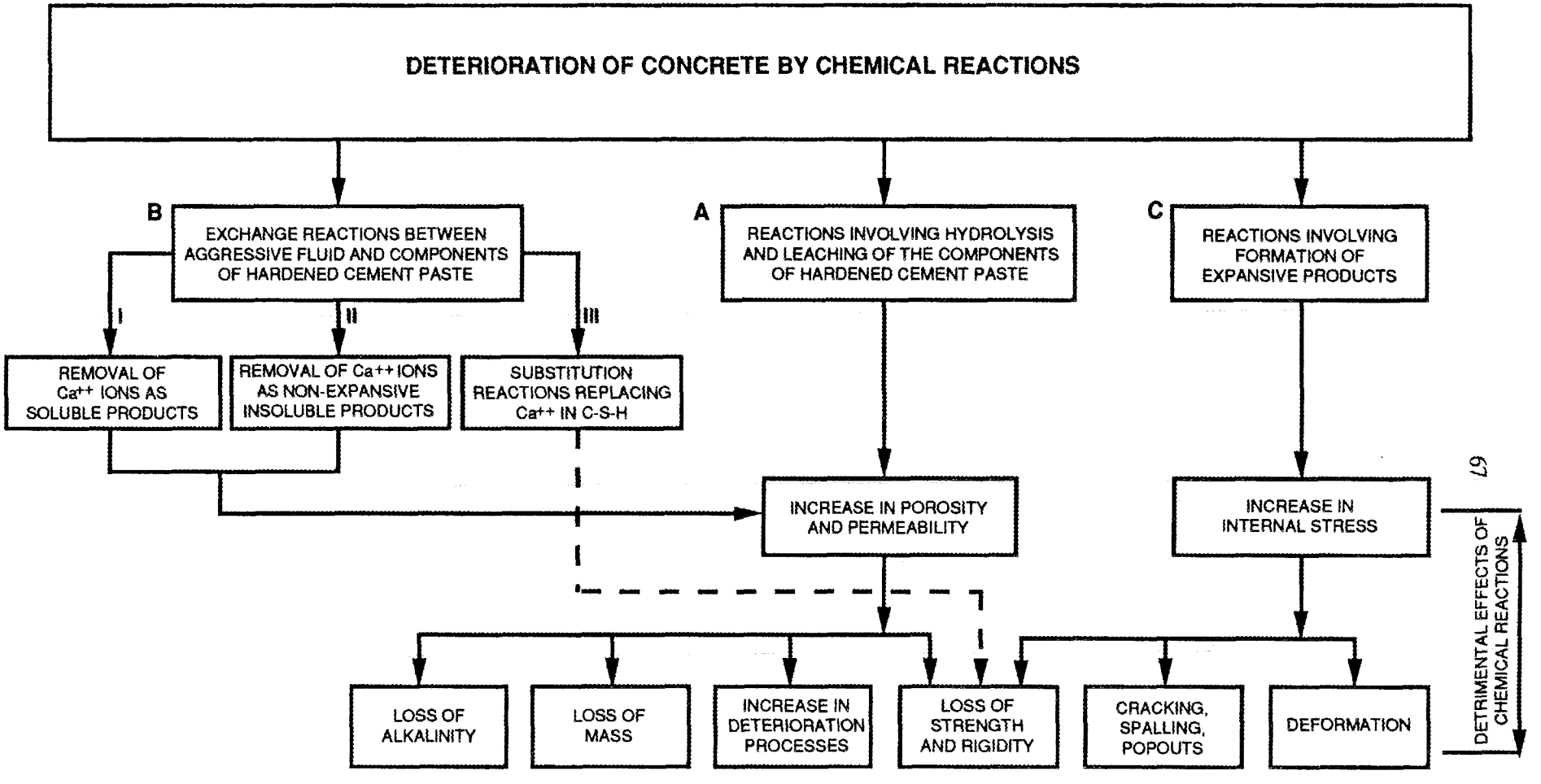

Fig. 3.1. Types of chemical reactions responsible for concrete deterioration. A: Softwater attack on calcium hydroxide and C-S-H present in hydrated portland cements; B(I): acidic solution forming soluble calcium compounds such as calcium sulfate, calcium acetate, or calcium bicarbonate; B(II): solutions of oxalic acid and its salts, forming calcium oxalate; B(III): long-term seawater attack weakening the C-S-H by substitution of Mg^{2+} for Ca^{2+}; C, (1) sulfate attack forming ettringite and gypsum, (2) alkali-aggregate attack, (3) corrosion of steel in concrete, (4) hydration of crystalline MgO and CaO. Source: P. K. Mehta and B. C. Gerwick, Jr., *Concr. Int.*, Vol. 4, pp. 45-51, 1982.

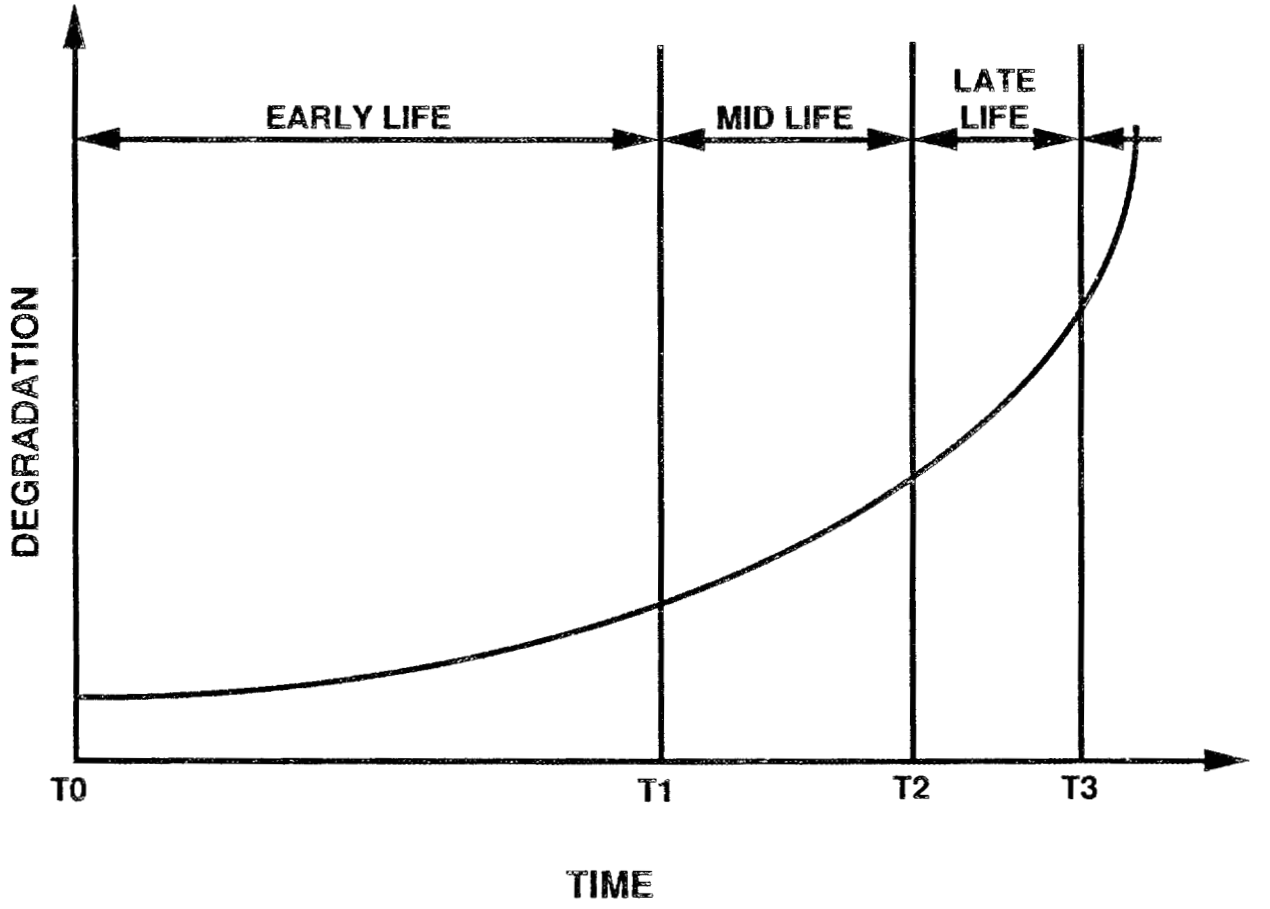

Fig. 3.2. General time rate of degradation curve for concrete structures.

