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Aging Degradation of Concrete Structures in Nuclear Power Plants

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EXECUTIVE SUMMARY

This report on the aging-related degradation of concrete structures in nuclear power plants was prepared by Battelle Seattle Research Center for the Swedish Nuclear Power Inspectorate (SKI). The purpose of this report is to provide an understanding of how concrete structures in nuclear power plants degrade over time. This report is based on the studies of concrete aging commissioned by the United States Nuclear Regulatory Commission (NRC).

Concrete structures are significant features of a nuclear power facility. They are designed to provide:

- structural support to the mechanical and electrical systems and components;
- protection of the systems and components from the environment; and
- shielding against radiation releases.

Studies into the aging of concrete structures in nuclear power plants have been funded by the NRC in two separate research programs. These programs are:

- the Nuclear Plant Aging Research (NPAR) program; and
- the Structural Aging (SAG) program.

The NPAR program was established by the NRC in 1983 to examine the aging-related degradation of all safety significant mechanical and electrical systems and components in a nuclear power plant.

In 1987 the SAG program was established by the NRC to continue the concrete aging work of the NPAR program and to gather and document the operational experience of concrete structures. Studies under the SAG program are to provide a technical basis to evaluate the reliability of concrete structures. The objectives of the program studies are to:

- identify significant aging mechanisms and their effect on overall structural reliability;

- assess the degraded strength of the structure over time as a result of environmental stressors and aging mechanisms;

- devise methods to assess the residual life of aged structures and how structures respond to design-basis events;

- evaluate non-destructive examination (NDE) techniques and in-plant strength measurement for assessing current condition and predicting residual life; and

- document the inspection procedures, frequency, and repair techniques.

The concrete aging studies under the NPAR and SAG programs focussed exclusively on concrete containment structures. The containment structures are where the problems resulting from nuclear power generation mainly occur. Other concrete structures of a nuclear power plant facility are considered to be conventional structures and are not significantly affected by the nuclear power generation process.

FUNCTIONS OF CONCRETE STRUCTURES

Concrete structures are classified according to the location and function of each structure. Studies of concrete aging under the SAG program use two classifications to group concrete structures. These are:

- safety significant; and
- environmental exposure.

Concrete structures that the NRC classifies as safety significant are called Category I concrete structures. Category I concrete structures perform one or more of the following safety-related functions:

- Prevention of uncontrolled liquid or airborne radiation releases;
- Radiation attenuation and shielding;
- Structural support for nuclear steam supply system and containment internal equipment;
- Structural support for redundant safety-related equipment;
- Structural support for heat sink equipment;
- Support for spent fuel pools;
- Protection of safety-related equipment from harmful environments; and

- Separation or "communication" function.

The durability and performance of concrete structures also depend on the severity of the environment in which the structure is located. The SAG program researchers determined that the effects of environmental exposure need to be considered as part of the aging assessment of concrete components. Category I concrete structures are typically exposed to one or more of the seven environment categories during plant operation. These environments are:

- Subterranean;
- Direct exposure to natural environment;
- Indirect exposure to natural environment;
- Continuous fluid exposure;
- Fluid/pressure retaining;
- Environment inside the primary containment; and
- Controlled environment inside auxiliary buildings.

MATERIALS AND STRESSORS OF CONCRETE CONTAINMENTS

As mentioned, concrete containment structures experience the majority of nuclear related degradation. In order to effectively perform the functions of load carrying, radiation shielding, and leak tightness, the concrete containment structures in nuclear power plants are constructed from a number of materials. These materials include:

- concrete;
- conventional steel reinforcement;
- prestressing steel;
- steel liner plate; and
- embedment steel.

A stressor, or degradation factor, is defined as an agent or stimulus resulting from fabrication or pre-service and operating conditions that can result in the aging process and failure of the system, structure, and component. Different materials within the concrete structure are affected by different types of stressor.

The stressors affecting the concrete material are:

- chemical - including the chemical processes of efflorescence and leaching, sulfate attack, bases and acids attack, salt crystallization, and alkali-aggregate reactions; and

- physical - including freezing and thawing cycles, thermal exposure and thermal cycling, irradiation, abrasion, erosion, cavitation, and fatigue and vibration.

The stressors affecting the mild steel reinforcement are:

- corrosion;
- elevated temperature;
- irradiation; and
- fatigue.

The stressors affecting the prestressing steel include the four stressors listed for the reinforcing steel, with an additional stressor known as the losses of prestressing forces and end effects.

The main stressors affecting the liner plate and structural steel are corrosion and fatigue.

Summaries of the stressors and degradation processes for different types of concrete containment structures are presented in Tables 1 to 5 on pages 42 to 46. Also included in Tables 2 to 5 are the inspection methods that are useful in identifying the potential failures of concrete structures.

TESTING METHODS FOR CONCRETE STRUCTURES

The testing methods to detect aging-related degradation of concrete structures belong in one of two categories. These categories are:

- direct methods, or destructive examinations, involve the visual inspection of the structure, and the removal of materials for testing and analysis; and

- indirect methods, or nondestructive examinations, involve the measurement of certain structural parameters based on which an estimate of the structural properties can be made using existing correlations. The structural properties include strength, elastic behavior, and the extent of degradation.

Presently, the detection of degradation of concrete structures is difficult since no single testing method will detect all degradation factors and processes. Combinations of testing methods are required to assess concrete structure degradation.

Tables 6 and 7, pages 49 to 52, list the non-destructive and destructive testing methods that are available and are used in the construction and general civil engineering industries. Although these testing methods are considered to be "available", many have not been used in nuclear power plants for various reasons.

Table 8, page 53, presents a list of the recommended testing method to detect concrete structure degradation. These recommendations are derived from the SAG researchers' evaluation of each method's technical capability based on its application in general construction practices.

SUMMARY

The conclusions of the aging studies are:

- The performance of concrete structures have been very reliable in both nuclear and general civil engineering services.
- Techniques, such as visual inspection, used to detect environmentally induced deterioration of concrete can provide sufficient qualitative assessments of the conditions. Complications arise when quantitative data are required to assess the concrete conditions.
- Proper techniques and materials used to repair damaged concrete structures will very likely restore the structural integrity of the structure completely.
- The durability of concrete structures are well recognized by the presence and continued service of many structures several hundred years after construction. However, well-documented data of concrete operational experience and longevity is lacking.
- Environmental stressors are the main causes of concrete structural degradation. These stressors typically result in localized cracks, loss of strength, and wear of all materials within the concrete structure.

CHAPTER 1: INTRODUCTION

This report on the aging-related degradation of concrete structures in nuclear power plants was prepared by Battelle Seattle Research Center for the Swedish Nuclear Power Inspectorate (SKI). The purpose of this report is to provide an understanding of how concrete structures in nuclear power plants degrade over time. The information presented in the following chapters is based on the extensive research studies on concrete degradation sponsored by the United States Nuclear Regulatory Commission (NRC).

Concrete structures in nuclear power plants are designed to provide:

- structural support to the mechanical and electrical systems and components;
- protection of the systems and components from the environment; and
- shielding against radiation releases.

The proper functioning of these concrete structures is necessary for the safety of plant personnel and the general public.

The aging-related degradation of concrete structures has been studied by the NRC under both the Structural Aging (SAG) program and the Nuclear Plant Aging Research (NPAR) program. The aging research sponsored by these programs has been directed at understanding and mitigating the degradation of concrete structures. The goal of the research studies has been to identify the concrete component most likely to fail, the causes of failure, how the component fails, and potential methods to mitigate the failure.

The NRC concrete aging programs are briefly reviewed in Chapter 2. The functions of concrete structures in nuclear power plants are examined in Chapter 3. Included in Chapter 3 are cut-away illustrations of the major concrete structures at typical nuclear power plants.

The next three chapters focus on the materials used in concrete containment structures (Chapter 4), the aging degradation stressors affecting nuclear plant concrete (Chapter 5), and testing methods to evaluate degradation (Chapter 6). Chapter 7 provides a summary of the conclusions of the concrete aging research studies.

Included in Chapters 5 and 6 are several useful tables that summarize the stressors, degradation mechanisms, and failure modes for various concrete containment structures. Also included are tables that summarize the available and recommended destructive and non-destructive testing methods to assess concrete degradation.

CHAPTER 2: THE NRC'S AGING RESEARCH OF CONCRETE

Studies into the aging of concrete structures in nuclear power plants have been funded by the NRC in two separate research programs. These programs are:

- the Structural Aging (SAG) program; and
- the Nuclear Plant Aging Research (NPAR) program.

All concrete aging studies are performed under the SAG program since the program's establishment in 1987. Prior to 1987, the studies of concrete belonged to the NPAR program.

THE STRUCTURAL AGING (SAG) PROGRAM

In 1987 the SAG program was established by the NRC to gather and document the operational experience of concrete structures (ORNL/NRC/LTR-92/3). Studies under the SAG program are to provide a technical basis to evaluate the reliability of concrete structures. The research activities have been performed by Oak Ridge National Laboratory in Oak Ridge, Tennessee. The objectives of the program studies are to:

- identify significant aging mechanisms and their effect on overall structural reliability;

- assess the degraded strength of the structure over time as a result of environmental stressors and aging mechanisms;

- devise methods to assess the residual life of aged structures and how structures respond to design-basis events;

- evaluate non-destructive examination (NDE) techniques and in-plant strength measurement for assessing current condition and predicting residual life; and

- document the inspection procedures, frequency, and repair techniques.

At the end of each calendar year, the SAG program researchers compile a technical progress report to document the activities and products of that year. The latest technical progress report available is for the 1992 calendar year. ORNL is currently working on the 1993 report. The SAG program is expected to be completed by the end of 1994. A summary of the program's accomplishments and products is expected in the middle of 1995.

The work under the SAG program has been divided into four main tasks: one management task and three technical tasks. The four tasks and the objectives of each task are discussed below.

Program Management - The management of the technical tasks includes planning, integrating, monitoring, reporting, and technology transfer.

Materials Property Database - This task is designed to establish and maintain a handbook and electronic database of structural materials property data. The database contains information on the time-dependent behavior of structural materials. The database will be used to assist in the prediction of potential long-term deterioration of critical concrete structures, and to identify the limits of adverse environmental exposure of these structures. These information are most useful in providing an idea of the aging process for parts of the concrete structure that are not easily accessible for monitoring and testing.

It is anticipated that the materials property database will continue to be maintained and expanded even after the SAG program is officially completed in 1994.

Structural Component Assessment/Repair Technology - The two main objectives of this SAG program task are to:

- develop a methodology to quantitatively assess the presence, magnitude, and significance of any aging factors on concrete structures; and

- recommend inservice inspection and testing/sampling procedures to obtain useful data for the evaluation of current structural condition and for trending the performance.

This task is considered by the SAG program researchers to be of primary importance for the consideration of extending the service life of nuclear power plants. This is because the residual life of a plant cannot be determined unless all degradation processes for each critical concrete structure in the reactor building has been examined in detail.

Quantitative Methodology for Continued Service Determinations - The objective of this task is to develop a useful method to quantitatively assess the current and future reliability of concrete structures. This task involves identifying and developing mathematical models to evaluate changes in concrete strength based on initial conditions, service load history, and environmental exposure.

THE NUCLEAR PLANT AGING RESEARCH (NPAR) PROGRAM

Prior to the establishment of the SAG program in 1987, studies of concrete degradation were conducted under the NPAR program (NUREG/CR-4652 and NUREG/CR-4731 Vols. 1 and 2).

The NPAR program was established by the NRC in 1983 to examine the aging-related degradation of all safety significant mechanical and electrical systems and components in a nuclear power plant (NUREG/CR-4731 Vol.1). Many national research laboratories in the United States have been and continue to be involved with conducting studies under the NPAR program. By 1997 the NPAR program is expected to be completed.

The objectives of the NPAR program are to:

- identify and prioritize systems, structures, and components (SSCs) with aging risk significance;

- identify, characterize, and understand aging mechanisms and the results of aging degradation, which, if not mitigated could reduce the performance of the SSCs and impair plant safety;

- identify inspection, surveillance, and monitoring methods, or determine the residual life of representative SSCs which will ensure timely detection of significant aging effects before safety function is lost; and

- evaluate the effectiveness of preventive maintenance, corrective maintenance, repair, and replacement practices in mitigating aging effects and diminishing the rate and extent of degradation caused by aging.

