Containment Liner Corrosion Operating Experience Summary
Technical Letter Report – Revision 1

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Executive Summary

As of June 2010, 104 nuclear power plants (NPPs) are in operation in the United States. Although several variations exist in containment building designs, 66 of the operating plants have containment buildings constructed with carbon steel liners in contact with concrete. This includes 55 pressurized-water reactors (PWRs) and 11 boiling-water reactors (BWRs). The focus of this work was to evaluate steel containment liner corrosion initiated at the liner/concrete interface. Available information on corrosion-related degradation of steel containment liners used with reinforced or post-tensioned concrete containment structures was reviewed and summarized. This information was compiled from a variety of sources including U.S. Nuclear Regulatory Commission (NRC) inspection reports, licensee inservice inspection reports, operational experience, and NRC informational notices.

Between 1999 and 2009, multiple instances of containment liner corrosion have been identified in U.S. plants where the corrosion initiated at the concrete/steel interface. All of the containments where significant corrosion was identified were constructed with reinforced concrete. In May 1999, at Brunswick Unit 2, three through-wall penetrations were identified in the steel liner. One of the through liner corrosion penetrations was caused by corrosion initiated the liner/concrete interface where a worker's glove was embedded in the concrete. In September 1999 at North Anna Unit 2, a through-wall penetration was discovered on a rusted section of a liner plate. Behind the hole was a small piece of wood embedded in the concrete. In March 2001 at D.C. Cook Unit 2, a small hole was discovered in the liner plate that was believed to be manmade; however, some external corrosion of the liner also occurred where a small wire brush handle was embedded in the concrete. Another through-wall penetration caused by an embedded piece of wood was found at Beaver Valley in June 2009. During the replacement of steam generators at Beaver Valley Unit 1 in March 2006, general and localized corrosion on the outer surface of the liner was discovered when the containment concrete was hydroblasted. Although the corrosion damage was not identified as being associated with embedded material in contact with the liner, it was noted that foreign material that may have been embedded in the concrete during construction could have been destroyed during the hydroblasting process.

In addition, significant corrosion of the personnel airlock sleeve was observed at Brunswick Unit 1 between 2004 and 2009. Although no through-wall corrosion was found, wall thinning, pitting corrosion, and bulging of the steel sleeve in the personnel airlock were discovered and the sleeve was replaced in 2010. Corrosion of the sleeve was thought to be caused by moisture trapped in felt intentionally wrapped around the outside of the sleeve to allow for thermal expansion.

The presence of foreign materials such as wood and worker's gloves or organic materials such as felt have clearly been shown to promote the corrosion the steel liner. These materials may retain moisture and promote crevice corrosion. Decomposition of organic materials also may produce locally acidic conditions that could lead to accelerated corrosion of the carbon steel containment liner. The role of other construction defects (such as voids in the concrete or bulges of the liner that lead to physical separation of the liner from the concrete) is not clear. International operating experience suggests that the presence of voids in the concrete adjacent to the liner may also promote corrosion of carbon steel containment liners.

In addition to the through-wall corrosion events, embedded wood from original construction was found in the concrete containment building at four other plants—Arkansas Nuclear One Unit 1, Point Beach Unit 1, D.C. Cook Unit 1, and North Anna Unit 1. At North Anna Unit 1, which also was constructed of reinforced concrete, one piece of embedded wood extended all the way though the concrete and was in contact with the containment liner; however, no measurable corrosion of the liner occurred.

Four different primary contractors built the eight NPPs where embedded material was observed. Five plants were constructed of reinforced concrete and three were subatmospheric plants. It is unclear whether such variables as differences in plant design and operation affect the susceptibility of containment liners to corrosion initiated at the liner/concrete interface.

All cases of through wall corrosion of the containment liner were observed many years after initial plant operation. While these incidents are associated with initial construction defects, plant aging may be significant in the future as more than one-half of the domestic NPPs have received license extensions to operate beyond 40 years. Degradation processes such as chloride ingress and carbonation of the concrete may contribute to degradation of the concrete containment and corrosion of the containment liner. In turn, these degradation processes may be accelerated as a result of concrete cracking and plant location.

This report is organized into six chapters. Chapter 1 describes the containment designs of the 66 plants of interest to this study along with a description of the NRC-required inspections. Chapter 2 includes the operating experience summarized from available sources. Chapter 3 includes a detailed analysis and discussion of the data. Chapter 4 contains discussions of aging and environmental degradation of concrete and steel. Chapter 5 summarizes the operating experience and analysis of the data to highlight the main points of this report. Chapter 6 lists the references.