4. STRUCTURAL AGING ASSESSMENT METHODOLOGY

The Structural Aging Assessment Methodology developed in this section uses a standard ranking system to characterize Category I concrete structures in terms of aging importance. As indicated in previous sections, the importance of structural aging is both a function of the structural/safety aspects of the structure as well as the likelihood of the structure to degrade over time. Four criteria were used to develop the quantitative ranking system for use in assessing aging importance of structures: (1) structural importance of subelements, (2) safety significance, (3) environmental exposure, and (4) degradation factor significance. Using these criteria, each Category I concrete structure can be evaluated and prioritized in accordance with standards and values as defined in Sections 2 and 3 of this report. The methodology is first applied to each subelement of a specific Category I concrete structure. From the ranking values of each subelement, a cumulative rank for the structure is computed.

Figure 4.1 presents a flow chart which identifies each activity of the structural aging assessment methodology. Procedural aspects of how to apply the methodology are provided in Section 4.1. Usage of a computer-based matrix approach which has been developed to implement and document the methodology is presented in Section 4.2. Finally, Section 4.3 presents application of the methodology to three representative LWR plants.

4.1 Procedural Development

Application of the structural aging assessment methodology (Fig. 4.1) involves five primary activities: (1) identification of Category I concrete structures, (2) subelemental division (of each structure), (3) determination of degradation factor grading values, (4) calculation of degradation factor significance, and (5) evaluation of the rankings of structures and subelements.

4.1.1 Identification of Category I Concrete Structures

Each Category I, or safety-related concrete structure, is identified at the LWR plant being evaluated. Typically these structures are listed in the plant's safety analysis report (SAR). However, additional information sources such as Q-listings (plant specific listing of all safety-related components) and structural drawings/specifications may be necessary to identify each structure. Other information such as design codes, plant material and testing records, and performance-related information is also collected at this stage.

4.1.2 Subelemental Division

Using structural drawings, original design calculations, and plant specifications, each Category I concrete structure is divided into pertinent subelements. A subelement is defined as a component such as a floor, column, beam, etc., which performs a specific or unique function (structural or otherwise), or which is exposed to a different operating environment. The boundaries for the subelements are established at this stage in the overall procedure. The intent of subelemental division is to enable the most critical components of structures to be identified with respect to structural aging importance.

Constituent materials, as well as their properties and characteristics, should be identified and listed for each subelement. These materials are typically identified in the SAR, structural drawings, specifications, and construction-stage material test reports.

4.1.3 Determination of Degradation Factor Grading Values

As noted previously, four criteria are used to develop the quantitative ranking system for use in assessing aging importance of the structures/subelements. These criteria include:

structural importance of subelements, safety significance, environmental exposure, and degradation factor significance.

Assignment of importance factors was discussed in Section 2.2. Values assigned to the subelements of Category I concrete structures for BWR and PWR plants are summarized in Tables 2.2 and 2.3, respectively. The values assigned reflect the overall importance of the subelement to the performance of the primary Category I concrete structure.

The basis for assignment of a safety significance ranking to a structure was provided in Section 2.3. Safety significance functions and safety significance ranking criteria/values were presented in Tables 2.4 and 2.5, respectively. The safety significance ranking values determined for each structure are applied to each subelement of the structure since the capability of a structure to meet its functional and performance requirements is dependent on the ability of its subelements.

The durability, or long-term, performance of each structure/subelement is dependent on its location and environmental exposure, i.e., relative severity of environment to which it is subjected. Section 2.4 describes seven environmental exposure conditions and Table 2.6 provides rating values for each of these conditions. The numerical values used for the environmental exposure rating are either directly selected from Table 2.6, or an average value is utilized where more than one environment concurrently influences the performance of the structure/subelement, e.g., different environments on either side of an exterior wall.

To establish the degradation factor grading values, subelements are evaluated in terms of materials of construction, existing conditions, and environmental exposure. Degradation factors which exist, or which may potentially exist, are listed and degradation factor grading values assigned. Table 3.1 lists the primary degradation factors that can impact the performance of the material systems utilized in Category I concrete structures. As indicated in Section 3.3, a range of numerical values exist for each concrete degradation factor/subelement combination. Tables 3.7(a) and 3.7(b) present ranges of values for the specific combinations involving concrete and metallic material systems, respectively. The user must select a specific degradation factor grading value from the appropriate range of possible values for each degradation factor/subelement combination. Selection of a high value reflects either the existence of the degradation factor, a high probability of occurrence, or possible synergistic behavior with other degradation factors.

4.1.4 Calculation of Degradation Factor Significance

After listing and assigning a degradation factor grading value to each subelement as described in the previous section, a conditional degradation factor significance value is calculated. The degradation factor significance value for a subelement is a simple average of up to three of the most significant degradation factor grading values and is calculated as follows

$$DFS = \left(\sum_{i=1}^{n} DFG_i \right) / n \quad , \tag{4.1}$$

where

DFS = degradation factor significance value,

DFG = degradation factor grading value (Section 3.3.2.2), and

n = number of degradation factors, up to a maximum of three.[5]

The resulting DFS value is to be rounded to the nearest integer, with a maximum possible value of 10.

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[5] In the case of subelements having more than three relevant degradation factors, the largest three values are used to calculate the degradation factor significance.

4.1.5 Ranking of Subelements and Structures

Determination of the relative ranks of the Category I concrete structures and subelements is based on the weighted contributions of the four criteria noted at the beginning of this chapter. A subelement rank within each Category I concrete structure is determined as follows

$$SR = w_1 (I) + w_2 (SS) + w_3 (DEG) \quad , \tag{4.2}$$

where

SR = subelement rank,
I = subelement importance (Section 2.2.3),
SS = safety significance (Section 2.3.2),
DEG = (EE + DFS)/2, rounded to nearest integer,
EE = environmental exposure (Section 2.4.2),
DFS = degradation factor significance (Section 4.1.4),
w_1 = weight applied to subelement importance,
w_2 = weight applied to safety significance, and
w_3 = weight applied to degradation effects.

Use of weighting factors (1 to 10, with 10 highest) permits certain components of Eq. (4.2) to be emphasized. The degradation factor significance (DFS) was considered to be heavily influenced by the surrounding environmental exposure (EE). Therefore, these two criteria were combined, averaged, and rounded to the nearest integer. Recommended values for w_1, w_2, and w_3 are 4, 9, and 7, respectively. These values are the result of a sensitivity analysis which is presented in Appendix A. Therefore, Eq. (4.2) becomes

$$SR = 4 (I) + 9 (SS) + 7 (DEG) . \tag{4.2'}$$

Utilization of this equation results in a possible range of subelement ranks between 20 and 200.

The cumulative rank for each Category I concrete structure is determined as follows

$$CR = \sum_{i=1}^{N} SR_i / N \quad , \tag{4.3}$$

where

CR = cumulative rank,
SR = subelement rank, and
N = number of subelements.

Application of this equation ensures that the cumulative rank of a Category I concrete structure is based on aging importance rather than total number of subelements. Since the cumulative rank that results for a structure may not adequately reflect the importance of a specific subelement or degradation factor due to the balance of subelements or degradation factors being evaluated low, results of both Eq. (4.2) and (4.3) should be considered when identifying critical structures and degradation factors of concern.

4.2 Computer-Based Matrix

A computer-based matrix format was developed to provide a simple method for implementing and documenting results of the structural aging assessment methodology. "R:BASE for DOS" was used as the software because of its flexibility of input format (integers, text, etc.), compatibility with other IBM software, and user friendliness. Also,

the software allows the programming of important equations [Eqs. (4.1) to (4.3)] such that the ranks for each subelement/structure are automatically completed after data entry. Output is provided in a standard format as displayed in Table 4.1.

The end product of the computer-based matrix presentation is a concise listing of Category I concrete structures and their subelements. The ranking values that result may be used to identify structures/subelements and degradation factors that are of most significance with respect to aging management. The resulting list may also be used to assist in determining appropriate methods and schedules for inspection/testing/maintenance.

4.3 Application of Structural Aging Assessment Methodology

Utilization of the methodology is demonstrated through its application to three LWR plants: (1) pressurized-water reactor plant with a large dry metal containment located in the Midwest, (2) boiling-water reactor plant with a conventionally reinforced concrete Mark II containment located in the East, and (3) pressurized-water reactor plant with a large dry prestressed concrete containment located in the Midwest. Appendix B provides commentary on application of the methodology as well as the computer-based matrix results for each of these plants.