The NPAR researchers consider certain concrete structures in nuclear plants to be safety-significant components. Thus the aging of concrete containment structures were examined along with a number of other safety-related mechanical components in the NUREG/CR-4731 Vols. 1 and 2 studies. The studies of NUREG/CR-4652 exclusively examined the aging degradation of the concrete containment structural component.

CHAPTER 3: FUNCTIONS OF CONCRETE STRUCTURES

Concrete structures are used to support, contain, and protect the many mechanical and electrical systems in a nuclear power plant. The proper functioning of these structures is necessary for the safety of plant personnel and the public. This chapter discusses the functions and purposes of concrete structures in nuclear power plants.

Concrete structures are classified according to the location and function of each structure. Studies of concrete aging under the SAG program use two classifications to group concrete structures. These are:

- safety significant; and
- environmental exposure.

The functional requirements of concrete structures under each of the two classifications are described in the following sections. Also included in this chapter is a brief overview of the different concrete containment structures used in U.S. nuclear power plants. Because of the importance of the concrete containment structures and the fact that they experience the majority of the nuclear related degradation, these structures have been the focus of the NRC sponsored aging research studies.

SAFETY SIGNIFICANT CONCRETE STRUCTURES

Concrete structures classified as safety significant are called Category I concrete structures. The design and construction requirements for Category I structures are specified by the American Concrete Institute, the United States Nuclear Regulatory Guide, and the General Design Criteria for Nuclear Plants in the United States Code of Federal Regulations (CFR).

Category I concrete structures perform one or more of the safety-related functions described below.

Prevention of uncontrolled liquid or airborne radiation releases - Concrete structures, specifically the primary and secondary containment structures in which the nuclear reactor is located, are required to prevent the release of radioactive fission products to the environment during normal plant operation and accident conditions.

All nuclear reactors are surrounded by a primary concrete containment structure. This structure is lined with steel on the inside surface to prevent leakage in the event of an accident.

For certain types of nuclear plants (some boiling water reactors) there is a large reinforced concrete building that encloses the primary containment structure and the reactor. This large reactor building is referred to as the secondary containment.

Figures of these structures are presented in the following sections of this chapter. A more detailed discussion of these structures are presented in Chapter 4.

Radiation attenuation and shielding - Concrete structures not only prevent the release of radiation, they also mitigate or reduce the amount of gamma radiation, neutron, and other irradiation that occur during normal and accident conditions from reaching the outside environment. The concrete structures involved in shielding radiation are specified by the U.S. Code of Federal Regulations to possess thick cross-sections to meet the limitations of allowable radiation exposure. Shielding structures include the primary or biological shield walls and the containment structure.

Structural support for nuclear steam system and containment internal equipment - Concrete structures provide support and constraint for the many components of the steam system. The support involves controlling the deflections and distortions of the steam systems, specifically the reactor pressure vessel, steam generators, coolant pumps, and pipes. The supporting structures are usually made from reinforced concrete.

Structural support for redundant safety-related equipment - The redundant safety-related equipment are used as backup for the main safety systems in the event of an accident. Most of the backup equipment is part of the cooling system and the electrical power generation system. Concrete structures used to support the backup equipment are considered to be performing a safety function. These structures include floor slabs, columns, and walls constructed from reinforced concrete.

Structural support for heat sink equipment - The nuclear reaction process produces a great amount of heat. Some of this heat must be discharged to a heat sink. The heat sink system includes piping for the intake, transport, and discharge of cooling water. This equipment and the supporting structures are usually located outside of the containment building. The reinforced concrete structures are designed to provide support and anchorage of these equipment during normal operating and accident conditions.

Support for spent fuel pools - Nuclear power plants have reinforced concrete pools lined with stainless steel for underwater storage of spent fuel rod assemblies and other potentially radioactive components. These supporting concrete structures have relatively large cross-sections in order to provide radiation shielding and meet the load support requirements.

Protection of safety-related equipment from harmful environments - Reinforced concrete structures are designed and constructed to shield safety-related components from harmful environments, impacts from missile or high-velocity projectiles, and other physical damage.

Separation or "communication" function - During an emergency some nuclear power plants rely on concrete structures to separate or direct the pressure and suppression function of the containment. These structures conform to the leaktight requirements during plant operations. These structures typically consist of the:

- divider barrier or ice condenser in some pressurized water reactor designs;
- drywell and weir walls in boiling water reactor Mark III designs; and
- diaphragm floor in boiling water reactor Mark II design.

ENVIRONMENTALLY EXPOSED CONCRETE STRUCTURES

The durability and performance of concrete structures not only depends on the function of the structures but also on the severity of the environment in which the structure is located. The SAG program researchers determined that the effects of environmental exposure should be examined as part of the aging assessment of concrete components.

Category I concrete structures are typically exposed to one or more of the seven environmental categories during plant operation. These environments are described below.

Subterranean - The concrete structures built below the existing level of soil/rock may be exposed to passive or aggressive effects of the environment. The sources of the degrading effects include groundwater, surrounding soils, and natural events such as floods, freezing/thawing cycles, wetting and drying. Typical Category I concrete structures found below the soil/rock level include the foundation and lower walls of the primary containment and reactor buildings, and the structures supporting the conveyance of cooling water to and from the heat sink.

Direct exposure to natural environment - The concrete structures that are exposed to the natural environment face the following degradation processes:

- carbonation;
- wet and dry cycles;
- freezing and thawing cycles;
- chemical attack;
- ocean salt spray; and
- acid rain.

Category I concrete structures that are directly exposed to the natural environment include the primary containments, enclosure and shield buildings, and other external structures.

Indirect exposure to natural environment - Indirect exposure to the natural environment means that the concrete structure is exposed to external temperature and humidity, but is shielded from other external conditions such as rain and wind. These structures experience less wear than those that are directly exposed to the environment. This type of exposure is common for pipe tunnel interior surfaces where the inside environment is not controlled be heating and air conditioning.

Continuous fluid exposure - In certain cases where there is no steel liner or internal pipe, the concrete structures supporting the intake and transport of water from the heat sink may be subjected to the constant exposure to fluids. The fluid is usually water from a cooling source such as lakes and rivers. Although the water may be chemically treated, it may contain microorganisms, solids, and chemicals potentially harmful to the concrete surfaces or reinforcing steel. The flow velocity of the fluid will affect the amount of erosion/corrosion of the concrete.

Fluid/pressure retaining - Category I concrete structures used as a fluid or pressure retainer are leaktight and are typically lined with carbon or stainless steel plate. The environmental effects experienced by the concrete include temperature gradients, bearing loads, and radiation fields. Examples of these structures are the concrete containment, primary reactor (biological) shield wall, spent fuel pool, and other pool structures.

Environment inside the primary containment - The concrete within the primary containment structure can be exposed to a severe environment of high humidity (up to 100% relative humidity), high temperature (65°C or higher), and large radiation fields. These concrete structures can also experience:

- exposure to chemicals;
- the movement of heavy loads causing abrasion and impact; and
- fatigue due to loading cycles and vibrations from pumps and turbines connected to the structure.

Areas of the concrete structures where these conditions may be intensified are the surfaces around the reactor or hot piping penetrations, the area near the reactor coolant pressure boundary components, and the area near locations of fluid buildup.

Controlled environment in the auxiliary buildings - The controlled environment in an auxiliary building is achieved by heating, air conditioning, ventilation, and dehumidification. Many of the safety-significant Category I structures are located within the controlled interior environment of the auxiliary buildings. These concrete structures are considered to be in a much less aggressive degradation environment than the concrete structures located inside the primary containment structure.

THE DESIGNS OF CONCRETE CONTAINMENT STRUCTURES

There are two principal types of nuclear power plants in the U.S. These are boiling water reactor (BWR) plants and pressurized water reactors (PWR) plants. The different designs of the containment structure are due to the different types and capacities of nuclear power plants. The primary differences of these designs are (ORNL/NRC/LTR-90/17):

- volume requirements;
- provisions for accident loadings and pressures; and
- layout of the containment internal structures.

A cut-away diagram of a BWR plant is provided in Figure 1. The reactor building contains the nuclear reactor, the fuel storage pool, and the primary containment structure around the reactor (item number 21 in the figure). The auxiliary buildings include the radwaste building, the turbine generator building, and the diesel generator building. The heat sink system for this plant in the desert of Eastern Washington State consists of dry cooling towers. As can be seen in the figure, the circulating water line (item number 19), and the pump circulating house are part of this heat sink cooling system.

Although the specific layout and design of other nuclear power plants in the U.S. and other countries will vary from the plant in Figure 1, the general information in this figure provides a good overview of the nuclear plant concrete structures.

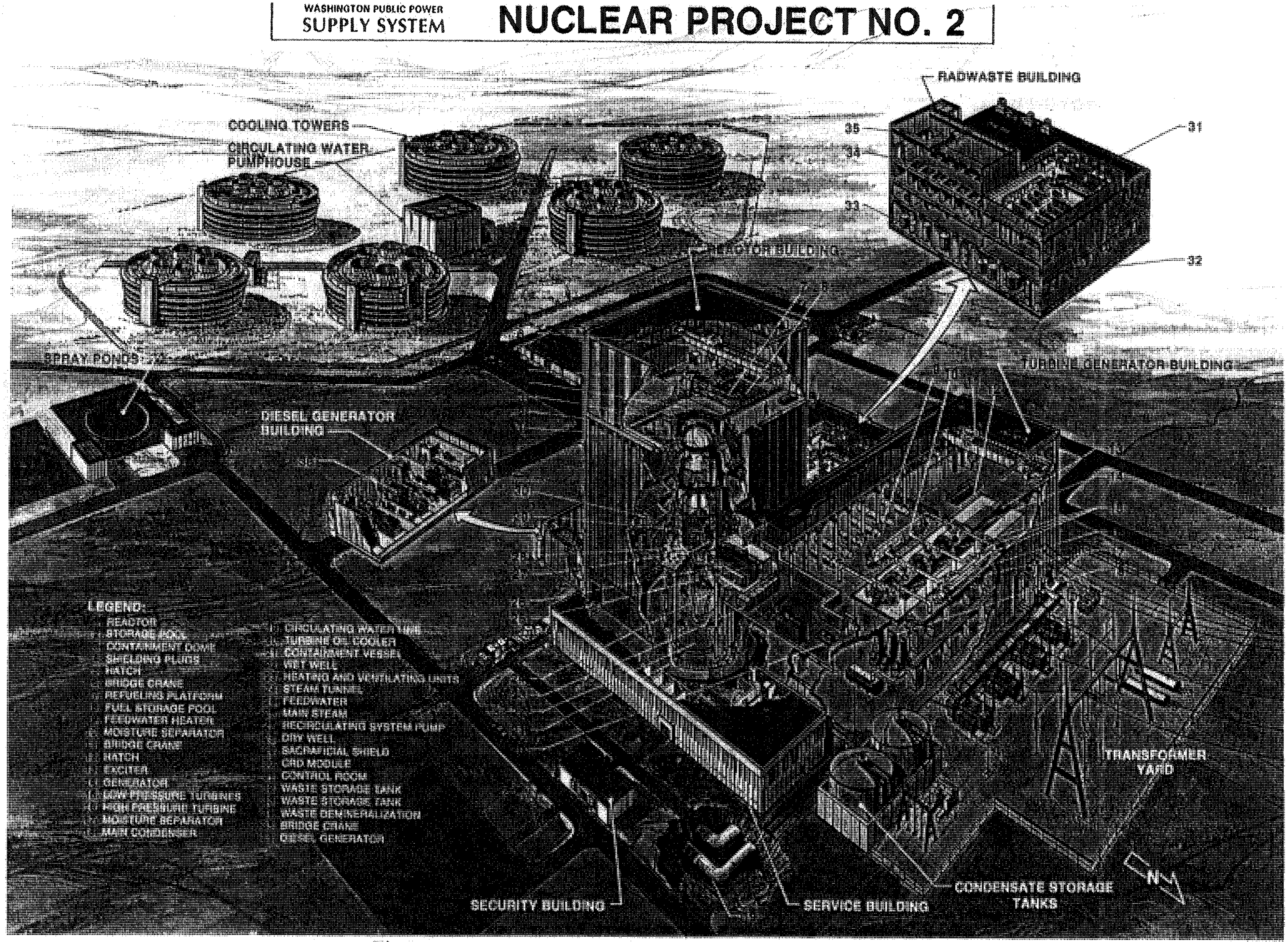

Figure 1. Cut-Away Diagram of a BWR Nuclear Power Plant Facility

There are currently 63 PWR nuclear plants in the U.S., all with concrete containment structures. Twenty-one of these structures use reinforced concrete. The other 42 structures use prestressed concrete. PWR concrete containments have three distinct functional designs. These are:

- subatmospheric reinforced concrete illustrated in Figure 2;
- ice condenser reinforced concrete illustrated in Figure 3; and
- large/dry reinforced and/or prestressed concrete illustrated in Figure 4.