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1.0 Introduction

Commercial production of electricity using nuclear power is accomplished by the fission of uranium-235 to generate heat. The heat generated is used to boil water, either directly as in a boiling-water reactor (BWR) or indirectly through a heat exchanger and secondary loop steam generator as in a pressurized-water reactor (PWR). The resulting steam drives a steam turbine. Conversion of mechanical energy to electrical energy is accomplished by connecting the shaft of the steam turbine to an electrical generator. In addition to generating heat, the fission of uranium-235 produces a number of radioactive decay products of various half lives. These fission products must be contained to avoid harmful exposures to power plant operators and security personnel and members of the public. In the United States, commercial nuclear power plants (NPPs) employ three barriers to radiation release. These barriers are the fuel cladding, the reactor containment vessel and coolant system boundary, and the containment building. Three barriers provide defense in depth against release of radioactive materials in the event of an accident.

1.1 Containment Descriptions

The 104 operating commercial NPPs in the United States comprise 35 BWRs and 69 PWRs. The construction of the reactor containment buildings varies considerably depending on plant type, containment design, and plant vintage (Hessheimer and Dameron, 2006; Naus, 1986; Naus, 2007). Table 1 summarizes the types of containment used by BWR plants. Of the 35 currently operating BWRs, 24 plants are constructed with a freestanding steel primary containment that is not in contact with the concrete (either reinforced steel or prestressed/post-tensioned) containment structure. Because the objective of this work is focused on corrosion of steel in contact with concrete, plants with freestanding steel primary containments are not included in this review. Currently, the 11 operating BWRs of interest include nine with a reinforced concrete primary containment with steel liner and two with a post-tensioned concrete primary containment with steel liner. These steel containment liners are typically 8 to 10 mm [$^{5}/_{16}$ to $^{3}/_{8}$ in] thick. Schematics of the various containment system designs are included in NUREG/CR-6906 (Hessheimer and Dameron, 2006) and NUREG/CR-6424 (Naus et al., 1996).

Table 2 summarizes the reactor containment building designs for PWRs. Of the 69 PWRs, 14 are constructed with a freestanding steel cylindrical containment building inside of a concrete enclosure or shield building. Because these plants do not have a concrete liner in contact with either a reinforced or a post-tensioned concrete structure, they are not of interest for the current study. Although the design and construction of the remaining 55 PWRs vary, all have a steel containment liner in contact with concrete and are of interest. These containment liners also are typically 8 to 10 mm [$^{5}/_{16}$ to $^{3}/_{8}$ in] thick.

It should be noted that the PWR subatmospheric plants identified in Table 2 have been converted to atmospheric pressure operation. These plants are described in Table 2 based on their original design and operation.

1.2 Containment Inspections and Operating Experience

ORNL/TM-2005/520 summarizes the evolution of containment inspection requirements (Naus et al., 2005). As a condition of licensing and operation of the primary reactor, containments are required to meet the containment leakage test requirements specified in Appendix J to 10 CFR 50. These tests provide preoperational and periodic verification of the leak-tight integrity for the primary reactor containment and systems and components that penetrate containment structure. This regulation includes three types of tests. Type A tests measure the primary reactor containment overall integrated leakage rate. Type B tests are intended to detect local leaks and to measure leakage across each pressure-containing or leakage-limiting boundary for primary reactor containment penetrations such as penetrations with seals and air lock door seals. Type C tests are intended to measure containment isolation valve leakage rates. Appendix J to 10 CFR Part 50 also requires a general inspection of the accessible interior and exterior surfaces of the containment structures and components.

In September 1995, the U.S. Nuclear Regulatory Commission (NRC) amended Appendix J (60 FR 49495) to provide a performance-based option for leakage-rate testing as an alternative to the then existing prescriptive requirements. The frequency of testing is reduced under the new performance-based requirements. If a licensee has shown an acceptable integrated leakage-rate test performance history, then Type A testing need only be performed one time every 10 years instead of three times every 10 years. If the plant chooses to reduce the frequency of Type A testing, the plant also must conduct a general inspection of accessible containment liner and concrete surfaces prior to each Type A test and during two other refueling outages before the next Type A test. Also under the performance-based requirements, the plant may reduce the frequency of both Type B tests and Type C tests based on the operating experience for each component. The performance-based requirement establishes controls to ensure continued performance during the extended testing interval.