Table 4.1

Matrix Format Used to Present Structural Aging Assessment Methodolgy Results

PRIMARY STRUCTURE	CUMULATIVE RANK	FUNCTION
	Eq. 4.3	

SUBELEMENT	IMPORTANCE	ENVIRONMENT EXPOSURE	SAFETY SIGNIFICANCE	SUBELEMENT RANK
Sec. 2.2.3.1 (Tables 2.2, 2.3)	Sec. 2.2.3.2 (Tables 2.2, 2.3)	Sec. 2.4.2 (Table 2.6)	Sec. 2.3.2 (Table 2.5)	Eq. 4.2'

COMPOSITION

KEY DEGRADATION FACTORS	RATING
Sec. 3.1 (Table 3.1)	Sec. 3.3.2.2 (Table 3.7)

SUBELEMENT	IMPORTANCE	ENVIRONMENT EXPOSURE	SAFETY SIGNIFICANCE	SUBELEMENT RANK

COMPOSITION

KEY DEGRADATION FACTORS	RATING

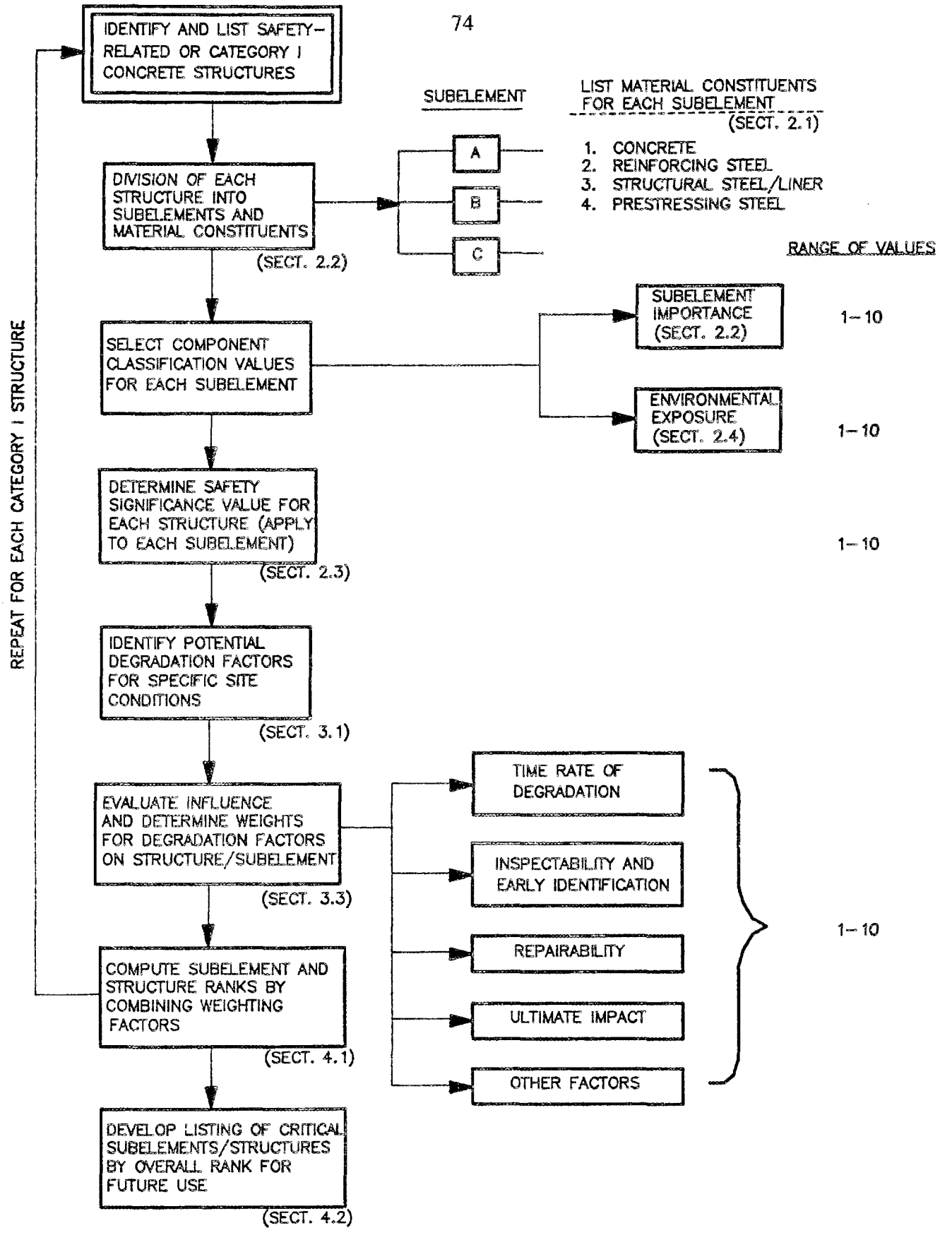

Fig. 4.1. Structural aging assessment methodology

5. SUMMARY

The objective of this study was to develop a procedure for use in identifying critical safety-related concrete structural elements in light-water reactor plants as well as degradation factors which can impact the performance of these components. In meeting this objective, a structural aging assessment methodology for concrete structures was developed. The methodology provides a means for categorizing and ranking the safety-related concrete elements in terms of their importance, safety significance, environmental exposure, and degradation factor significance. Utilization of the structural aging assessment methodology was demonstrated through its application to three LWR plants.

APPENDIX A
SENSITIVITY ANALYSIS OF WEIGHTING FACTORS

The primary ranking equation for subelements,

$$SR = w_1 I + w_2 SS + w_3 (DEG) \quad , \tag{4.2}$$

contains three weighting factors that are used to assign appropriate emphasis to the ranking criteria. The goal of this sensitivity analysis is to demonstrate that the subelement ranks resulting from use of the recommended weighting factors ($w_1 = 4$, $w_2 = 9$, and $w_3 = 7$) are reasonable, and that there is sufficient "spread" in numerical results between lowest-ranked and highest-ranked subelements to be distinguishable.

A number of requirements were built into the sensitivity analysis to ensure that suitable results were provided. These requirements address the relationship between the three weighting factors and include the following:

1. All weighting factors shall be in the range of 1 to 10, with 10 highest, and the summation of the weighting factors shall be 20. These range and summation requirements ensure that the resulting rank for a subelement is 200, or less.
2. The weighting factors shall have the following relationship with respect to magnitude of values used: (a) $w_1 < w_3$ or w_2 and (b) $w_3 < w_2$. These relationships ensure that the appropriate importance is placed on each of the criterion that are involved in development of a subelement ranking.
3. All weighting factors are integers.

To perform the sensitivity analysis, a known high ranking subelement (e.g., primary containment wall) and a known low ranking subelement (e.g., intake structure wall) were used. These subelements had the assumed ranking criteria values presented in Table A.1. Various combinations of weighting factors, conforming to the above requirements, were then utilized to determine the most appropriate weighting factors for ranking the subelements. Table A.2 presents a summary of the subelement rankings that were determined for the primary containment wall and the intake structure wall. As shown in the table, the weighting factor combination of $w_1 = 4$, $w_2 = 9$, and $w_3 = 7$ was the only one which produced subelement ranks near the average value for both the primary containment wall and intake structure wall.

To further assess the appropriateness of selection of the weighting factor combination of $w_1 = 4$, $w_2 = 9$, and $w_3 = 7$, various combinations of ranking criteria values ranging from 1 to 10 were used in conjunction with the weighting factor combinations presented in Table A.2. The results of this assessment are presented in Table A.3 and again indicate that the recommended weighting factor values provide reasonable results.

Table A.1. Assumed Ranking Criteria Values for Sensitivity Analysis

Ranking Criteria	Subelement	
	Primary Containment Wall	Intake Structure Wall
Importance Factor (I)	9	6
Safety Significance (SS)	9	4
Environmental Exposure (EE)	8	5
Degradation Factor Significance (DFS)	7	7

Table A.2. Subelement Rankings Resulting from Different Combinations of Weighting Factors

Weighting Factor Combination, w_1 - w_2 - w_3	Subelement: Primary Containment Wall, Ranking Value[a]	Subelement: Intake Structure Wall, Ranking Value[a]
1 - 10 - 9	167	100
2 - 10 - 8	168	100
3 - 10 - 7	170	100
4 - 10 - 6	171	100
5 - 10 - 5	173	100
2 - 9 - 9	167	102
3 - 9 - 8	168	102
4 - 9 - 7	170	102
5 - 9 - 6	171	102
4 - 8 - 8	168	104
5 - 8 - 7	170	104
6 - 8 - 6	171	104
6 - 7 - 7	170	106
Total/Average	2204/169.5	1326/102

[a]$SR = w_1 I + w_2 SS + w_3[(EE + DFS)/2]$ where values for I, SS, EE, and DFS are presented in Table A.1, and (EE+DFS)/2 is rounded to the nearest integer.