There are currently 12 BWR plants in the U.S. having three distinct types of concrete containments. The number and types of containments are:

- two Mark I reinforced concrete containments illustrated in Figure 5;
- six Mark II reinforced concrete containments illustrated in Figure 6;
- to Mark III reinforced concrete containments illustrated in Figure 7; and
- two Mark II prestressed concrete containments.

The BWR reactor shown in the Figure 1 cut-away diagram is an example of a BWR Mark II reinforced concrete containments. The components and materials used to construct these containment structures are similar and are discussed in the following chapter.

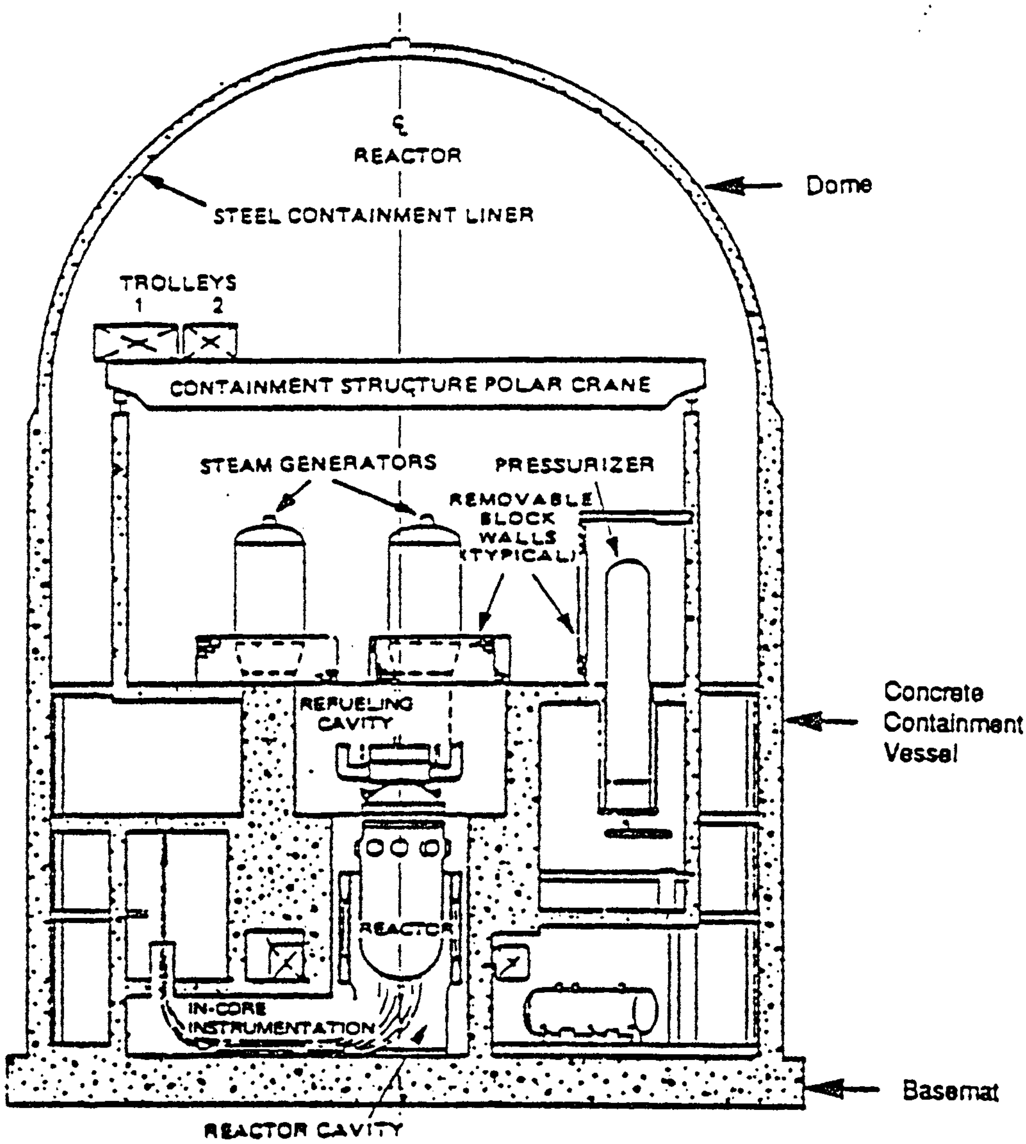

Figure 2. PWR Subatmospheric Type Reinforced Concrete Containment.

Source: (ORNL/NRC/LTR-90/17)

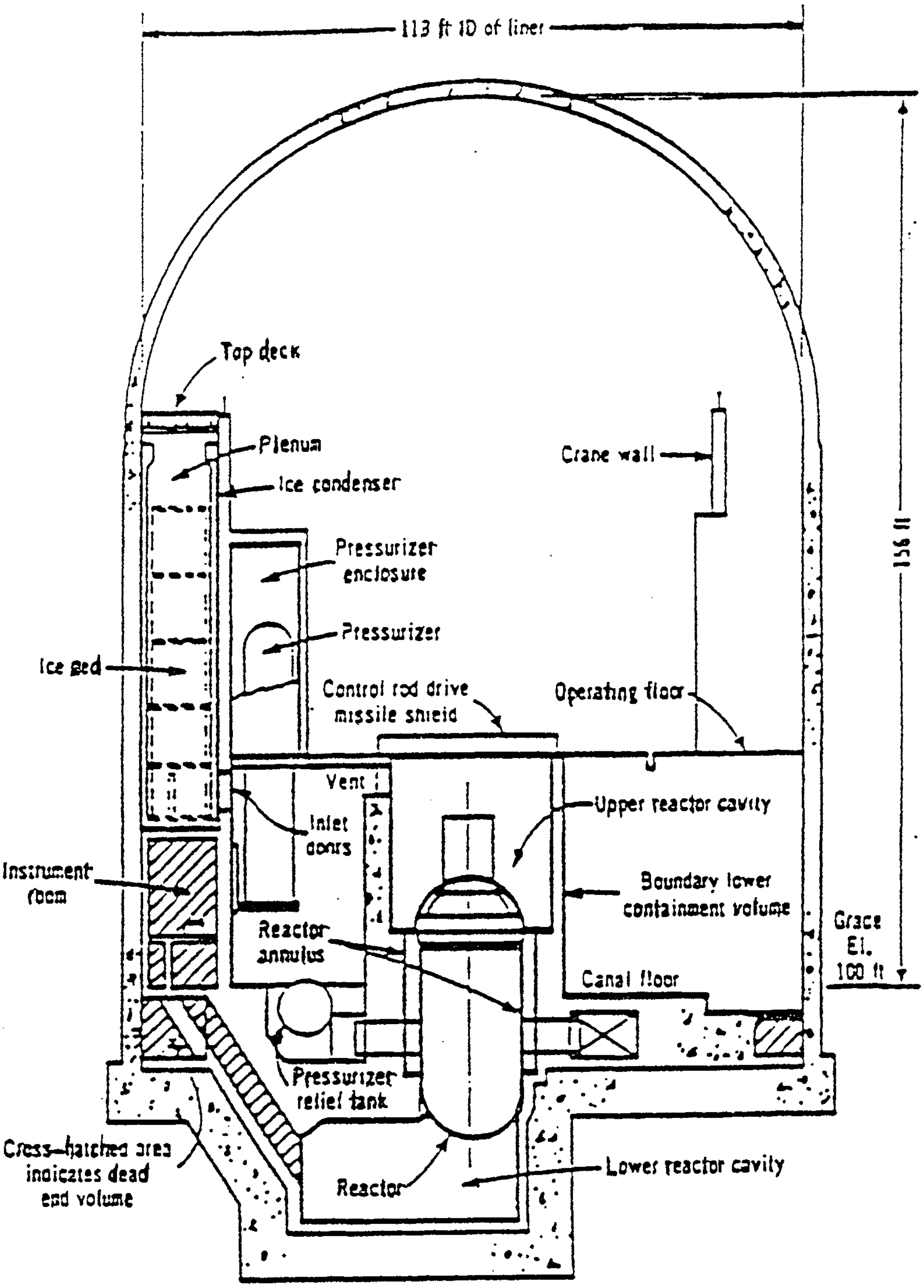

Figure 3. PWR Ice Condenser Type Reinforced Concrete Containment.
Source: (ORNL/NRC/LTR-90/17)

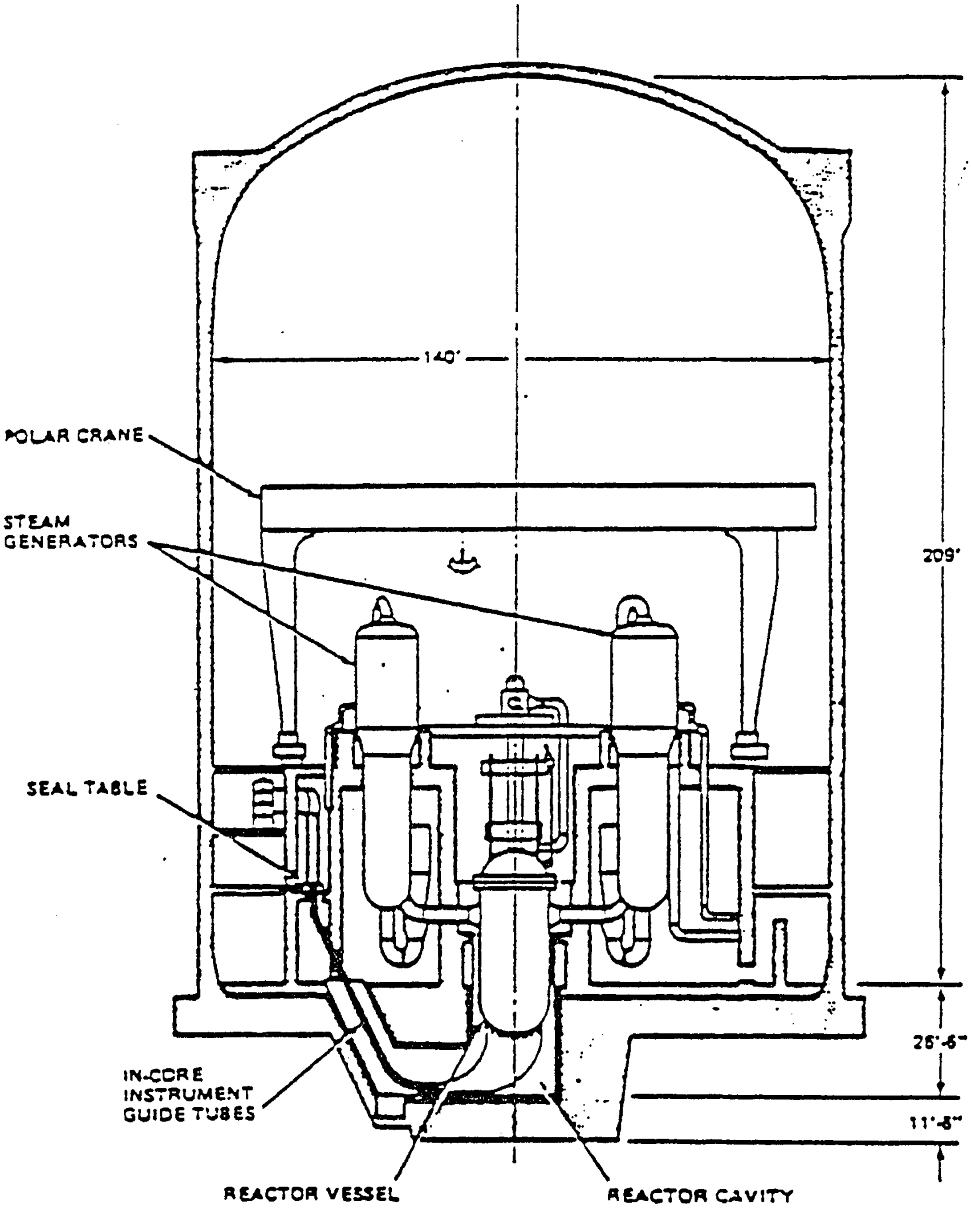

Figure 4. PWR Large/Dry Type Prestressed Concrete Containment.
Source: (ORNL/NRC/LTR-90/17)