Inspections conducted prior to Type A integrated leak tests have identified numerous instances of corrosion of the containment liners. Most observed cases of liner corrosion have been associated with degraded coatings, degraded moisture barrier seals, or accumulation of water as a result of leaks, seepage, and improperly functioning drains. Based on this operating experience, NRC amended its regulations (Title 10 of the Federal Code of Regulations, Part 50.55a, 10 CFR 50.55a) to incorporate by reference the 1992 Edition and Addenda of Subsections IWE and IWL of Section XI of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code to ensure that critical areas of the containments are routinely inspected to detect and to take corrective action for defects that could compromise the integrity of the containment structure. This amendment to 10 CFR 50.55a was included in a *Federal Register* Notice dated August 8, 1996 (61 FR 41303). NRC Information Notice 97-29 (NRC, 1997a) clarified the implementation requirements. Specifically, NRC Information Notice 97-29 stated that the amended rule became effective on September 9, 1996. Licensees were required to incorporate the new requirements into their inservice inspection (ISI) plans and to complete the first containment inspection within 5 years (i.e., no later than September 9, 2001).

Since the revision of 10 CFR 50.55a, three incidents of exterior corrosion and perforation of containment liners have occurred at U.S. NPPs. In each of these incidents, reported from 1999 to 2009, the presence of foreign material embedded in the concrete adjacent to the degraded area was reported. The 1999 North Anna Unit 2 and the 2009 Beaver Valley Unit 1 findings both involved wood used either as forms for the concrete or to maintain rebar position during construction. Foreign material in the concrete in contact with the containment liner also was found during the containment liner repairs at Brunswick Unit 2 in May 1999 and during the repair of a through-wall hole in the liner at D.C. Cook Unit 2 (which was attributed to man-made causes) in March 2001. Although the wood pieces and other foreign material should have been removed, they were inadvertently left in place and became embedded in the concrete. In all cases, the foreign material was believed to be in direct contact with the steel containment liner. After discovery of the through-wall penetration, a section of the liner was removed and the foreign material was extracted from the concrete. After the concrete repair, the liner plate was repaired, replaced, and tested.

1.3 Objective and Scope

The objective of this report is to summarize and analyze the available data on corrosion-related degradation of steel containment liners used with reinforced or prestressed post-tensioned concrete containment structures. It is of interest to evaluate the corrosion of the steel containment liner that has initiated from the exterior surface that is in contact with the concrete containment structure. Under normal circumstances, corrosion of the steel liner would be expected to proceed at a very slow rate owing to the stabilization of a passive oxide film on the steel by the alkaline concrete environment. Information on the degradation of the containment structure including the steel containment liner and concrete structure is compiled from a variety of sources including NRC inspection reports, licensee inservice inspection reports, operational experience, and NRC informational notices.

Table 1. Containment Descriptions for Domestic Boiling-Water Reactors

Containment Description	Containment Type	Construction	Plants
Freestanding Steel Primary Containment	Mark I	Steel Drywell and Wetwell	Cooper Browns Ferry 1, 2, and 3 Dresden 2 and 3 Duane Arnold Edwin Hatch 1 and 2 Fermi 2 Hope Creek 1 James Fitzpatrick Monticello Nine Mile Point 1 Oyster Creek Peach Bottom 2 and 3 Pilgrim 1 Quad Cities 1 and 2 Vermont Yankee
	Mark II	Steel Drywell and Wetwell	WNP-2
	Mark III	Reinforced Concrete Drywell, Steel Wetwell	Perry 1 River Bend 1
Reinforced Concrete Primary Containment with Steel Liner	Mark I	Reinforced Concrete Drywell and Wetwell	Brunswick 1 and 2
	Mark II	Reinforced Concrete Drywell and Wetwell	Limerick 1 and 2 Nine Mile Point 2 Susquehanna 1 and 2
	Mark III	Reinforced Concrete Drywell and Wetwell	Clinton 1 Grand Gulf 1
Post-Tensioned Concrete Primary Containment with Steel Liner	Mark II	Reinforced Concrete Drywell Post-Tensioned Wetwell	Lasalle 1 and 2