Table A.3. Subelement Ranking Resulting from Different Combinations of Weighting Factors and Ranking Criteria

Subelement Ranking Values for Various Weighting Factor and Subelement Ranking Criteria Combinations									
	Subelement Ranking Criteria Combinations								
Weighting Factor Combinations	IF = 10 SS = 10 EE = 10 DFS = 10	10 1 10 10	10 10 1 10	10 10 10 1	10 1 1 10	10 1 10 1	10 10 1 1	10 1 1 1	1 1 1 1
1-10-9	200	110	160	160	70	70	119	29	20
2-10-8	200	110	164	164	74	74	128	38	20
3-10-7	200	110	169	169	79	79	137	47	20
4-10-6	200	110	173	173	83	83	146	56	20
5-10-5	200	110	178	178	88	88	155	65	20
2-9-9	200	119	160	160	79	79	119	38	20
3-9-8	200	119	164	164	83	83	128	47	20
4-9-7*	200	119	169	169	88	88	137	56	20
5-9-6	200	119	173	173	92	92	146	65	20
4-8-8	200	128	164	164	92	92	128	56	20
5-8-7	200	128	169	169	97	97	137	65	20
6-8-6	200	128	173	173	101	101	146	74	20
6-7-7	200	137	169	169	106	106	137	74	20
	Avg. = 200	119	168	168	87	87	136	55	20

* Recommended set of Weighting Factors.
(Wt 1) = 4, (Wt 2) = 9, and (Wt 3) = 7

Table A.3. (cont.)

Subelement Ranking Values for Various Weighting Factor and Subelement Ranking Criteria Combinations									
Weighting Factor Combinations	Subelement Ranking Criteria Combinations								
	IF = 10 SS = 10 EE = 10 DFS = 10	1 10 1 1	1 1 10 1	1 1 1 10	1 10 10 1	1 10 1 10	1 1 10 10	1 10 10 10	1 1 1 1
1-10-9	200	110	61	61	151	151	101	191	20
2-10-8	200	110	56	56	146	146	92	182	20
3-10-7	200	110	52	52	142	142	83	173	20
4-10-6	200	110	47	47	137	137	74	164	20
5-10-5	200	110	43	43	133	133	65	155	20
2-9-9	200	101	61	61	142	142	101	182	20
3-9-8	200	101	56	56	137	137	92	173	20
4-9-7*	200	101	52	52	133	133	83	164	20
5-9-6	200	101	47	47	128	128	74	155	20
4-8-8	200	92	56	56	128	128	92	164	20
5-8-7	200	92	52	52	124	124	83	155	20
6-8-6	200	92	47	47	119	119	74	146	20
6-7-7	200	83	52	52	115	115	83	146	20
	Avg. = 200	101	52	52	133	133	84	165	20

* Recommended set of Weighting Factors.
(Wt 1) = 4, (Wt 2) = 9, and (Wt 3) = 7

APPENDIX B
APPLICATION OF STRUCTURAL AGING ASSESSMENT METHODOLOGY TO REPRESENTATIVE LWR PLANTS

Utilization of the methodology is demonstrated through its application to three LWR plants: (1) pressurized-water reactor with a large dry metal containment located in the midwestern United States, (2) boiling-water reactor with a reinforced concrete Mark II containment located in the eastern United States, and (3) pressurized-water reactor with a large dry prestressed concrete containment located in the midwestern United States. Commentary and the step-by-step procedure (Fig. 4.1) utilized to develop subelement rankings as well as cumulative rankings for the Category I concrete structures are provided in the following sections.

B.1 PWR – Large Dry Metal Containment

The initial step in application of the methodology is to identify all Category I concrete structures. This is best accomplished by reviewing the most recent edition of the plant's Safety Analysis Report (SAR), along with other plant documentation (Q-listing, etc.). Structural drawings should be obtained to finalize the physical configuration and boundaries of the primary structures. Primary structures identified for this plant include: (1) containment internal structures, (2) shield building (around metal containment), (3) plant screenhouse (heat sink areas), (4) turbine building (housing safeguards equipment), and (5) auxiliary building (including radwaste area). The primary structures are then divided into their subelements based on physical configuration and functional differences. The primary structure (including its function), its subelements and the constituent materials are entered into the matrix format as shown in Table B.1. Importance factors are assigned to each subelement using Section 2.2.3 criteria and entered into the matrix format.

Using conservative judgement, review of plant conditions, and guidelines provided in Sections 2.3 and 2.4, safety significance and environmental exposure values are selected and entered into the matrix format for each subelement. In this example, the assignment of environmental exposure ratings was influenced by the plant site and other geographical considerations, i.e., relatively nonaggressive cooling water, but large number of freeze-thaw cycles. This plant was constructed on fill material and has a fairly high water table. Also, as supported by documentation, strict controls on materials of construction were maintained throughout plant fabrication.

Key degradation factors for each subelement are identified and entered into the matrix format. Degradation factor grading values (ratings) are selected for each potential degradation factor using guidance provided in Section 3.3. Prior to entry of these values into the matrix format, they may have to be adjusted slightly to accommodate specific plant environmental conditions, physical conditions, or other influencing factors. Knowledge of the current condition of the subelement is especially helpful in the assignment of specific values. Equation (4.1) is then utilized to determine a degradation factor significance value for each subelement, i.e., the degradation factor significance is equal to the summation of the degradation factor grading values (≤ 3) divided by the number of degradation factors.

A ranking for each subelement is determined using Eq. (4.2)' in conjunction with the subelement importance, safety significance, environmental exposure, and degradation factor significance values determined above. Finally, the cumulative rank for each structure is determined by summing the subelement ranks and dividing by the number of subelements. Application of the structural aging assessment methodology to the example plant indicates that the highest ranking primary structure is the shield building, and the highest ranking subelement is the reactor cavity walls of the containment internal structures.

B.2 BWR – Reinforced Concrete Mark II Containment

Review of the SAR identified the following Category I concrete structures: (1) containment vessel, (2) containment internal structures (diaphragm slab, reactor pressure vessel pedestal, and primary shield wall), (3) reactor building (secondary containment), (4) control building, (5) diesel generator buildings, (6) ESSW pumphouse and spillway, and (7) spray pond. Review of plant structural drawings were utilized to divide the primary structures into their subelements and materials of construction. This information was entered into the matrix format as shown in Table B.2. Importance factors were assigned to each subelement using Section 2.2.3 criteria and entered into the matrix format.

Safety significance and environmental exposure values were selected and entered into the matrix format for each subelement. As the primary containment structure is completely enclosed in the reactor building (except for the basemat foundation) and the plant is located at a considerable distance from salt or brackish water sources, the environmental exposure ratings for certain primary structures have been slightly reduced. Also, since the plant is located directly on bedrock as well as being rurally located, the environmental effects are not considered to be as severe as for the previous example, e.g., concrete degradation through ground water attack, as well as reinforcing and liner steel corrosion, has a lower probability of occurrence.

Key degradation factors for each subelement are identified and entered into the matrix format. Due to the somewhat tempered environmental exposure, as noted above, the degradation factor grading values (ratings) have been reduced slightly, i.e., values were obtained from the lower portion of the ranges presented in Tables 3.7(a) and 3.7(b). Equation (4.1) was then used to determine a degradation factor significance value for each subelement.

Based on information that has been entered into the matrix format and the degradation factor significance values determined above, Eq. (4.2)' is used to develop a ranking value for each subelement. Finally, a cumulative rank is calculated for each primary structure. Application of the methodology to this plant indicates that the highest ranking subelement is the base slab of the containment vessel, and the highest ranking primary structure is the containment vessel.

B.3 PWR – Large Dry Prestressed Concrete Containment

Review of the SAR identified the following Category I concrete structures: (1) containment vessel, (2) containment internal structures, (3) auxiliary building, (4) turbine building (portions of slabs/walls), (5) cribhouse (portions), and (6) intake crib. These structures were subdivided into subelements and materials of construction. This information was entered into the matrix format as shown in Table B.3. Importance factors were assigned to each subelement and entered into the matrix format.

Safety significance and environmental exposure values were established and entered into the matrix format. The primary containment structure, as well as many of the other safety-related structures at this plant, are exposed to a natural environment. However, a number of these structures have been protected with coatings to prevent external degradation. The plant is founded on fill material and cooled by fresh water. Certain groundwater parameters are periodically measured, and the prestressing system is partially accessible for inspection. Each of these conditions was considered as being favorable with respect to assignment of criteria values.