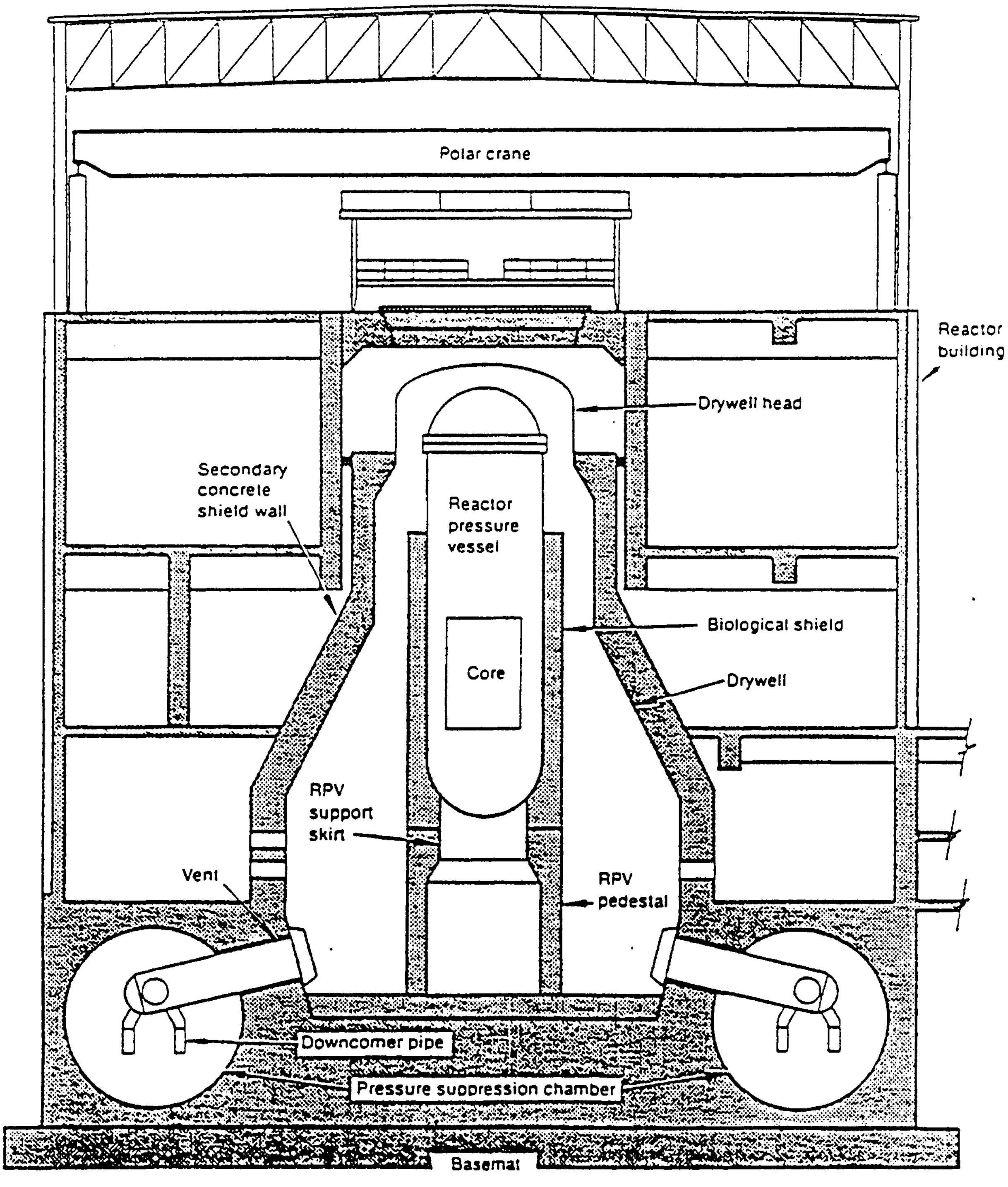

Figure 5. BWR Mark I Type Metal Containment Enclosed in a Reactor Building.
Source: (ORNL/NRC/LTR-90/17)

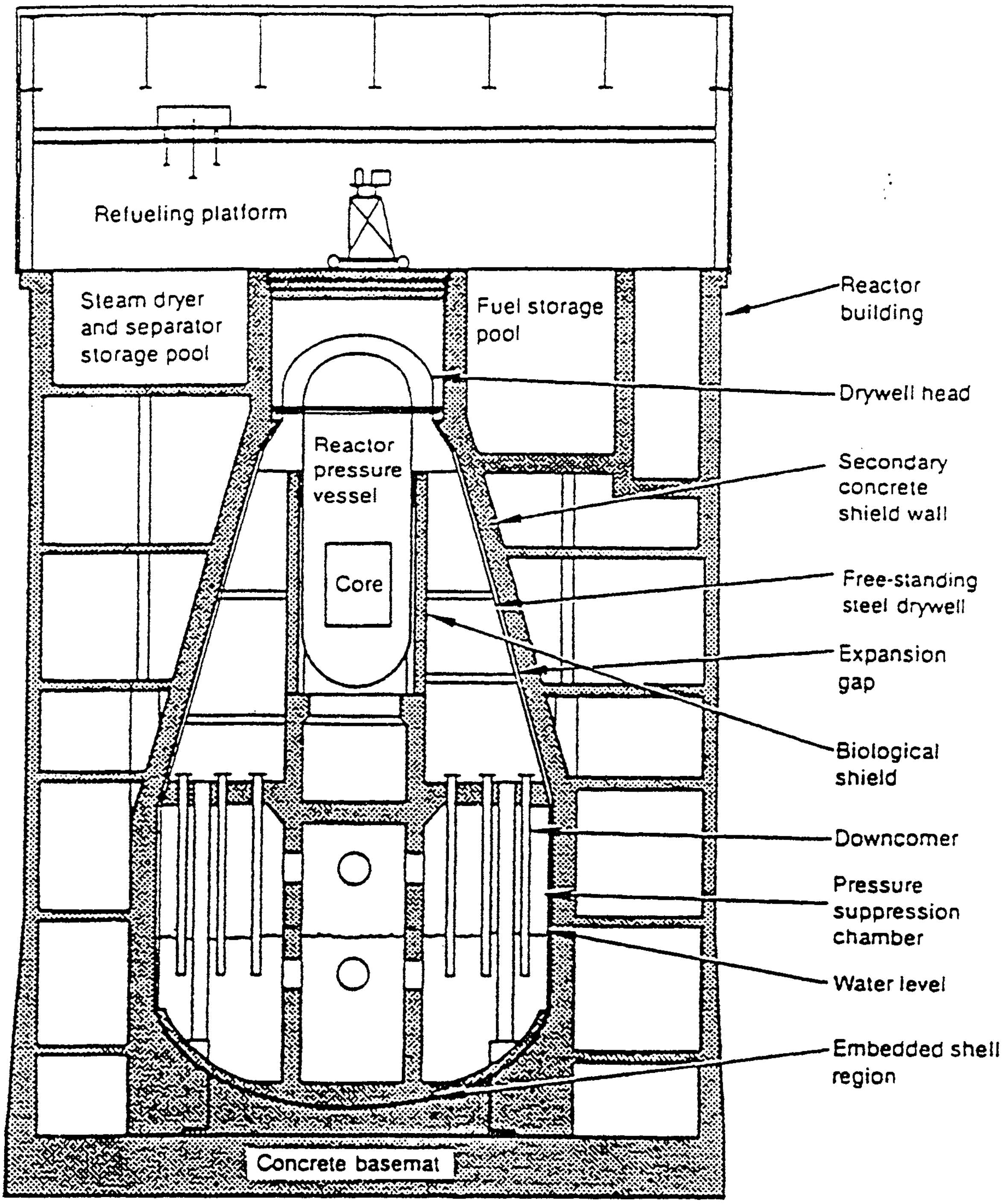

Figure 6. BWR Mark II Type Metal Containment Enclosed in a Reactor Building.
Source: (ORNL/NRC/LTR-90/17)

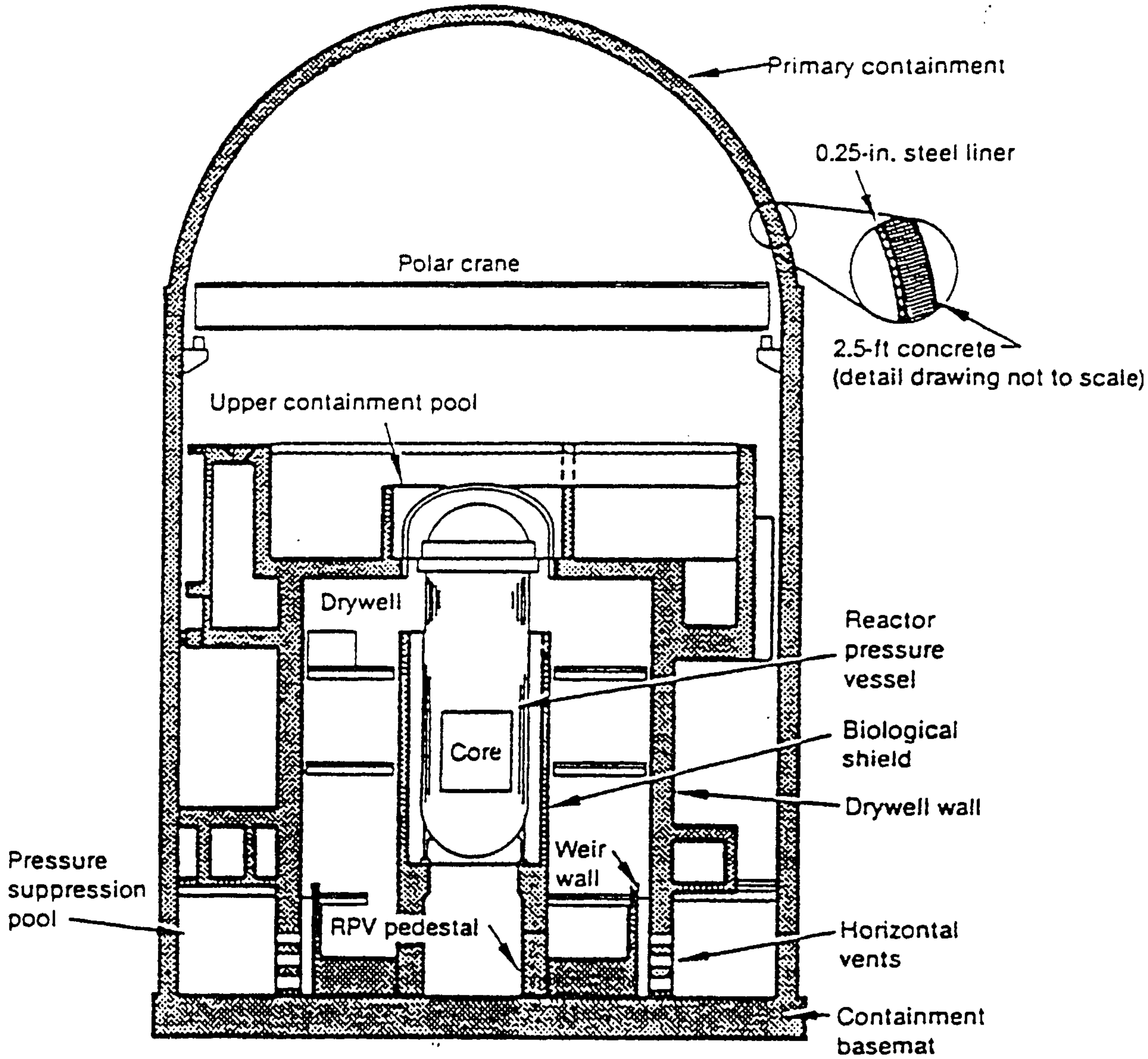

Figure 7. BWR Mark III Type Metal Containment Enclosed in a Reactor Building.