Table 2. Containment Descriptions for Domestic Pressurized-Water Reactors

Containment Description	Containment Construction	Plant
Large Dry Primary Containment with Freestanding Steel	Steel Cylinder with Concrete Enclosure Building	Davis-Besse Kewaunee Prairie Island 1 and 2 St Lucie 1 and 2 Waterford 3
Large Dry Primary Containment with Steel Liner	Reinforced Concrete with Steel Liner	Comanche Peak 1 and 2 Diablo Canyon 1 and 2 Indian Point 2 and 3 Salem 1 and 2 Shearon Harris 1
	Reinforced Concrete with Steel Liner and Secondary Containment	Seabrook 1
	1-D Vertical Post-Tensioned Concrete Cylinder with Steel Liner	Ginna H.B. Robinson
	Diagonal Post-Tensioned Concrete Cylinder with Steel Liner	Ft. Calhoun
	3-D Post-Tensioned Concrete Cylinder with Steel Liner	Arkansas Nuclear 1 and 2 Braidwood 1 and 2 Byron 1 and 2 Callaway Calvert Cliffs 1 and 2 Crystal River 3 Farley 1 and 2 Oconee 1, 2, and 3 Palisades Palo Verde 1, 2, and 3 Point Beach 1 and 2 San Onofre 2 and 3 South Texas 1 and 2 Virgil C. Summer Three Mile Island 1 Turkey Point 3 and 4 Vogtle 1 and 2 Wolf Creek
	3-D Post-Tensioned Concrete Cylinder with Steel Liner and Secondary Containment	Millstone 2
Subatmospheric Primary Containment	Reinforced Concrete Cylinder with Steel Liner	Beaver Valley 1 and 2 Millstone 3 North Anna 1 and 2 Surry 1 and 2
Ice Condenser Primary Containment with Steel Liner	Reinforced Concrete Cylinder with Steel Liner	D.C. Cook 1 and 2
Ice Condenser Primary Containment with Freestanding Steel	Reinforced Concrete Shield Building Surrounding Freestanding Steel Cylinder	Catawba 1 and 2 McGuire 1 and 2 Sequoyah 1 and 2 Watts Bar 1

2. Operating Experience

This section contains a summary of previous experience where concrete degradation and containment corrosion have been reported. Some of these events do not involve a containment liner in contact with concrete, but this information is included for completeness. Information to compile this summary was collected from multiple sources including previous U.S. Nuclear Regulatory Commission (NRC)-supported research, license renewal inspections, operating experience, licensee event reports, licensee in service inspection reports, steam generator replacement operations, and reactor head replacement operations.

2.1 External Corrosion of the Containment Liner

Between 1999 and 2009, three incidents of containment liner perforation were reported in the United States. In all three cases, corrosion that initiated at the continent liner/concrete interface was discovered by visual examination of the liner. Details of these events are compiled from licensee reports, NRC inspection reports, and NRC information notices.

In May 1999 at Brunswick Unit 2, three areas were identified where corrosion had penetrated the drywell liner. The licensee reported that the root cause for the through-wall defects identified at the 5.5 m [18 ft] elevation and the 21.3 m [70 ft] elevation was pitting corrosion initiated on the coated surface of the liner plate due to a break in the protective coating film. The root cause for the through-wall defects identified at the 17 m [56 ft] elevation was general corrosion from the concrete side of the liner plate. This condition was caused by the presence of a void in the concrete containing debris identified as a cloth work glove which wicked moisture to the back of the liner plate and provided a collection point for oxygen. The steel corroded from the back side in the presence of moisture and oxygen until it eventually penetrated the liner plate (Carolina Power and Light, 2002). . The licensee repaired the damaged areas of the liner plate.

In September 1999, North Anna Unit 2 discovered a through-wall hole in the containment liner at the 75 m [246 ft] elevation of the containment building during investigation of a rusted spot on the liner. Removal of the liner plate in the area of the through-wall hole revealed a piece of wood that was about 10 cm x 10 cm x 1.8 m [4 in x 4 in x 6 ft]. The wood was apparently left in the concrete during original construction and had been in contact with the liner and present since the initial concrete placement. The wood was removed, the void was grouted, and the liner plate was replaced with nominal wall thickness plate. An Integrated Leak Rate Test (Type A) was performed following repairs. The repaired area was to be reexamined by ultrasonic (UT) thickness in future outages in accordance with ASME XI Section IWE.

In June 2009, Beaver Valley Unit 1 was conducting an ASME XI IWE general visual examination of the reactor containment building during a refueling outage. A suspect area about 3 inches in diameter with blistered paint (Figure 1) was identified on the steel liner at the 227.4 m [746 ft] elevation. After paint removal and cleaning, rectangular-shaped corrosion penetration measuring about 2.5 x 1 cm [1 x $^{3}/_{8}$ in] was observed (Figure 2). Thickness measurements conducted using UT indicated a local area around the penetration where thinning of the liner had occurred (Figure 3). A section of the liner plate was removed and a piece of wood, which was about 5 x 10 x 15 cm [2 x 4 x 6 in], was discovered to be embedded in the concrete (Figure 4). The wood was subsequently removed and the concrete was repaired with grout. The liner was repaired by installing a replacement section.