As a result of variability in existing protective media and exposure conditions at this plant, evaluation of the degradation factors and their grading values required careful

consideration. Such degradation mechanisms as corrosion of the containment prestressing steel system and irradiation of the reactor pressure vessel pedestal were considered to be relatively important, and thus degradation factor grading values (ratings) were selected from the higher portion of the ranges presented in Tables 3.7(a) and 3.7(b). Degradation factor significance values, subelement rankings, and primary structure's cumulative rankings were determined as described previously. Application of the methodology to this plant indicates that the highest ranking primary structure is the containment vessel, and the highest ranking subelement is the mat foundation of the containment vessel.

TABLE B.1

RESULTS OF APPLICATION OF STRUCTURAL AGING ASSESSMENT METHODOLOGY: PWR METAL LARGE-DRY CONTAINMENT

Primary Structure	Cumulative Rank	Function
PWR Containment-Internal Structures	151	The containment-internal structures of the large-dry PWR provide many functions including radiation shielding, refueling support, equipment anchorage, personnel access, pipe break or missile protection, etc. These structures are massive in size and were placed using cast-in-place techniques.

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Reactor Cavity Walls	8	9	9	176

Composition

Deformed Reinforcing Steel, Portland Cement Concrete, Stainless Steel Liner

Key Degradation Factors	Rating
Reinforcing Corrosion	10
Thermal Exposure/Cycling	8
Irradiation	8
Fatigue	7
Chemical Attack	6
Reinforcing Fatigue	2
Reinforcing Therm. Exp.	2

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Bottom Slab	8	9	8	167

Composition

Deformed Reinforcing Steel, Portland Cement Concrete

Key Degradation Factors	Rating
Reinforcing Corrosion	10
Chemical Attack	8
Irradiation	6
Fatigue	6
Thermal Exposure/Cycling	8
Abrasion	3
Reinforcing Therm. Exp.	4

Table B.1
Page 2

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Reactor Coolant Pump Vault Walls	8	8	7	151

Composition

Deformed Reinforcing Steel, Portland Cement Concrete

Key Degradation Factors	Rating
Reinforcing Corrosion	10
Thermal Exposure/Cycling	8
Irradiation	7
Chemical Attack	6
Fatigue	5
Reinforcing Therm. Exp.	4

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Refueling Area Slab	7	6	8	149

Composition

Deformed Reinforcing Steel, Portland Cement Concrete, Stainless Steel Liner

Key Degradation Factors	Rating
Reinforcing Liner Corrosion	10
Thermal Exposure/Cycling	7
Chemical Attack	6
Irradiation	6
Abrasion	5
Fatigue	5
Reinforcing Therm. Exp.	3
Reinforcing Fatigue	3

Table B.1
Page 3

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Slabs	6	7	7	136

Composition

Deformed Reinforcing Steel, Portland Cement Concrete

Key Degradation Factors	Rating
Reinforcing Corrosion	10
Chemical Attack	6
Fatigue	4
Thermal Exposure/Cycling	6
Reinforcing Fatigue	3
Irradiation	4
Abrasion	3

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Refueling Area Walls	6	6	7	136

Composition

Deformed Reinforcing Steel, Portland Cement Concrete, Stainless Steel Liner

Key Degradation Factors	Rating
Reinforcing Liner Corrosion	10
Thermal Exposure/Cycling	7
Irradiation	6
Fatigue	6
Chemical Attack	6
Abrasion	4
Reinforcing Therm. Exp.	4
Reinforcing Fatigue	3

Table B.1
Page 4

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Reactor Coolant Pump Vault Beams	4	8	8	144

Composition

Deformed Reinforcing Steel, Portland Cement Concrete

Key Degradation Factors	Rating
Reinforcing Corrosion	10
Thermal Exposure/Cycling	6
Chemical Attack	6
Irradiation	6
Abrasion	5
Reinforcing Therm. Exp.	4

Primary Structure	Cumulative Rank
Shield Building	154

Function

The Shield Building performs a multitude of functions including radiation shielding and containment, structural support for equipment and environmental protection. The exterior surfaces/structures are subjected to the natural environment or subterranean conditions while the interior environment is somewhat controlled. Provisions for pipe breaks and missiles impact loads were also taken at the design stage.

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Foundation	10	8	8	168

Composition

Portland Cement Concrete, Deformed Reinforcing Steel

Key Degradation Factors	Rating
Chemical Attack	10
Reinforcing Corrosion	10
Fatigue	3
Irradiation	3
Thermal Exposure/Cycling	3
Reinforcing Therm. Exp.	3

Table B.1
Page 5

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Shield Walls (vertical)	8	7	8	160

Composition

Deformed Reinforcing Steel, Liner Plate, Portland Cement Concrete

Key Degradation Factors	Rating
Freeze/Thaw Cycling	6
Reinforcing Corrosion	10
Chemical Attack	8
Thermal Exposure/Cycling	6
Irradiation	3
Reinforcing Fatigue	3

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Dome	6	7	8	152

Composition

Deformed Reinforcing Steel, Portland Cement Concrete

Key Degradation Factors	Rating
Reinforcing Corrosion	10
Chemical Attack	8
Thermal Exposure/Cycling	6
Freeze/Thaw	6

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Slabs (including composite beams)	6	4	8	138

Composition

Deformed Reinforcing Steel, Portland Cement Concrete

Key Degradation Factors	Rating
Reinforcing Corrosion	10
Chemical Attack	6
Thermal Exposure/Cycling	4
Abrasion	4
Reinforcing Therm. Exp.	3

Table B.1
Page 6

Primary Structure	Cumulative Rank	Function
Plant Screenhouse	119	The intake of cooling water for ultimate heat sink required pumping, screening and conveyance components which are considered safety-related. Concrete structures within the screenhouse itself were provided to support this equipment and protect it from the natural environment. This primary structure includes a submerged concrete crib which allows emergency cooling water intake.

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Foundation	10	8	4	132

Composition

Portland Cement Concrete, Deformed Reinforcing Steel

Key Degradation Factors	Rating
Reinforcing Corrosion	10
Chemical Attack	9
Abrasion	6
Fatigue	4

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Submerged Intake Crib	10	6	4	132

Composition

Portland Cement Concrete, Deformed Reinforcing Steel, Structural Steel Piles

Key Degradation Factors	Rating
Abrasion	8
Reinforcing or Pile Corrosion	10
Chemical Attack	8

Table B.1
Page 7

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Slabs	6	4	4	102

Composition

Portland Cement Concrete, Deformed Reinforcing Steel

Key Degradation Factors	Rating
Reinforcing Corrosion	10
Abrasion	6
Fatigue	6
Chemical Attack	6
Freeze-Thaw	2

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Walls	8	5	4	110

Composition

Portland Cement Concrete, Deformed Reinforcing Steel

Key Degradation Factors	Rating
Reinforcing Corrosion	9
Chemical Attack	8
Freeze/Thaw Cycling	6
Abrasion	6
Thermal Exposure Cycling	3

Primary Structure	Cumulative Rank	Function
Turbine Building (housing safeguards equipment) PWR	106	Portions of the Turbine Building are considered Category 1 because it houses safeguards electrical equipment, diesel generators, ventilating equipment and safety-related (UHS) piping. These structures are enclosed within the Turbine Building and exposed to controlled environments. The control room is also enclosed in the Turbine Building.