Source: (ORNL/NRC/LTR-90/17)

CHAPTER 4: THE SUB-STRUCTURES AND MATERIALS OF CONCRETE CONTAINMENT STRUCTURES

The concrete structure aging studies under the NPAR and SAG programs focussed exclusively on concrete containment structures. According to these NRC program researchers, the containment building is where the problems resulting from nuclear power generation mainly occur. Other concrete structures, or auxiliary buildings, that surround the reactor building are considered to be conventional civil engineering structures and are not significantly affected by the nuclear power generation process.

The sub-structures and problems experienced by the concrete containment are discussed in the remainder chapters of this report.

SUB-STRUCTURES OF CONCRETE CONTAINMENTS

The large containment structures of both PWR and BWR nuclear plants are comprised of a number of similar sub-structures. These sub-structures are the:

- primary containment structure;
- containment internal structures;
- reactor building; and
- fuel storage pools.

Primary containment structures - These structures are designed for maximum radiation absorption. The primary containment structure can be seen in Figures 2 to 7. In Figures 5 and 6, the primary containment is labeled as the "secondary concrete shield wall" and is enclosed in a secondary concrete structure called the reactor building.

The operating requirements for the primary containment structures in PWR and BWR nuclear power plants are similar. These requirements are to:

- provide an essentially leaktight barrier against uncontrolled release of radioactive substances in all design basis accident conditions;

- withstand the predicted pressure and temperature conditions resulting from a loss of coolant accident;

- withstand periodic leak-rate testing at the highest pressure level that may occur in an accident;

- permit periodic inspection and testing of all significant components and surfaces; and

- support all core internal systems using the foundation, or basemat, to transfer loading to the ground.

Containment internal structures - The containment internal structures of both PWR and BWR plants typically contain floor slabs, walls, and columns. These structures perform one or more of the following functions:

- radiation shielding;
- provisions for personnel accessibility;
- nuclear steam system and other internals components anchorage, support, and protection;
- resistance to jet, pipe whip, and other loadings in emergency conditions;
- lateral stability for containment;
- transfer of containment loads to foundation below;
- channeling or routing the steam and air through ice condensers in PWR ice condenser containments.

Reactor building - The reactor buildings provide a secondary boundary for radiation containment. The reactor building can be seen in Figures 5 and 6. These structures are typically made of reinforced concrete. These safety-related structures perform the following functions:

- provide additional shielding in conjunction with the primary containment;
- resist environmental and operational loadings; and
- enclose safety-related mechanical equipment, spent fuel, and the primary metal or concrete containment.

Fuel storage pools - The fuel storage pools are designed to store new-fuel and spent-fuel rods. These structures are typically four walls with a bottom slab all made from reinforced concrete. The insides of the walls and slab are lined with stainless steel. These structures generally have large cross-sections in order to support large pools of water. The fuel storage and other pools in BWR plants are located within the reactor building (see items number 2 and 8 in Figure 1). The storage pools for PWR plants are typically located in an auxiliary building near the containment building.

MATERIALS USED IN CONCRETE STRUCTURES

In order to effectively perform the functions of load carrying, radiation shielding, and leak tightness, the concrete structures in nuclear power plants are constructed from a number of materials. These materials include:

- concrete;
- conventional steel reinforcement;
- prestressing steel;
- steel liner plate; and
- embedment steel.

These materials are reviewed below.

Concrete

The concrete used in safety-related Category I structures contains the following ingredients:

- Type II portland cement;
- fine aggregates such as sand;
- water;
- other ingredients to enhance concrete properties and performance; and
- normal weight or heavy weight coarse aggregate.

Type II portland cement is used because, in comparison to Type I portland cement, it has improved sulfate resistance and lower heat of hydration. Type II portland cement is also the main ingredient in many large concrete civil engineering structures such as buildings and dams.

The water and coarse aggregates are usually acquired locally at the site of the nuclear plant. Both materials undergo testing and material characterization before being used. The coarse aggregates include gravel, crushed gravel, or crushed stone. The coarse aggregates for primary containment concrete structures are dense or heavyweight aggregates. These materials include barites, limonites, magnetites, and ilmenites.

Sand and other ingredients are added to the concrete mixture to:

- improve air entrainment for enhanced durability;
- improved workability;
- modify hardening or setting characteristic;
- aid in curing;
- reduce evolution of heat; and
- provide other concrete property improvement.

The specified unconfined compressive strength for concrete ranges from 13 MPa to 55 MPa (mega pascal). Commonly, the compressive strength of concrete is about 28 MPa.

Conventional Steel Reinforcement

The conventional, or mild, reinforcing steels within concrete structures are used to resist and transfer the primary tensile and shear stress. This steel is made of plain carbon steel bar stock with lug or protrusion deformations on the surface. These steel bars conform to the manufacturing standards and specifications developed by the American Society for Testing and Manufacturing (ASTM). The minimum yield strength of these bars ranges from 270 MPa to 415 MPa. Commonly, the yield strength is 415 MPa.

Conventional reinforcing steel includes:

- welded wire fabric;
- deformed wire;
- bar and rod mats; and
- all accessory steel parts such as the seats and ties for positioning and placing the reinforcement.

Prestressing Steel

Some concrete containment structures use prestressing steel tendons to provide resistance to tensile loads. These tendons are in tubes and are embedded inside the concrete. These tendon tubes are typically filled with organic corrosion inhibitors. Prestressing tendons are tensioned and anchored to the hardened concrete structure by buttonheads, wedges, or nuts. There are three types of tendons: wire, strand, or bar. The standards for these prestressing steels are specified by ASTM, with the minimum ultimate strengths ranging from 1035 MPa to 1860 MPa.

Liner Plate

The leakproof characteristic of concrete containment structures is provided by the liner plate. The typical liner plate is made from steel with a thickness less than 13 mm. Separate plates are joined by welding, and are attached to the concrete by studs, structural steel shapes, or other steel products.

The dry-well sections of BWR and PWR containments are usually lined with carbon steel. The linings of the wet-well and the fuel pool containments are made from various stainless steel. The manufacturing standards and performance specifications for these steels are developed by ASTM and the American National Standards Institute (ANSI).

Embedment Steel

Embedment steel is used to anchor heavy equipment such as structural members, piping, ductwork, and cable trays to the concrete. The embedment steel is designed to meet certain requirements including:

- ease of installation;
- load capacity;
- susceptibility to vibration;
- preload retention;
- temperature range;
- corrosion resistance; and
- ease of inspection.

The loads experienced by the embedment steel include a combination of tension, bending, shear, and compression. The embedment anchors include embedded bolts, grouted bolts, embedded studs, expansion anchors, and wedge anchors. The embedded steel may also be made from material similar to that of the structural plates used during concrete placement.

The embedment steel material specifications also follow the standards of ANSI and ASTM.

CHAPTER 5: AGING-RELATED DEGRADATION OF CATEGORY I CONCRETE STRUCTURES

The reliability and longevity of Category I safety-related concrete structures depend on the ability of these structures to withstand the time-dependent deterioration. Concrete reliability and longevity can be improved by limiting the exposure of the concrete structures to deteriorating effects and by proper inspection and maintenance methods.

The aging research of concrete structures is to identify and mitigate the time-dependent deterioration forces on concrete. In these studies, the researchers reviewed the operational experience of concrete structures used in nuclear service in order to gain an understanding of how these structures are likely to fail. This chapter presents the findings of these studies including the stressors affecting concrete, the resulting failure modes, failure mechanisms, and failure causes.

STRESSORS AFFECTING CONCRETE STRUCTURES

A stressor, or degradation factor, is defined as an agent or stimulus resulting from fabrication or pre-service and operating conditions that can result in the aging process and failure of the system, structure, and component. Different materials within the concrete structure are affected by different types of stressor (NUREG/CR-4652 and ORNL/NRC/LTR-90/17). The four principal materials (concrete, mild steel reinforcement, prestressing steel, and liner/structural steel) and their likely stressors are discussed below. Included at the end of this chapter are tables that summarize the information on stressors, degradation mechanisms, potential failure modes, and in-service inspection methods. Also included is a table that presents a summary of the stressors and potential degradation sites for various materials examined in this chapter.

Stressors Affecting the Concrete Material

Operational experience indicate that concrete can be highly reliable and requires no maintenance provided the concrete is:

- properly designed for the environment in which it is exposed;

- produced with high quality control; and
- subjected to proper construction methods.

Despite the high reliability, certain environments can expose the concrete to potential stressors. Each of these stressors belong in one of two categories: chemical or physical stressors. These stressors cause concrete deterioration by adversely affecting the performance of the cement-paste matrix or the aggregate ingredients in the concrete.

Chemical Stressors on Concrete Material

These stressors are a result of the chemical reactions between the environment and the cement paste or the coarse aggregate. The chemical reactions typically occur at concrete surfaces and between cracks. However, the entire cross-section of the structure can be affected by the presence of cracks and prolonged exposure.

The degree to which chemical stressors affect the concrete material depends on the pH of the attacking fluid and the concrete's permeability, alkalinity, and reactivity. Chemical stressors attack the concrete structures in various processes. These different processes are:

- efflorescence and leaching;
- sulfate attack;
- bases and acids;
- salt crystallization; and
- alkali-aggregate reactions.

Each of these processes of chemical attack on concrete is discussed below.

Efflorescence and Leaching

Efflorescence is a result of the dissolution of salts contained in the cement matrix following the percolation of water through the concrete material. The salt is leached out of the concrete and crystallized at the surface when the water is evaporated or when interaction with atmospheric carbon dioxide occurs. Efflorescence is considered by the researchers to be an aesthetic problem and not a performance degrading problem. Efflorescence by itself indicates that changes to the cement paste are occurring within the concrete.

Leaching is a mild chemical stressor that alters the cement paste matrix by dissolving elements containing calcium through hydrolysis. The leaching rate depends on the cement's permeability, temperature, and reactivity. The primary effect of leaching is an increase in
pores and permeability of the concrete. The resulting changes in concrete due to leaching are:

- lower compressive strength;
- more vulnerable to environmental attacks such as water saturation and freeze/thaw cycles; and
- corrosion of the steel reinforcements due to chloride penetration.

The Category I structures that are most susceptible to leaching are those structures that are exposed to rain water, cooling water, or ground water.

Sulfate Attack

Sulfate attack has deteriorated a number of concrete structures that are in contact with alkali soils and waters. The chemical attackers include sulfates of sodium, potassium, and magnesium. These sulfates react with the hydrated lime and calcium aluminate in cement paste to form calcium sulfate and calcium sulfoaluminate. These resultant elements can cause the following concrete deterioration:

- considerable expansion and disruption or cracking of the concrete; and
- reduction in the cohesion of the cement hydration leading to loss of strength.

The rate of sulfate attack depends on the reactivity of the cement paste and the concentration of the sulfate compounds in the environment. The researchers determined that sulfate levels in soils and waters of 1200 ppm (parts per million) and higher can aggressively attack concrete used in nuclear power plants.

Bases and Acids

Bases and acids are additional types of chemical attacks on concrete structures. Bases are compounds that dissolve in water to produce OH^- ions. Bases and acids readily react with each other to produce a neutral solution. The hydrated cement paste is an alkaline material with a pH level of 12.5 or higher. Thus the cement/concrete will not likely react with other basic solutions. Nevertheless, concrete deterioration by processes other than chemical reaction with hydroxide ions (OH^-) is possible when the concrete is in prolonged contact with high concentrations of alkaline solutions from water treatment or other industrial processes.