In March 2001, D.C. Cook Unit 2 discovered a through-wall hole in the containment liner plate at about elevation 183.5 m [602 ft] in the annulus area at azimuth 112 degrees. The hole was circular with a diameter of about 0.47 cm [$^{3}/_{16}$ in] on the exterior surface and 1.9 cm [¾ in] on the interior surface. The licensee reported that the hole appeared to be manmade. After the damaged liner plate section was cut out, a piece of wood was found embedded in the concrete. The piece of wood was determined to be a wire brush with a wooden handle. Some minor corrosion was noted on the concrete side of the liner plate in the area of the embedded wire brush. The licensee replaced an area about 77 cm^2 [12 in^2] of the liner plate and performed a local leak rate test.

Figure 1. Paint Blister with Corrosion Products Identified at Beaver Valley Unit 1 in 2009 (FirstEnergy, 2009).

Figure 2. Perforation in the Containment Liner of Beaver Valley Unit 1 (2009) Observed After the Paint Blister and Corrosion Products Were Removed (FirstEnergy, 2009).

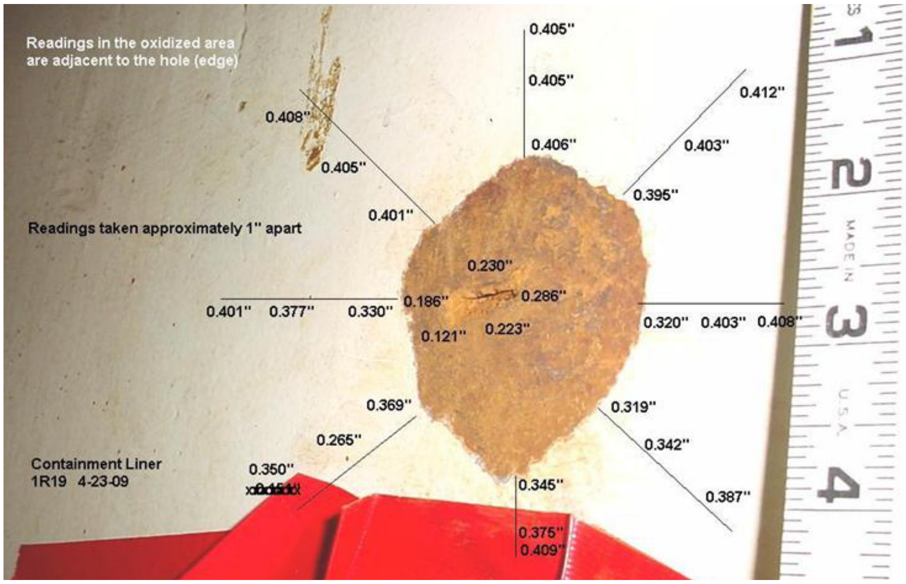

Figure 3. Perforation in the Containment Liner of Beaver Valley Unit 1 (2009) Showing the Results of Ultrasonic Thickness Measurements (FirstEnergy, 2009).

Figure 4. Wood Embedded in the Concrete Discovered at Beaver Valley Unit 1 in 2009 After a Section of the Containment Liner with Through-Liner Corrosion Was Removed (FirstEnergy, 2009).

2.2 Temporary Openings in Containment for PWR Component Replacement

Because of the stress corrosion cracking susceptibility of Alloy 600 in pressurized-water reactor (PWR) primary water environments, many operating PWR plants have replaced steam generators and reactor pressure vessel heads (IAEA, 2008). As of December 2009, a total of 55 PWRs have replaced steam generators and 30 PWRs have replaced reactor pressure vessel heads. Because of the constraints that exist inside the containment building, the replacements of these components have often been accomplished by making a temporary opening in the containment building. The location of the temporary opening is typically above the interior biologic shield wall to allow the components to be removed with minimal interference. The temporary openings are usually made in the vertical portions of the containment building; however, temporary openings in the dome of the containment buildings have been used at some plants.