Table B.1
Page 8

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Slabs	6	3	3	86

Composition

Portland Cement Concrete,
Deformed Reinforcing Steel

Key Degradation Factors	Rating
Reinforcing Corrosion	8
Thermal Exposure/Cycling	4
Chemical Attack	8
Fatigue	3
Abrasion	3
Reinforcing Therm. Exp.	3

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Walls	8	3	3	94

Composition

Portland Cement Concrete,
Deformed Reinforcing Steel

Key Degradation Factors	Rating
Reinforcing Corrosion	8
Thermal Exposure/Cycling	4
Chemical Attack	8
Reinforcing Therm. Exp.	3

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Control Room Walls (and cable spreading structure)	8	2	7	116

Composition

Portland Cement Concrete,
Deformed Reinforcing Steel

Key Degradation Factors	Rating
Reinforcing Corrosion	6
Thermal Exposure/Cycling	4
Chemical Attack	3
Fatigue	3

Table B.1
Page 9

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Control Room Floor Slab (and cable spreading structure)	6	3	7	115

Composition

Deformed Reinforcing Steel, Portland Cement Concrete

Key Degradation Factors	Rating
Reinforcing Corrosion	6
Thermal Exposure/Cycling	3
Abrasion	4
Chemical Attack	6
Fatigue	1

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Diesel Generator Room Slabs	6	4	5	104

Composition

Portland Cement Concrete, Deformed Reinforcing Steel

Key Degradation Factors	Rating
Chemical Attack	7
Fatigue	3
Reinforcing Corrosion	7
Thermal Exposure/Cycling	4
Abrasion	4
Reinforcing Fatigue	3

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Diesel Generator Room Walls	8	5	5	119

Composition

Portland Cement Concrete, Deformed Reinforcing Steel

Key Degradation Factors	Rating
Chemical Attack	7
Thermal Exposure/Cycling	4
Reinforcing Corrosion	7
Fatigue	3
Reinforcing Fatigue	2

Table B.1
Page 10

Primary Structure	Cumulative Rank	Function
Auxiliary Building	120	The Auxiliary Building houses both safety-related and balance-of-plant equipment necessary for the operation of the PWR. The concrete structures are generally subject to controlled interior environmental conditions. The function of this structure is to provide structural support, environmental protection and radiation shielding during all plant operating conditions.

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Foundation	10	10	6	150

Composition

Portland Cement Concrete,
Deformed Reinforcing Steel

Key Degradation Factors	Rating
Chemical Attack	10
Reinforcing Corrosion	9
Thermal Exposure	2

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Walls (exterior)	8	5	5	119

Composition

Portland Cement Concrete,
Deformed Reinforcing Steel

Key Degradation Factors	Rating
Fatigue	2
Chemical Attack	8
Reinforcing Corrosion	8
Freeze/Thaw Cycling	6
Thermal Exposure/Cycling	4
Reinforcing Fatigue	2

Table B.1
Page 11

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Internal Floor Slabs	6	3	5	97

Composition

Portland Cement Concrete,
Deformed Reinforcing Steel

Key Degradation Factors	Rating
Reinforcing Fatigue	2
Chemical Attack	8
Reinforcing Corrosion	7
Thermal Exposure/Cycling	4
Fatigue	3
Abrasion	3

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Crane Support Structure	4	3	6	98

Composition

Portland Cement Concrete,
Deformed Reinforcing Steel

Key Degradation Factors	Rating
Fatigue	8
Chemical Attack	4
Reinforcing Corrosion	6
Abrasion	4

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Internal Walls	5	3	5	93

Composition

Portland Cement Concrete,
Deformed Reinforcing Steel

Key Degradation Factors	Rating
Reinforcing Corrosion	6
Thermal Exposure/Cycling	4
Chemical Attack	4

Table B.1
Page 12

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Fuel Pool Bottom Slab	6	5	8	138

Composition

Portland Cement Concrete,
Deformed Reinforcing Steel,
Stainless Steel Liner Plate

Key Degradation Factors	Rating
Reinforcing Corrosion	10
Chemical Attack	7
Fatigue	6
Thermal Exposure/Cycling	6
Irradiation	4
Reinforcing Therm. Exp.	2
Reinforcing Irradiation	2
Reinforcing Fatigue	6

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Fuel Pool Walls	8	5	8	146

Composition

Portland Cement Concrete,
Deformed Reinforcing Steel,
Stainless Steel Liner

Key Degradation Factors	Rating
Reinforcing Corrosion	10
Chemical Attack	7
Thermal Exposure/Cycling	7
Irradiation	4
Reinforcing Therm. Exp.	2
Reinforcing Irradiation	2
Reinforcing Fatigue	6

TABLE B.2

RESULTS OF APPLICATION OF STRUCTURAL AGING ASSESSMENT METHODOLOGY: BWR CONCRETE MARK II PLANT

Primary Structure	Cumulative Rank	Function
Containment Vessel	172	The containment vessel of this Mark II BWR performs radiation shielding and containment, structural support, and environmental protection. The vessel was constructed using cast-in place techniques and is in the form of a truncated cone. The dome is constructed of plate steel and was not considered.

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Base Slab	10	8	10	186

Composition

Portland Cement Concrete, Deformed Reinforcing Steel

Key Degradation Factors	Rating
Chemical Attack	8
Irradiation	2
Fatigue	2
Reinforcing Corrosion	10

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Vertical and Inclined Walls (suppression chamber and drywell)	8	5	10	171

Composition

Portland Cement Concrete, Deformed Reinforcing Steel, Structural Steel, Liner Plate

Key Degradation Factors	Rating
Reinforcing Corrosion	10
Thermal Exposure/Cycling	6
Irradiation	6
Fatigue	4
Reinforcing Steel/Liner Corrosion	10
Reinf. Thermal Exp.	4
Reinforcing Fatigue	3
Chemical Attack	8

Table B.2
Page 2

Primary Structure	Cumulative Rank	Function
Containment-Internal Structures	153	Provides structural support and radiation shielding for all plant operating conditions. Resists the effects of plant accidents and unusual events. Transfers structural loadings to the base slab. Provides separation of drywell and wetwell.

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Diaphragm Slab	7	7	8	149

Composition

Portland Cement Concrete, Deformed Reinforcing Steel, Structural Steel, Liner Plate

Key Degradation Factors	Rating
Chemical Attack	6
Thermal Exposure	6
Irradiation	6
Fatigue/Vibration	4
Reinforcing Corrosion	9
Reinforcing Irradiation	2
Reinforcing/Liner Fatigue	4

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
RPV Pedestal	9	8	8	164

Composition

Portland Cement Concrete, Deformed Reinforcing Steel, Structural Steel, Liner Plate

Key Degradation Factors	Rating
Chemical Attack	6
Thermal Exposure	9
Irradiation	6
Fatigue	7
Reinforcing Corrosion	6
Reinforcing Therm. Exp.	7
Reinforcing Irradiation	7
Reinforcing/Liner Fatigue	7

Table B.2
Page 3

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Primary Shield Wall	6	8	8	152

Composition

Portland Cement Concrete, Deformed Reinforcing Steel, Structural Steel, Liner Plate

Key Degradation Factors	Rating
Chemical Attack	7
Thermal Exposure	9
Conc. Irradiation	10
Conc. Fatigue	7
Reinforcing/Liner Corrosion	5
Reinforcing Therm. Exp.	7
Reinforcing Irradiation	7
Reinforcing/Liner Fatigue	7

Primary Structure	Cumulative Rank	Function
Reactor Building (secondary containment)	136	Provides secondary containment and radiation shielding function. Protects containment vessel and internal plant equipment from the natural environment. Houses plant fuel storage pools and protects the surrounding environment from radioactive contamination. Primarily of flat plate and wall construction.

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Foundation	10	9	7	159

Composition

Portland Cement Concrete, Deformed Reinforcing Steel, Waterproofing, Mud Mat (concrete)

Key Degradation Factors	Rating
Chemical Attack	9
Reinforcing Corrosion	9
Reinforcing Fatigue	4

Table B.2
Page 4

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Floor Slabs	6	4	7	128

Composition

Portland Cement Concrete, Deformed Reinforcing Steel, Structural Steel

Key Degradation Factors	Rating
Chemical Attack	6
Thermal Exposure	4
Irradiation	3
Abrasion	2
Fatigue	1
Reinforcing Corrosion	7
Reinforcing Therm. Exp.	2

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Spend Fuel Pool Slabs	6	5	7	129

Composition

Portland Cement Concrete, Deformed Reinforcing Steel, Stainless Steel Liner

Key Degradation Factors	Rating
Chemical Attack	6
Thermal Exposure	5
Conc. Irradiation	4
Fatigue	6
Reinforcing/Liner Corrosion	8
Reinforcing Therm. Exp.	3

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Vertical Walls (exterior/ interior)	8	6	7	137

Composition

Portland Cement Concrete, Deformed Reinforcing Steel, Waterproofing

Key Degradation Factors	Rating
Chemical Attack	7
Freeze/Thaw	4
Thermal Exposure	3
Reinforcing Corrosion	9

Table B.2
Page 5

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Spent Fuel Pool Walls	6	5	7	129

Composition

Portland Cement Concrete,
Deformed Reinforcing Steel,
Stainless Steel Liner

Key Degradation Factors	Rating
Chemical Attack	5
Thermal Exposure	5
Irradiation	5
Fatigue	6
Reinforcing/Liner Corrosion	8
Reinforcing Therm. Exp.	3

Primary Structure	Cumulative Rank	Function
Control Building	127	Provide structural support and environmental protection for main plant control room during all operating conditions. Primarily of flat plate and shear wall construction.