Acidic solutions are naturally more reactive to the basic cement/concrete structures. Acids are compounds that dissolves in water to produce H^+ ions. Examples of acids that surround nuclear plant concrete structures include:

- sulfuric acid in ground water;
- carbonic acid in ground water; and
- certain plant internal fluids such as boric acid.

The acidic solutions and portland cement paste chemically react by exchanging cations. This reaction produces calcium salts. The salts can be removed from the concrete internals by the leaching process described above, resulting in the increase of concrete porosity and permeability. The rate of acidic chemical attack on concrete depends on the pH of the fluid and the duration of exposure. The structures of primary concern are those Category I structures below ground and are exposed to potentially acidic ground water.

Salt Crystallization

Salt crystallization occurs when the concrete contacts water containing large amounts of dissolved solids such as calcium sulfate ($CaSO_4$), sodium chloride (NaCl), and sodium sulfate (Na_2SO_4). This type of water can permeate the concrete and evaporate, leaving the salts to crystallize within the concrete pores. The repeated cycles of evaporation and crystallization can cause the amount of salt deposits increase. This increase in salt deposit can approach the level where the stresses generated are high enough to cause micro-cracks in the concrete. Concrete structures susceptible to salt crystallization damage are those in contact with fluctuating water levels or with salted ground water.

Alkali-Aggregate Reactions

Alkali-aggregate reactions involve the presence of alkali ions in portland cement, hydroxyl ions, and certain silicon-type ingredients present in aggregates. The occurrence of Alkali-

aggregate reactions are due to the following factors:

- large amount of alkali ions;

- moist environment; and
- presence of reactive silica, silicate, or carbonate aggregate materials.

Alkali-aggregate reactions deteriorate concrete structures through the process of alkali-silica reaction. This reaction involves the swelling of the alkali-silica gel when in contact with water, causing an increase in hydraulic pressure within the concrete. Other alkali-silica reactions involve the sand-gravel and the sedimentary rock aggregates contained in rivers

This process can cause significant cracking of concrete and loss of mechanical properties. The primary structures most susceptible to alkali-aggregate reactions are the Category I concrete structures exposed to rain, ground water, cooling water, or humidity inside containment areas.

Concrete deterioration due to alkali-aggregate reactions typically occur within 10 years after plant construction, but some structures show no sign of deterioration until 15 to 25 years after construction. This delay indicates that there is a less reactive form of silica to hinder these reactions. The deterioration of concrete is in the form of map or continuous cracking, popouts, and spalls. These blemishes can be visually detected and repaired. However, the repair cost and effort may be substantial if the deterioration occurs in certain Category I structures such as the primary containment. Figure 8 summarizes the degradation process of concrete by chemical reactions.

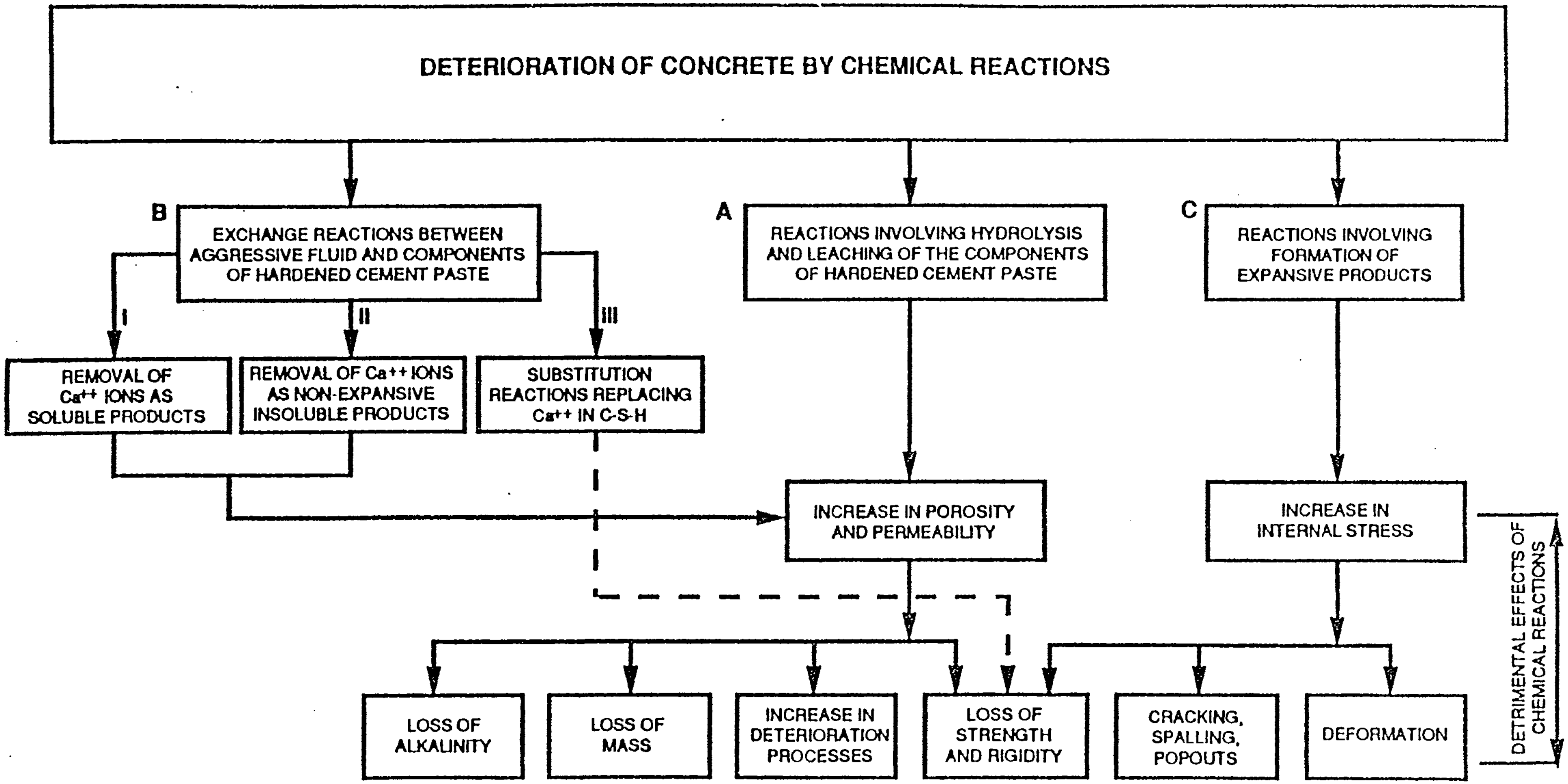

Figure 8. Types of Chemical Reactions Responsible for Concrete Deterioration. A: Softwater attack on calcium hydroxide in hydrated portland cement; B(I): Acidic solution forming soluble calcium compounds; B(II): Solutions of oxalic acids and its salts, forming calcium oxalate; B(III): Long-term seawater attack; C: Attacks of sulfate and alkali-aggregate, and corrosion of steel in concrete. Source: ORNL/NRC/LTR-90/17

Physical Stressors on Concrete Material

At times, the physical stressors can be difficult to distinguish from the chemical stressors. Physical stressors are defined by the researchers to include degradation factors due to environmental and mechanical effects. The different types of physical stressors on concrete material are:

- freezing and thawing cycles;
- thermal exposure and thermal cycling;
- irradiation;
- abrasion, erosion, and cavitation; and
- fatigue and vibration.

Freezing and Thawing Cycles

Concrete materials that are saturated or nearly saturated with water can be damaged by the repeated freezing and thawing cycles. The water within the concrete pores expand as it freezes, causing an increase in hydraulic pressure within the concrete. In the northern U.S., the freeze/thaw cycles occur up to 50 times per year. Damages to concrete structures usually take the form of scaling or flaking, spalling, and pattern cracking.

The Category I structures most susceptible to freeze/thaw damage are those in the intake, conveyance, and management of cooling water. These damages can be visually detected at exposed surfaces, and are usually identified before loss of structural property occurs.

The following practices are used by the building industry to control or to increase the concrete's resistance to freeze/thaw damage:

- air entrainment - the sizing and spacing of air bubbles in cement paste are controlled;

- ideal water to cement ratio - the ratio should not exceed certain levels (depending on the type of cement and concrete structure) to minimize the presence of large pores in the concrete;

- curing - concrete should be cured prior to frost exposure;

- strength - the lower strength air-entrained concrete will have improved resistance to frost; and

- degree of saturation - limiting the exposure of the concrete to be soaked or saturated with water will decrease the freeze/thaw damage.

Thermal Exposure and Thermal Cycling

Thermal exposure and thermal cycling stresses are due to elevated temperature and thermal gradients across the concrete material. The strength and stiffness of concrete are adversely affected by thermal stresses. These changes in mechanical properties are due to the changes in moisture content of the concrete ingredients. Another factor is the deterioration of the cement paste and aggregate, especially if the two materials have different thermal expansion rates.

Concrete material does not significantly deteriorate until the dehydration of calcium hydroxide (CaOH) reaches about 400°C. At 90°C, the concrete may lose 10% of its room temperature strength and modulus of elasticity. Category I concrete structures are limited to maximum temperatures of 65°C by the plant's technical specifications. But at certain areas of the structure, the concrete material may be heated to much higher temperatures approaching that of the steam system coolant. These local areas include the piping penetrations and improperly ventilated areas.

Signs of excessive thermal exposure in the concrete material can be seen by the cracking and spalling at exposed surfaces.

Irradiation

Irradiation stressor on concrete comes from two sources:

- the bombardment of fast and thermal neutrons from the reactor core; and
- the gamma rays produced when the neutrons are captured by steel members in contact with the concrete.

The fast neutrons can cause displacements within the concrete matrix, resulting in significant growth of certain aggregate such as flint. The gamma rays produce radiolysis of the water in cement paste. Gamma rays affect the creep and shrinkage behavior of concrete to a limited extent.

The approximate levels of irradiation necessary to cause measurable damage in concrete were reported to be 1 x 10^{19} neutrons per square centimeter (n/cm^2) for neutron fluence, and 10^{10} rads of gamma radiation dose. These values indicate that irradiation damage of the primary concrete containment may occur after over 40 years of operation. The researchers indicated that the damage due to irradiation may be reduced by such factors as air gaps and insulation.

Excessive irradiation of concrete is manifested as cracks and spalls at exposed surfaces and losses in tensile and compressive strengths and the modulus of elasticity.

Abrasion, Erosion, and Cavitation

The forces and processes of abrasion, erosion, and cavitation causes the progressive loss of material at the concrete surface. Abrasion is the dry attrition of the concrete. Erosion is the wear due to flowing fluids. Cavitation is the loss of material due to the rapid formation and collapse of vapor bubbles in flowing water.

Concrete structures can be made to resist abrasion and erosion by improving the quality of the concrete mixture. High quality concrete mixtures are those that produce low porosity and high strength. Cavitation can be avoided by adjusting the pump speed.

The Category I structures affected by abrasion, erosion, and cavitation are those in providing water intake, water transport, or flow management.

Fatigue and Vibration

Fatigue and vibration are mechanical stressors due to the fluctuations in loading, temperature, and moisture content. Concrete deterioration by fatigue begins as microscopic cracks in the cement paste near areas of large aggregate particles, reinforcing steel, or defects where stresses tend to concentrate. The large scale concrete failure due to fatigue is manifested by excessive cracking, excessive deflections, and brittle fracture. Vibration on concrete structures occurs at the supports for the piping system and the pumps and turbines.

The nuclear industry has reported no significant fatigue-related concrete failures.

Stressors Affecting the Mild Steel Reinforcement

The mild steel reinforcement within concrete structures are subjected to the following stressors:

- corrosion;
- elevated temperature;
- irradiation; and
- fatigue.

Corrosion

Corrosion is the main cause of deterioration for reinforcing steel. The corrosion of reinforcing steel is by a process called electrochemical. This electrochemical potential to cause corrosion may be generated by:

- embedding two different metals into the concrete, leading to the formation of galvanic cells. These cells can also be formed when there is significant variations in surface characteristics of the steel; and

- the presence of different concentrations of dissolved ions such as alkalies, chlorides, and oxygen near the steel, causing the formation of concentration cells.