Of the plants of interest that are constructed with either reinforced or post-tensioned concrete in contact with a steel containment liner, 21 PWRs have replaced steam generators and/or reactor pressure vessel heads using a temporary opening in containment. Openings vary according to needs but are often 6.1 x 6.1 m [20 x 20 feet] and sometimes slightly larger. The method of making the temporary openings also has varied. The first temporary opening in containment, at Palisades, was constructed using a combination of core drilling, sawing and pneumatic hammering. More recently, high-pressure water has been used to remove the concrete in a process called hydroblasting. This process leaves the reinforcement and the liner plate free of concrete.

Table 3 shows a summary of the 21 PWRs that have replaced steam generators and/or reactor pressure vessel heads using a temporary opening in containment. During the replacement process, the main activity is the replacement of the primary system components and the condition of the liner plate is not always well described. Information on the condition of the liner plate was collected by reviewing NRC on-site inspector reports and licensee documents including inservice inspection reports. It should be noted that most of these reports do not include an assessment of the corrosion or metal loss of the containment liner.

In March 2006, Beaver Valley Unit 1 was found to have three areas of corrosion in the containment liner plate during the creation of a temporary construction opening in the containment structure for the replacement of the steam generators and reactor vessel head. Three areas of corrosion were identified with local measured metal loss (corrosion depth) between 1.1 and 5.8 mm [45 to 227 mils] (Figures 5 to 8). The sections of the liner removed for analysis were replaced with new plate material. The root cause of the corrosion was indeterminate; however, the probable cause reported was that the corrosion of the liner occurred during the construction phase because of exposure to oxygen and water that has since abated. Several pieces of wood were found during a subsequent inspection of the concrete debris pile; however, no clear evidence is available to confirm that the corrosion damage to the liner was a result of contact with embedded foreign material. Foreign material that may have been in contact with the liner could have been destroyed by the hydroblasting operation. The affected liner plate sections were replaced.

In 12 of the 21 reactor component replacements that required a temporary opening in containment, information included in the NRC onsite inspector’s reports clearly indicated that the inspectors witnessed activity that involved the liner plate. Inspection of the liner plate welds during containment restoration was frequently described. In all cases, no indication of containment liner corrosion was mentioned. Although an assessment of containment liner corrosion is not specifically included, reports of damage induced by the excavation process suggest that if corrosion damage were present, it would likely have been identified and described. Damage was reported at Braidwood 1 in 1998 as a result of the concrete chipping and cutting operation that was repaired by welding. Damage also was reported at Turkey Point 4 in 2005 as a result of the concrete hydroblasting operation that required replacing five sections of the liner plate.

Figure 5. Beaver Valley Unit 1 Containment Liner with Three Areas of Corrosion Identified (FirstEnergy, 2006).

Figure 6. Closeup of Corrosion Area 1 Observed at Beaver Valley Unit 1 in 2006 (FirstEnergy, 2006).

Figure 7. Closeup of Corrosion Area 2 Observed at Beaver Valley Unit 1 in 2006 (FirstEnergy, 2006).

Figure 8. Closeup of Corrosion Area 3 Observed at Beaver Valley Unit 1 in 2006 (FirstEnergy, 2006).

In 5 of the 21 reactor component replacements that required a temporary opening in containment, no specific mention of corrosion of the containment liner or reinforcement is provided in the inspection report; however, the extent of examination of the liner is not clear from the information contained in the NRC inspector's reports. In these reports, there is no description consistent with NRC inspectors witnessing containment liner cutting, removal, restoration, or weld inspection activities. In the case of the Palisades steam generator replacement in 1991, core drilling and cutting were used to make the temporary opening in containment. It is not clear how well the containment liner could be examined after this operation. There is no mention of the containment liner condition during the component replacement at Comanche Peak 1 in April 2007, which occurred with full knowledge of the corrosion damage observed at Beaver Valley Unit 1 in 2006.

In the component replacement at Ft. Calhoun in 2006, no corrosion of the containment liner was reported and the NRC inspector's report included documented observation of liner plate welding and concrete placement operations. The NRC inspector's report does indicate that voids were identified during concrete demolition. No foreign material was identified during the demolition process.

The three most recent cases that were initiated in the fall 2009 refueling outages included Three Mile Island Unit 2, San Onofre Unit 2 and Crystal River Unit 3. The NRC inspector's reports for these plants indicated that no evidence of corrosion of the liner or the reinforcement was observed and no evidence of voids or foreign material was found during concrete removal.