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Foundation	9	9	6	146

Composition

Portland Cement Concrete,
Deformed Reinforcing Steel,
Waterproofing

Key Degradation Factors	Rating
Chemical Attack	8
Reinforcing Corrosion	8

Table B.2
Page 6

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Vertical Walls (interior/ exterior)	8	5	6	128

Composition

Portland Cement Concrete, Deformed Reinforcing Steel, Waterproofing (lower portions)

Key Degradation Factors	Rating
Chemical Attack	6
Freeze/Thaw	4
Reinforcing Corrosion	9

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Floor Slabs	6	2	6	106

Composition

Portland Cement Concrete, Deformed Reinforcing Steel

Key Degradation Factors	Rating
Chemical Attack	4
Reinforcing Corrosion	6
Abrasion	4

Primary Structure	Cumulative Rank	Function
Diesel Generator Buildings	117	Provide structural support and environmental protection of the safety-related diesel generators during all plant operating conditions. Primarily of flat plate and shear wall construction.

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Mat Foundation	10	9	5	134

Composition

Portland Cement Concrete, Deformed Reinforcing Steel, Waterproofing

Key Degradation Factors	Rating
Chemical Attack	6
Fatigue	3
Reinforcing Corrosion	6

Table B.2
Page 7

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Vertical Walls	8	5	5	119

Composition

Portland Cement Concrete, Deformed Reinforcing Steel

Key Degradation Factors	Rating
Chemical Attack	6
Freeze/Thaw	4
Reinforcing Corrosion	8

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Concrete Floor Slab	6	2	5	97

Composition

Portland Cement Concrete, Deformed Reinforcing Steel

Key Degradation Factors	Rating
Chemical Attack	6
Fatigue	3
Reinforcing Corrosion	6
Abrasion	3

Primary Structure	Cumulative Rank	Function
ESSW Pumphouse	107	Provides structural support and environmental protection of safety-related heat sink equipment. The structure primarily consists of flat plate and shear wall construction.

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Mat Foundation	10	9	4	132

Composition

Portland Cement Concrete, Deformed Reinforcing Steel, Waterproofing

Key Degradation Factors	Rating
Chemical Attack	6
Reinforcing Corrosion	7

Table B.2
Page 8

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Vertical Walls	8	5	4	110

Composition

Portland Cement Concrete,
Deformed Reinforcing Steel,
Waterproofing (lower portions)

Key Degradation Factors	Rating
Chemical Attack	4
Freeze/Thaw	8
Reinforcing Corrosion	9

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Floor Slab	6	3	4	88

Composition

Portland Cement Concrete,
Deformed Reinforcing Steel,
Structural Steel

Key Degradation Factors	Rating
Chemical Attack	5
Fatigue	2
Thermal Exposure	3
Abrasion	3
Reinforcing Corrosion	6

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Roof Slab	5	5	4	98

Composition

Portland Cement Concrete,
Deformed Reinforcing Steel,
Structural Steel

Key Degradation Factors	Rating
Chemical Attack	7
Reinforcing Corrosion	6
Freeze/Thaw	6

Primary Structure	Cumulative Rank	Function
Spray Pond	103	A free-formed reservoir for containing cooling water for normal and emergency plant operations. Liner consists of a reinforced concrete slab, 5 to 8 inches thick, under the entire pond area.

Table B.2
Page 9

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Concrete Liner	5	7	3	103

Composition

Deformed and Plain Reinforcing Steel, Portland Cement Concrete

Key Degradation Factors	Rating
Freeze/Thaw Damage	8
Chemical Attack	8
Reinforcing Corrosion	9
Abrasion	6

TABLE B.3

RESULTS OF APPLICATION OF STRUCTURAL AGING ASSESSMENT METHODOLOGY: PWR PRESTRESSED LARGE-DRY PLANT

Primary Structure	Cumulative Rank	Function
Containment Vessel	171	The containment vessels provide structural support and radiation shielding and containment for safe operation of the PWR. This containment is of sufficient volume to support pressure requirements of a pipe break accident. The vessel supports all internal equipment and transfers loading into the underlying soil. These structures were all cast-in-place.

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Dome	8	6	10	178

Composition

Prestressing Reinforcement, Deformed Reinforcement, Portland Cement Concrete, Liner Plate, Structural Steel

Key Degradation Factors	Rating
Chemical Attack	6
Freeze/Thaw	5
Thermal Exposure	3
Fatigue	3
Reinforcing Corrosion	9
Reinforcing Therm. Exp.	3
Prestressing Corrosion	10
Prestressing Fatigue	2
Prestressing Relaxation	7

Table B.3
Page 2

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Vertical Walls (including buttresses)	8	7	10	178

Composition

Prestressing Reinforcement, Deformed Reinforcement, Portland Cement Concrete, Liner Plate, Structural Steel, Waterproofing

Key Degradation Factors	Rating
Chemical Attack	8
Freeze/Thaw	4
Thermal Exposure	5
Fatigue	4
Reinforcing/Liner Corrosion	10
Reinforcing Therm. Exp.	4
Prestressing Corrosion	10
Prestressing Fatigue	2
Prestressing Relaxation	8
Abrasion	3

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Mat Foundation	10	10	10	200

Composition

Deformed Reinforcement, Portland Cement Concrete, Waterproofing, (prestressing reinforcement - local)

Key Degradation Factors	Rating
Chemical Attack	10
Thermal Exposure	4
Irradiation	3
Reinforcing Corrosion	10
Prestressing Corrosion	6
Prestressing Relaxation	4

Table B.3
Page 3

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Ring Girder	9	6	10	182

Composition

Prestressing Reinforcement (anchorages), Deformed Reinforcement, Portland Cement Concrete

Key Degradation Factors	Rating
Chemical Attack	5
Freeze/Thaw	4
Fatigue	3
Reinforcing Corrosion	9
Prestressing Corrosion	10
Prestressing Relaxation	7

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Tendon Gallery	3	10	4	118

Composition

Deformed Reinforcement, Portland Cement Concrete, Waterproofing, Structural Steel

Key Degradation Factors	Rating
Chemical Attack	10
Reinforcing Corrosion	10

Primary Structure	Cumulative Rank	Function
Containment-Internal Structures	144	Provide structural support and radiation shielding for NSSS equipment for all operating conditions. Provides human access to primary components and support for refueling operations. These structures are massive in section and were cast-in-place.

Table B.3
Page 4

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Bottom Slab (cast above bottom liner plate)	7	6	7	133

Composition

Deformed Reinforcement, Portland Cement Concrete, Liner Plate, Structural Steel

Key Degradation Factors	Rating
Chemical Attack	7
Thermal Exposure	4
Irradiation	3
Abrasion	4
Fatigue	6
Reinforcing Corrosion	8
Reinforcing Therm. Exp.	4
Reinforcing Irradiation	4
Reinforcing Fatigue	3

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Polar Crane Support Wall (part of missile barrier)	6	7	7	136

Composition

Deformed Reinforcement, Portland Cement Concrete

Key Degradation Factors	Rating
Chemical Attack	4
Thermal Exposure	3
Irradiation	2
Abrasion	4
Fatigue	8
Reinforcing Corrosion	8
Reinforcing Therm. Exp.	3
Reinforcing Irradiation	2
Reinforcing Fatigue	5

Table B.3
Page 5

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Floor Slabs	6	7	6	120

Composition

Deformed Reinforcement, Portland Cement Concrete, Liner Plate, Structural Steel

Key Degradation Factors	Rating
Chemical Attack	6
Thermal Exposure	6
Irradiation	3
Abrasion	4
Fatigue	4
Reinforcing Corrosion	7
Reinforcing Therm. Exp.	4
Reinforcing Irradiation	2
Reinforcing Fatigue	3

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Missile Barrier Walls (reactor coolant compartment)	7	7	8	156

Composition

Deformed Reinforcement, Portland Cement Concrete

Key Degradation Factors	Rating
Chemical Attack	7
Thermal Exposure	6
Irradiation	4
Fatigue	4
Reinforcing Corrosion	10
Reinforcing Therm. Exp.	5
Reinforcing Irradiation	5
Reinforcing Fatigue	5

Table B.3
Page 6

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Reactor Cavity (and support)	8	9	9	169

Composition

Deformed Reinforcement, Portland Cement Concrete, Stainless Steel Liner, Structural Steel

Key Degradation Factors	Rating
Chemical Attack	7
Thermal Exposure	8
Irradiation	6
Fatigue	7
Reinforcing Corrosion	10
Reinforcing Therm. Exp.	6
Reinforcing Irradiation	7
Reinforcing Fatigue	7

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Walls (and short columns)	7	7	8	149

Composition

Deformed Reinforcement, Portland Cement Concrete

Key Degradation Factors	Rating
Chemical Attack	6
Thermal Exposure	5
Irradiation	3
Fatigue	4
Reinforcing Corrosion	9
Reinforcing Therm. Exp.	3
Reinforcing Irradiation	2
Reinforcing Fatigue	4

Primary Structure	Cumulative Rank	Function
Auxiliary Building	126	The Auxiliary Building provides structural support, radiation shielding and environmental protection for internally housed safety-related equipment. Provides human access to equipment and "contains" radioactive contamination. Comprised of shear walls and floor slabs.