The galvanic cells and the concentration cells cause the steel reinforcements to be anodic and cathodic (possessing negative or positive ions). The end result is the increased likelihood and ease of steel corrosion.

Concretes that are of high-quality, well compacted, and having adequately covered reinforcing steel are not susceptible to corrosion. The high alkalinity of concrete (pH>12) protects the steel from anodic activity. With a reduction of the pH level to less than 11 due to leaching, corrosion can result in rust forming on the reinforcing steel.

Other causes of steel reinforcement corrosion include stray electrical currents, different electromotive forces, and the galvanic reaction between embedded steel of different metallurgy.

Elevated Temperature

Elevated temperature stressor on the steel reinforcement is considered to be negligible because the operating temperatures of concrete are far lower than the threshold temperature of 200°C where the properties of the steel are affected.

Irradiation

Irradiation by neutron fluence can produce changes in mechanical properties such as the yield strength and ductile/brittle transition temperature of carbon steel. The effects of irradiation include a reduction of ductility, increasing the risk of brittle fracture. The steel most susceptible to irradiation damage is located in the shield wall of primary containment. The concrete cover over the steel provides shielding from the neutron fluence. The preliminary research under the SAG program indicated that irradiation is not detrimental to the reinforcing steel. But the researchers recommended that additional research should be conducted to evaluate in more detail the possible the impact of irradiation on the reinforcing steel.

Fatigue

The effects of fatigue on reinforcing steel is similar to those of the concrete described. The loss in the bonding strength of the steel and concrete is expected due to vibration. But overall, failures of steel reinforcement due to fatigue is not likely to occur.

Stressors Affecting the Prestressing Steel

Failures of the prestressing steel tendons were determined to be caused by the following stressors:

- corrosion;
- elevated temperature;
- irradiation;
- fatigue; and
- losses of prestressing forces and end effects.

Corrosion

Corrosion of the prestressing steel parts can occur in localized areas or uniformly throughout the steel. Most corrosion-related failures of prestressing parts are due to localized attacks.
The following prestressing steel failures have been identified as caused by localized corrosion:

- pitting - the electrochemical process resulting in material loss of the prestressing tendon surface, reducing its capability to support loads;

- stress corrosion cracking (SCC) - SCC results in the fracture of a normally ductile material under stress and in corrosive environments; and

- hydrogen embrittlement - this corrosive process occurs when hydrogen atoms enter the metal lattice, reducing its ductility.

To protect against corrosion, the ducts containing the post-tensioned tendons are filled with organic corrosion inhibitors. These inhibitors include waxes such as petrolatums or portland cement grout.

Elevated Temperature

Elevated temperature can be potentially harmful to heat treated and drawing steel wires. However, the researchers determined that short-term heating of 3 to 5 minutes at temperatures up to 400°C may not harm the prestressing wire's mechanical properties. Stress relaxation and creep properties of prestressing tendons are also affected by elevated temperatures. Thermal damage to prestressing steels occurs only at certain localized areas where the steel is exposed to temperature approaching 200°C for extended periods. This exposure can harm the properties of the steel.

Irradiation effects on prestressing steel are similar to those described for the reinforcing steel.

Fatigue

Fatigue due to stress cycles and vibration causes failures in structural elements in the following ways:

- concrete failure due to flexural compression;
- concrete failure due to diagonal tension or shear forces;
- prestressing steel failure due to flexural and tensile stress variations;
- failure of pre-tensioned beams due to loss of bonding; and
- failure of the end anchorages of post-tensioned structures.

Most fatigue failures are at the tendons and are caused by stress concentrations at crack locations.

Losses of Prestressing Forces and End Effects

Losses of prestressing forces - The prestressing tendons are all installed with an initial force level, known as the prestressing force. This initial force can be lost due to the following factors:

- friction;
- end anchorage deflection;
- elastic shortening;
- tendon stress relaxation; and
- concrete creep and shrinkage.

Of these factors, only the tendon stress relaxation and the concrete creep/shrinkage were considered by the researchers to be aging-related degradation processes. Stress relaxation is when the strain (or elongation) of the tendon steel does not vary after a gradual decrease in stress of a preloaded tendon. The extent of stress relaxation depends on material properties, initial stress level, temperature, and time under loading. Concrete creep and shrinkage are changes in volume that reflect aging of the structure. Creep and shrinkage can raise the level of stress experienced by the tendons.

End effects are localized notching damage of the tendons due to the tensioning and loosening. The tendons most affected are the strand tendons in the containment areas. The cycles of loosening and applying tension are in compliance with the inspection and maintenance requirements for these Category I structures. The notching can be a source of further deterioration due to stress concentration.

Stressors Affecting the Liner Plate and Structural Steel

Corrosion is the main degradation method of liner plate and structural steel. The structural steel include those embedded in concrete and inside containment areas. The corrosion process for these liner plate and structural steel is similar as for the reinforcing steel.
For the metal liner plate, the corrosion process include one or more of the following:

- galvanic corrosion;
- pitting;
- crevicing; and
- stray electrical currents or biological effects.

Corrosion of the liner plate is usually localized and is caused by a loss of coating, impact, or failure of adjoining floor sealant. Studies of corrosion for BWR metal containment vessel, having similar material as the liner plate, reported the corrosion rate to be between 0.45 to 1.3 mm/year.

Concern about liner plate corrosion is high in the nuclear industry due to the consequence of liner plate failure on the leak tightness of primary containment. Corrosion damage can be avoided by periodic inspection and maintenance of the coatings. Proper maintenance will allow the liner plate to operate trouble-free for its service life of 40 years.

Localized corrosion affects structural steel at a rate of 0.02 to 0.04 mm/year in an industrial environment. For low carbon steel in polluted seawater, the corrosion rate can approach 0.056 mm/year. Structural steel is embedded inside concrete where it is protected from the environment. But the presence of pores and high concrete permeability can allow aggressive fluids to reach the steel and increasing the corrosion rate.

Fatigue due to load cycles and vibration is the other cause of liner plate and structural steel degradation. Generally, the design and manufacturing of liner plates and structural steel have adequately address the fatigue issues. Fatigue problems occur as a result of unforeseen circumstance such as material flaws and stress concentration factors. For liner plates, the possible fatigue sites include:

- base metal delaminations;
- weld defect areas;
- arc strike areas;
- shape changes near penetrations;
- structural attachments; and
- concrete to floor boundaries.

For structural steel members, the possible fatigue sites are the large containment penetration framing and the liner anchorages near vibrating load conditions.

Summary of the Aging-Related Degradation of Concrete Structures

Table 1 presents a summary of the stressors and potential degradation sites for three of the four concrete structure materials described in this chapter.

Summaries of the aging degradation processes of BWR and PWR concrete containment structures are presented in Tables 2 to 5. The information in these tables are from studies conducted by the Idaho National Engineering Laboratories. Inspection methods to identify the potential failures that are being used in the U.S. are included in Tables 2 to 5.

Table 1. Summary of Stressors and Potential Affected Areas in Category I concrete Structures.

Material	Stressor	Potential Areas of Degradation
Concrete		
	Chemical attack	Subterranean areas, surfaces exposed to cooling water sources, containment floors and slabs, containment shield, auxiliary buildings exposed to rain, ocean air, alkali-aggregate reaction
	Free/thaw cycles	External structures where water can collect, intake/discharge structures particularly at water line of cooling water source
	Thermal exposure, thermal cycling	Containment shield structures, areas near reactor pressure vessel or hot piping systems
	Irradiation	Containment structures near reactor pressure vessel, localized areas of certain containment designs
	Abrasion, erosion, cavitation	Floor and slab elements, cooling water intake or discharge structures
	Fatigue, vibration	Local areas in containment near liner anchors, local areas under equipment supports
Mild steel reinforcement		
	Corrosion	Outer layer of conventional steel reinforcing in all structures
	Irradiation	Containment structures near reactor pressure vessel boundary
	Fatigue	Local areas in structures subjected to repeated equipment loads
Prestressing steel		
	Corrosion	Containment buildings
	Stress relaxation	In-containment buildings, fuel pool structures

Source: ORNL/NRC/LTR-90/17

Table 2. Summary of Degradation Processes for BWR Steel Reinforced Concrete Containments*

Degradation Site	Stressors	Degradation Mechanisms	Potential Failure Modes	In-service Inspection Methods
Reinforcing bars	Corrosive external environment (Mark III), stray electrical current	Corrosion, fatigue	Loss of structural integrity	None
Mark I and Mark II suppression pool steel liner below water line	Cyclic thermal and mechanical loads, corrosive internal environment, microorganisms	Corrosion caused by differential aeration, microbially influenced corrosion, fatigue	Leakage of radioactive gases	Visual inspection, leakage testing as required by 10 CFR 50 Appendix J
Drywell steel liner, suppression pool steel liner above water line	Moisture, corrosive internal environment, cyclic thermal and pressure loads	Corrosion, fatigue	Leakage of radioactive gases	Visual inspection, leakage testing
Concrete	Aggressive external environment, internal chemical reactions, nuclear heat, leakage testing	Cracking, spalling, loss of free water	Degradation of shielding properties	Visual inspection

* Note: The degradation sites are listed from highest to lowest significance based on the consequences of the potential failure modes. For the sites with similar failure modes, the higher significance is given to the site that is more susceptible to failure.

Source: NUREG/CR-4731 Volume 2 (1989)

Table 3. Summary of Degradation Processes for BWR Mark II Prestressed Concrete Containments*

Degradation Site	Stressors	Degradation Mechanisms	Potential Failure Modes	In-service Inspection Methods
Posttensioning system anchors	Trapped water, steady-state stress	Hydrogen embrittlement, corrosion	Loss of stress	Tendon surveillance program, visual inspection
Posttensioning tendon wire or strand	Moisture, trapped water, microorganisms, steady state stress	Pitting, microbially influenced corrosion, stress relaxation	Loss of stress	Tendon surveillance program
Suppression pool steel liner below water line	Cyclic thermal and mechanical loads, fatigue, corrosive internal environment, microorganism	Fatigue, corrosion caused by differential aeration, microbially influenced corrosion	Leakage of radioactive gases	Visual inspection, leakage testing as required by 10 CFR 50 Appendix J
Drywell steel liner, suppression pool steel liner above water line	Moisture, corrosive internal environment, cyclic thermal pressure loads	Corrosion, fatigue	Leakage of radioactive gases	Visual inspection, leakage testing as required by 10 CFR 50 Appendix J
Reinforcing bars	Stray electrical currents	Corrosion	Loss of structural integrity	None
Concrete	Internal chemical reaction, nuclear heat, leakage testing	Cracking, spalling, creep, loss of free water	Degradation of shielding properties, loss of stress in posttensioning tendons	Visual inspection

* Note: The degradation sites are listed from highest to lowest significance based on the consequences of the potential failure modes. For the sites with similar failure modes, the higher significance is given to the site that is more susceptible to failure.

Source: NUREG/CR-4731 Volume 2 (1989)

Table 4. Summary of Degradation Processes for PWR Prestressed Concrete Containments*

Degradation Site	Stressors	Degradation Mechanisms	Potential Failure Modes	In-service Inspection Methods
Posttensioning anchors	Material properties and trapped water	Hydrogen embrittlement	Loss of stress	Tendon surveillance program
Posttensioning tendon wire of strand	Moisture, trapped water, breakdown of grease material	Pitting, microbiological-induced corrosion	Loss of stress	Tendon surveillance program
Steel liner dome and wall	Moisture, acidic environment, mechanical stress	Corrosion and cracking	Liner-concrete interaction, leakage of radioactive gases	Leakage testing as required by 10 CFR 50 Appendix J
Steel liner over base slab	Moisture, acidic environment, and stress	Corrosion	Leakage of radioactive material	Leakage testing as required by 10 CFR 50 Appendix J
Dome, wall, and base slab reinforcing steel	Aggressive environment	Corrosion	Loss of structural integrity	Visual
Concrete	Aggressive environment, and internal chemical reactions	Cracking and spalling	Loss of integrity, corrosion of reinforcing steel	Visual, rebound methods, core concrete samples if required

* Note: The degradation sites are listed from highest to lowest significance based on the consequences of the potential failure modes. For the sites with similar failure modes, the higher significance is given to the site that is more susceptible to failure.