Table 3. Summary of Liner Observations During PWR Component Replacement Operations with Temporary Openings in Containments

Reactor	Year	SG/RPVH	Containment	Liner Damage	Liner corrosion	Additional Information
Palisades	1991	SG	Large Dry, Post-Tensioned	No	No	Extent of NRC Inspector examination not reported. 26 x 28 foot temporary opening in containment using sawing and core drilling
Ginna	1996	SG	Large Dry, Post-Tensioned	No	No	Temporary opening in the containment dome. NRC inspector witnessed dome restoration.
Byron 1	1998	SG	Large Dry, Post-Tensioned	No	No	NRC inspector witnessed containment restoration including SMAW of containment liner.
Braidwood 1	1998	SG	Large Dry, Post-Tensioned	Yes	No	Temporary opening in containment by concrete chipping and cutting. Damage to the liner plate as a result of chipping was repaired by welding.
ANO 2	2000	SG	Large Dry, Post-Tensioned	No	No	NRC inspectors witnessed torch cutting of liner plate.
North Anna 2	2003	RPVH	Sub Atm, Reinforced	No	No	NRC inspectors observed fit-up, tack welding of the liner, cadweld splicing of the rebar, and installation of the reinforced concrete.
North Anna 1	2003	RPVH	Sub Atm, Reinforced	No	No	NRC inspectors visually inspected the final weld surfaces, observed in-process welding and NDE activities and cadweld splicing of the rebar.
Surry 2	2003	RPVH	Sub Atm, Reinforced	No	No	Extent of NRC inspector observation uncertain.
Surry 1	2003	RPVH	Sub Atm, Reinforced	No	No	NRC inspectors observed in-process welding and inspection, liner weld surfaces, rebar restoration, and concrete placement.
Oconee 1	2004	SG/RPVH	Large Dry, Post-Tensioned	No	No	Extent of NRC inspector observation uncertain.
Oconee 2	2004	SG/RPVH	Large Dry, Post-Tensioned	No	No	NRC inspectors witnessed welding and inspection of liner plate.
Oconee 3	2004	SG/RPVH	Large Dry, Post-Tensioned	No	No	Extent of NRC inspector observation uncertain.
Turkey Point 3	2005	RPVH	Large Dry, Post-Tensioned	No	No	NRC inspectors observed liner plate removal and containment restoration including welding and concrete placement.
Turkey Point 4	2005	RPVH	Large Dry, Post-Tensioned	Yes	No	NRC inspectors reviewed/observed liner plate repair of 5 sections damaged during concrete excavation using hydroblasting.
ANO 1	2005	SG/RPVH	Large Dry, Post-Tensioned	No	No	NRC inspectors reviewed or observed the cutting of the containment wall, rebar mat, and the liner plate and observed containment restoration.
Beaver Valley 1	2006	SG	Sub Atm, Reinforced	Yes	Yes	Corrosion of containment liner observed in three locations. No foreign objects identified.
Ft Calhoun	2006	SG/RPVH	Large Dry, Post-Tensioned	No	No	Voids in concrete discovered during excavation. NRC inspectors observed liner plate welding and concrete pouring.
Comanche Peak 1	2007	SG/RPVH	Large Dry, Reinforced	No	No	Extent of NRC inspector observation uncertain.
Crystal River 3	2009	SG	Large Dry, Post-Tensioned	No	No	Concrete delamination. No report of containment liner corrosion
San Onofre 2	2009	SG	Large Dry, Post-Tensioned	No	No	NRC inspector observed containment restoration activities including for the liner plate, reinforcement, and concrete
TMI- 1	2009	SG	Large Dry, Post-Tensioned	No	No	NRC inspector reported structurally sound concrete and no evidence of liner corrosion

2.3 Recent Inservice Inspection Reports

Previous assessments such as NUREG/CR-4652 (Naus,1986) reviewed information contained in documents such as licensee event reports; therefore, the review of inservice inspection reports conducted in preparation of this report was limited to the period from 1999 to February 2010. Because licensees were required to incorporate the requirements contained in subsections IWE and IWL of Section XI of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code in containment inspections by September 9, 2001, the increased requirements for inservice inspection of containment structures have been in place for 8 years (NRC, 1997a). During the course of the review, attention was primarily focused on descriptions of observed containment liner corrosion, factors the licensee reported that contributed to liner corrosion, and corrosion mitigation and repair efforts. In addition, the licensees' assessment of the condition of the concrete containment structure was also reviewed. Of particular interest were licensee reports of concrete cracking and degradation, water ingress, embedded foreign material, rebar corrosion, and concrete repair. Efforts were focused on the 11 boiling-water reactor (BWR) and the 55 PWR plants with steel containment liners in contact with a concrete containment structure.