Table B.3
Page 7

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Mat Foundation	10	10	6	164

Composition

Deformed Reinforcement, Portland Cement Concrete, Waterproofing

Key Degradation Factors	Rating
Chemical Attack	10
Reinforcing Corrosion	9

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Walls	8	3	5	105

Composition

Deformed Reinforcement, Portland Cement Concrete, Waterproofing

Key Degradation Factors	Rating
Chemical Attack	7
Freeze/Thaw	4
Thermal Exposure	3
Fatigue	3
Reinforcing Corrosion	7
Reinforcing Fatigue	2

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Floor Slabs (including slabs under roof)	6	3	5	97

Composition

Deformed Reinforcement, Portland Cement Concrete

Key Degradation Factors	Rating
Chemical Attack	6
Thermal Exposure	3
Abrasion	3
Fatigue	3
Reinforcing Corrosion	7
Reinforcing Fatigue	3

Table B.3
Page 8

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Fuel Pool Walls, Slab	6	5	8	138

Composition

Deformed Reinforcement, Portland Cement Concrete, Stainless Steel Liner, Structural Steel

Key Degradation Factors	Rating
Chemical Attack	7
Thermal Exposure	4
Irradiation	4
Fatigue	6
Reinforcing Corrosion	10
Reinforcing Therm. Exp.	2
Reinforcing Irradiation	2
Reinforcing Fatigue	6

Primary Structure	Cumulative Rank	Function
Turbine Building	106	Provides structural support and environmental protection of enclosed equipment, including safety-related electrical cabinets, control room and diesel generators.

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Floor Slabs (safety-related)	6	3	4	88

Composition

Deformed Reinforcement, Portland Cement Concrete

Key Degradation Factors	Rating
Chemical Attack	6
Thermal Exposure	2
Abrasion	3
Fatigue	2
Reinforcing Corrosion	7
Reinforcing Fatigue	2

Table B.3
Page 9

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Walls (safety-related)	8	3	4	96

Composition

Deformed Reinforcement, Portland Cement Concrete

Key Degradation Factors	Rating
Chemical Attack	7
Freeze/Thaw	2
Thermal Exposure	4
Fatigue	3
Reinforcing Corrosion	7
Reinforcing Fatigue	2

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Control Room - Floor Slab	6	3	6	106

Composition

Deformed Reinforcement, Portland Cement Concrete

Key Degradation Factors	Rating
Chemical Attack	6
Thermal Exposure	2
Abrasion	4
Fatigue	1
Reinforcing Corrosion	7
Reinforcing Fatigue	1

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Control Room - Walls	8	3	6	114

Composition

Deformed Reinforcement, Portland Cement Concrete

Key Degradation Factors	Rating
Chemical Attack	6
Thermal Exposure	3
Fatigue	2
Reinforcing Corrosion	7
Reinforcing Fatigue	2

Table B.3
Page 10

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Diesel Generator - Floor Slabs	6	5	5	111

Composition

Deformed Reinforcement, Portland Cement Concrete

Key Degradation Factors	Rating
Chemical Attack	7
Thermal Exposure	4
Abrasion	4
Fatigue	3
Reinforcing Corrosion	7
Reinforcing Fatigue	3

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Diesel Generator - Walls	8	5	5	119

Composition

Deformed Reinforcement, Portland Cement Concrete

Key Degradation Factors	Rating
Chemical Attack	7
Thermal Exposure	4
Fatigue	3
Reinforcing Corrosion	7
Reinforcing Fatigue	2

Primary Structure	Cumulative Rank	Function
Cribhouse	99	Provides structural support and environmental protection of equipment required for ultimate heat sink.

Table B.3
Page 11

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Floor Slabs (safety-related)	6	4	4	95

Composition

Deformed Reinforcement, Portland Cement Concrete

Key Degradation Factors	Rating
Chemical Attack	8
Abrasion	3
Reinforcing Corrosion	8
Freeze/Thaw	3

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Walls (safety-related)	8	4	4	103

Composition

Deformed Reinforcement, Portland Cement Concrete

Key Degradation Factors	Rating
Chemical Attack	7
Reinforcing Corrosion	8
Freeze/Thaw	2

Primary Structure	Cumulative Rank	Function
Intake Crib	123	Provides for the intake of cooling water under all plant operating and environmental conditions.

Subelement	Importance	Environment Exposure	Safety Significance	Subelement Rank
Concrete Foundation	6	10	4	123

Composition

Deformed Reinforcement, Portland Cement Concrete

Key Degradation Factors	Rating
Chemical Attack	10
Freeze/Thaw	2
Abrasion	5
Fatigue	2
Reinforcing Corrosion	10

APPENDIX C
GLOSSARY OF KEY WORDS

AGING	– Cumulative changes with the passage of time that may occur within a structure because of: (1) natural internal chemical or physical processes during operation; (2) external stressors caused by storage or operating environment; (3) service wear including changes in dimensions and/or relative positions of individual parts or subassemblies by operational cycling; (4) excessive testing; and (5) improper installation, applications, and maintenance.
CONVENTIONAL REINFORCING STEEL	– Reinforcing steel composed of plain carbon steel bars which are under little or no stress at the time of installation. These bars have lugs or protrusions on the outer surface which improve bond and load transfer. These bars vary in diameter based on required load carrying capacity.
DEGRADATION	– The act or process of impairing physical properties of a structure due to environmental or service-related conditions. Degradation is typically included in the definition of aging.
DEGRADATION FACTOR	– A specific act or process that results in degradation of a structure.
DETERIORATION	– The act or process causing a structure to become inferior in quality or function. For the purposes of this report, this term is considered to be interchangeable with degradation.
DRY WELL	– The area within a boiling water reactor containment that houses the reactor and other components, and which is maintained in an unsubmerged state.
DURABILITY	– The ability of a structure to perform, or maintain its ability to perform, its function over a long period of time without accruing substantial degradation.
ENVIRONMENTAL EXPOSURE	– The resulting atmosphere acting upon a structure as influenced by nature or modification of nature's characteristics.
HEAVY WEIGHT CONCRETE	– Concrete composed of a binder element (typically portland cement), water, fine aggregate (sand, etc.) and large aggregate which is specially selected for its increased density and absorption characteristics (ilmenite, etc.). In the nuclear industry, this concrete is used in construction of primary radiation shield walls.
INSERVICE INSPECTION	– A phase of quality control which, by means of examination, observation or measurement, determines the conformance of materials/structures in service to predetermined quality requirements.
INTEGRITY	– The quality of state of a structure of being complete or unimpaired to perform its stated function.

LINER	– A metallic component, typically comprised of carbon steel plate with nominal thickness less than 13 mm, which is installed around the inside perimeter of a concrete containment to prevent leakage. The liner is anchored directly to the concrete vessel.
PRESTRESSING TENDON	– A high strength steel component, consisting of wires, strands made of several wires, or bars, which are installed and pretensioned to a certain level to create beneficial conditions and improve the performance of a structure. The tendons may (bonded) or may not (unbonded) be installed integral with the concrete component of a structure. Prestressing tendons were utilized primarily in the construction of certain containment vessels.
RELIABILITY	– The quality of state of a structure which results in continued achievement of its function and performance.
REPAIR	– The act of returning/restoring the condition or function of a structure through additional materials or processes application.
SAFETY-RELATED	– Components and structures of a nuclear power plant which are required to function under all operating conditions while meeting the requirements of 10CFR.
SAFETY SIGNIFICANCE	– The significance level of a specific structure's function to the overall safety of the nuclear power plant.
SUBELEMENT	– A specific portion of a structure as defined in terms of physical, functional, or compositional differences.
ULTIMATE HEAT SINK	– Components or structures necessary to ensure that a satisfactory amount of cooling water is available for the safety-related systems under all operating conditions.
WET WELL (TORUS)	– Portion of the boiling water reactor containment that provides for pressure suppression as required during operations (partially submerged).

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