Source: NUREG/CR-4731 Volume 1 (1987)

Table 5. Summary of Degradation Processes for PWR Reinforced Concrete Containments*

Degradation Site	Stressors	Degradation Mechanisms	Potential Failure Modes	In-service Inspection Methods
Dome and wall reinforcing steel	Aggressive environment	Corrosion	Loss of structural integrity	Visual
Base slab reinforcing steel	Aggressive environment	Corrosion	Loss of structural integrity	Visual
Steel liner over dome and wall	Moisture, acidic environment, mechanical stress	Corrosion	Liner-concrete rubbing, leakage of radioactive gases	Leakage testing as required by 10 CFR 50 Appendix J
Steel liner over base slab	Moisture, acidic environment, mechanical stress	Corrosion	Leakage of radioactive material	Leakage testing as required by 10 CFR 50 Appendix J
Dome and wall concrete	Aggressive environment, internal chemical reaction	Cracks and spalling	Loss of structural integrity, corrosion of reinforcing steel	Visual, rebound methods, core concrete samples if required
Base slab concrete	Aggressive environment, internal chemical reactions	Cracks and spalling	Loss of structural integrity, corrosion of reinforcing steel	Visual, rebound methods, core concrete samples if required

* Note: The degradation sites are listed from highest to lowest significance based on the consequences of the potential failure modes. For the sites with similar failure modes, the higher significance is given to the site that is more susceptible to failure.

Source: NUREG/CR-4731 Volume 1 (1987)

CHAPTER 6: TESTING METHODS TO EVALUATE CONCRETE STRUCTURE DEGRADATION

The development and evaluation of concrete testing and monitoring methods are the focus of Task 3 of the SAG program. The testing methods to detect aging-related degradation of concrete structures belong in one of two categories. These categories are (ORNL/NRC/LTR-90/29):

- direct methods, or destructive examinations, involve the visual inspection of the structure, and the removal of materials for testing and analysis; and

- indirect methods, or non-destructive examinations, involve the measurement of certain structural parameters based on which an estimate of the structural properties can be made using existing correlations. The structural properties include strength, elastic behavior, and the extent of degradation.

Presently, the detection of degradation of concrete structures is difficult since no single testing method will detect all the degradation factors and processes. Combinations of testing methods are required to assess concrete structure degradation.

The available nondestructive testing methods to detect concrete structure degradation are summarized in Table 6. Table 7 presents the available destructive testing methods. These testing methods are adopted from the latest in construction technology. Thus these testing methods are not exclusive to nuclear service concrete structures. Although these testing methods are considered to be "available", many have not been used in nuclear power plants for various reasons.

The recommendations of which testing methods are most effective in detecting specific aging stressors of concrete structures are presented in Table 8. These recommended methods are derived from the SAG researchers' evaluation of each method's technical capability based on its application in general construction practices. According to the researchers, there were few laboratory tests conducted to assess the in-service capability of these testing methods in a nuclear plant.

Table 6. Available Non-Destructive Testing Methods to Detect Concrete Structure Degradation.

Test Method	Principle	Main Application	Advantages	Limitations
Visual	Includes detailed visual examination of observed distress areas	To obtain general information of concrete distress	Provides valuable information as to causes of distress and extent of damage	Provides information on the condition of the exposed surface only. Additional testing method required
Ultrasound method	Using the difference in sounds to distinguish between delaminated and nondelaminated areas being tested	To locate delaminations and voids	Quick and inexpensive method. No extensive training required	Very subjective results based on the person performing the test
Electrical method	Uses the resistance and potential difference measurements of a structure to determine the moisture content and rate of corrosion	To determine the rate of corrosion	Quick and inexpensive. No extensive training required	Provides only a potential rate of corrosion and not the actual amount of corrosion present. It is also affected by moisture content
Impulse radar	Uses the principle of transmitted and reflected waveforms to locate objects in the structure	To locate voids, embedded reinforcement, delaminations, flaws in concrete, tanks and utilities embedded in the ground	Quick, portable and accurate in locating objects. No damage to concrete	Affected by moisture. Skills required in analyzing results
Infrared thermography	Uses the principle that all objects emit infrared rays. Infrared camera receives these rays and displays them in a color monitor	To locate voids	Quick and portable. No damage to concrete	Affected by moisture. Skills required in analyzing results. Temperature dependent

Table 6. Continued

Test Method	Principle	Main Application	Advantages	Limitations
Magnetic method	Generates a magnetic field and determines the intensity of the magnetic field	To determine depth and location of reinforcement	Quick and inexpensive method. No extensive training required	Temperature dependent. Ineffective in heavily reinforced area
Microscopic refraction	Estimates time traveled from the point of impact to the receiver	To locate cracks, voids, and assess quality of concrete	Quick and causes no damage to concrete	Influenced by the method of impact used
Modal analysis	Dynamic test based on vibrations induced to a structure	Determines vibrational response of a structure	Provides information about nature of structure when subjected to a dynamic load	Relatively slow and costly process
Nuclear method	Emits gamma rays and receives the amount returned	To determine the density of hardened concrete	Has the ability to determine moisture present as a function of depth	Expensive, heavy, slow and needs skilled operator. The density found is only for the top portion of the concrete
Radiography	Gamma radiation attenuate when passing through the concrete. Extent of attenuation is controlled by density and thickness of concrete	Locating internal cracks, voids and variations in density, and composition of concrete	Portable and relatively inexpensive compared to X-ray. Internal defects can be detected. No damage is done to concrete	Radiation intensity cannot be adjusted. Qualified technician is required to operate the instruments. Two opposite surfaces of the specimen must be accessible

Table 6. Continued

Test Method	Principle	Main Application	Advantages	Limitations
Rebound hammer	Measures surface hardness. Spring driven hammer strikes the surface of concrete and rebound distance is noted on scale	Estimation of compressive strength, uniformity and quality of concrete	Inexpensive. Large amount of data can be quickly obtained. Good for determining uniformity of concrete. No damage to concrete	Results are affected by the condition of the concrete surface. Does not give precise strength predictions. Results dependent on test location
Ultrasonic pulse velocity	Measures the transit time of an induced-pulsed compression wave propagating through the concrete	Estimation of the quality and uniformity of concrete. Locates voids, cracks, and estimates depth of reinforcement	Test can be performed very quickly. No damage to structure	Does not give precise estimation strength. Skills required in analyzing results. Moisture variation and presence of steel can affect results

Source: ORNL/NRC/LTR-90/29

Table 7. Available Destructive Testing Methods to Detect Concrete Structure Degradation.

Test Method	Principle	Main Application	Advantages	Limitations
Air permeability	Determines the rate of air recovery in a test hole after evacuation	Insitu assessment of the resistance of concrete to carbonation and to penetration of aggressive ions	Locates corrosion and voids in grouted structural members	Only a research model has been built
Break-off test	Measures the lateral force required at the top to break off the core at the bottom	Estimation of strength of concrete	Inexpensive and quick	Minor repairs needed
Chemical method	Determines chemical characteristics of the concrete through different tests	To identify chemical characteristics and determine chemical contents in concrete	Provides information that may assist in determining causes of distress	Destructive and slow
Cores	Physical measurement of actual condition using standard ASTM test methods	To supplement and/or verify nondestructive testing results	Very informative	Destructive and slow. Very local
Probe penetration (Windsor Probe test)	Measures the depth of penetration into the concrete. Surface and subsurface hardness can be measured	Estimation of concrete strength, uniformity and quality of concrete	Equipment is simple and durable. Good for determining quality of surface concrete	Damages small areas. Does not give precise prediction of strength. Results dependent upon firing mechanism
Pullout test	Measures the force required to pull out a steel rod with an enlarged head cast into the concrete	Estimates the compressive and tensile strength of concrete	Measures directly the inplace strength of concrete	Pullout devices must be inserted during construction or placed by drilling in hardened concrete. Correlation to compressive strength is questionable

Source: ORNL/NRC/LTR-90/29

Table 8. Recommended Testing Method to Assess Concrete Structure Degradation.*

Material	Degradation Factor	Symptom	Recommended Testing Methods: Identify Occurrence	Recommended Testing Methods: Assess Level of Damage
Concrete				
	Alkali-aggregate reactivity	Cracking, expansion	Core	Visual Pulse velocity Impact echo Pulse echo Modal analysis
	Sulfate attack	Cracking, expansion	Core Core/chemical	Visual Pulse velocity Impact echo Pulse echo Modal analysis
	Efflorescence and leaching	Surface deposits of efflorescence	Visual Core Sample & X-ray diffraction	Visual
	Bases, acids, salt crystallization	Disintegration and loss of paste	Core Chemical analysis	Visual
	Moisture changes	Cracking	Visual Core	Visual Infrared thermography Pulse velocity Impact echo Pulse echo Modal analysis
	Freeze/thaw	Scaling, spalling, cracking	Visual Core	Visual Pulse velocity Impact echo Pulse echo Modal analysis
	Thermal exposure and cycling	Spalling, cracking, loss of strength	Visual Core	Visual Pulse velocity Impact echo Pulse echo Modal analysis
	Irradiation	Spalling, cracking, loss of strength	Visual Core	Visual Pulse velocity Impact echo Pulse echo

* Note: The testing methods listed in this Table are listed in order of highest recommendation to lowest. These recommended methods are derived from the perceived view of each method's technical capability based on its application in general construction practices.

Table 8. Continued

Material	Degradation Factor	Symptom	Recommended Testing Methods	
			Identify Occurrence	Assess Level of Damage
Concrete				
	Abrasion, erosion, cavitation	Surface wear	Visual	Visual
	Fatigue, vibration	Microcracks, cracking, excessive deflection	Visual Core	Visual Pulse velocity Impact echo Pulse echo Modal analysis
Mild Steel Reinforce-ment				
	Creep	Cracking, excessive deflection	Visual	Visual Modal analysis
	Corrosion	Corrosion	Visual Core/visual Electrical method Chemical method Air permeability Nuclear	Visual Impact echo Pulse echo Radiography
	Corrosion	Cracking, delamination	Visual Core Audio method Impact echo Pulse echo	Visual Infrared thermography Audio method Pulse velocity Impact echo Pulse echo
Prestressing Steel				
	Corrosion, temperature, irradiation	Corrosion	Visual	Visual Mechanical testing Chemical analysis
	Corrosion, temperature, irradiation	Loss of force	Lift-off test	Lift-off test

Note: The testing methods listed in this Table are listed in order of highest recommendation to lowest. These recommended methods are derived from the perceived view of each method's technical capability based on its application in general construction practices.
Source: ORNL/NRC/LTR-90/29

CHAPTER 7: SUMMARY AND CONCLUSIONS

Concrete structures are significant safety-related components in any nuclear power plants. The structures provide support and protection for the many mechanical and electrical systems and components within the plant. The concrete structures also protect plant personnel and the public from high temperature and radiation.

The aging research of concrete structures are sponsored by the U.S. Nuclear Regulatory Commission. The research studies are to identify safety-significant concrete structures and the degradation causes that can affect the performance of the concrete structures. The conclusions of the aging studies are:

- The performance of concrete structures have been very reliable in both nuclear and general civil engineering services. Instances of concrete structural failures or distress are due to errors in construction or material flaws.

- Techniques, such as visual inspection, used to detect environmentally induced deterioration of concrete can provide sufficient qualitative assessments of the conditions. Complications arise when quantitative data are required to assess the concrete conditions. The complications are due to:

    - development of correlation curves;
    - embedment steel effects on measured quantities such as time of ultrasonic wave transmission; and
    - accessibility to certain structural locations to conduct the test.

- Proper techniques and materials used to repair damaged concrete structures will very likely restore the structural integrity of the structure completely.

- The durability of concrete structures are well recognized by the presence and continued service of many structures several hundred years after construction. However, well-documented data of concrete operational experience and longevity is lacking. Such data is needed for use as a basis for concrete life-extension evaluation. The lack of concrete operational experience database was addressed by the establishment of the Structural Aging (SAG) Program. SAG is currently developing a materials property database.

- Environmental stressors are the main causes of concrete structural degradation. These stressors typically result in localized cracks, loss of strength, and wear of all materials within the concrete structure.

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