2.3.1 BWR Containment Liner and Concrete Assessments

Eleven BWR plants have the steel liner plate in contact with the concrete shield building. Table 4 summarizes the information contained within inservice inspection reports for these 11 BWR plants. In two cases, the inservice inspection report contained little information, but later resident inspector reports provided more detail that is included here. Moisture barrier degradation leading to degradation of the liner coating and liner was observed in two plants. Seven isolated instances of interior liner corrosion were reported. Corrosion of the exterior liner leading to bulging of the interior surface was reported at two plants. Of these 11 BWR plants, only one plant reported embedded foreign material.

Internal liner corrosion in the containment shell:

- In 1998, during the 11th refueling outage at Brunswick Unit 1, the vent line plate adjacent to the top weld channel showed damage although the type of damage was not specified. The damage was classified as "minor" (as per IWE 5222) and the base metal was repaired. A subsequent pressure leak test was deferred until the next scheduled leakage test.

- At Grand Gulf Unit 1, the licensee reported a weld overlay repair to the containment liner. The repair was performed in March 2004. No further information is given.

- Three instances of liner corrosion were reported at Limerick Unit 1.

    - In 2000 during the eighth refueling outage, the licensee reported recordable indications in the containment vessel internals at 53.9 m [177 ft] elevation. The indication was determined to be insignificant.
    - In 2004 during the 10th refueling outage, several indications were recorded in the submerged space of the suppression pool liner. All indications were determined to be acceptable as per IWE-3000 and NE-101 specifications. The thickness of the liner plate was measured at four locations, and low corrosion rates of <0.03 to 0.04 mm/yr [<1 to 1.6 mpy] were recorded.
    - In 2006 during the 11th refueling outage, the licensee reported pitting on the Quadrant 2 1B panel within the suppression pool liner. Measured pit depths ranged from 2 to 3.1 mm [80-122 mils]. Further pitting was prevented by the application of a coating.

- During the seventh refueling outage at Nine Mile Point Unit 2, the licensee reported cracked and blistered paint at the steel-to-concrete interface on the drywell floor. The areas of most extensive corrosion were tested for thickness ultrasonically. All areas of the liner plate showed negligible thickness loss. The affected liner plates were cleaned and recommended for recoating.

External Liner Corrosion in the airlock sleeve penetration leading to bulging:

- In 2004 during the 14th refueling outage at Brunswick Unit 1, the licensee reported blistering of the coating and bulging of the steel liner in the 1-X-2 Personnel Airlock Penetration. Removal of the blistered coating revealed pitting corrosion. UT examination indicated that the plate thickness in the pitting area was below expected wall thickness and that the wastage occurred on the exterior of the liner plate. Areas of the plate below design thickness were repaired by overlay welding. The licensee attributed the wastage to a material defect during initial construction. No further degradation was observed until the 16th refueling outage in 2008. During the 16th refueling outage, the licensee reported 2 additional bulged areas in the 1-X-2 airlock. Additional UT examination revealed that the liner plate was below minimum wall thickness although the total area of low wall thickness was less than 3 percent. During this outage, the penetration sleeve was evaluated to be degraded but operable. The licensee has submitted plans to install a new concentric liner within the degraded 1-X-2 penetration sleeve that would serve as the new pressure boundary. The installation was scheduled for February 2010.

  In the inservice inspection report, the licensee attributed the corrosion on the external surface of the liner plate to a flaw during initial construction. The penetration sleeve was lined with two layers of felt and a layer of 1.5 mm [60 mils] of ethylene propylene film to allow for thermal expansion. From analysis of boat samples of the liner including corrosion products and felt wrapping, the licensee concluded that pitting corrosion was caused by wetting of the felt wrapping from leakage of pore water during the initial curing of the concrete surrounding the penetration sleeve. Wall thinning occurred on the exterior of the lining while buildup of high-volume corrosion products caused bulging across the wall thickness to the interior of the liner. It was surmised that since the corrosion products and felt from the boat samples were dry, the corrosion process was no longer active.

- Because degradation of the penetration liner had been observed in the 1-X-2 penetration liner at Brunswick Unit 1, the licensee performed an examination of the corresponding 2-X-2 penetration liner in Brunswick Unit 2 during the 16th refueling outage in 2005. The licensee reported bulging of the penetration liner similar to what had been observed in the Brunswick Unit 1 case. UT examination indicated that areas of the 2-X-2 liner were below minimum thickness. The corrosion and bulging on the 2-X-2 penetration liner was attributed to same process as described for Brunswick Unit 1. The areas were repaired by overlay welding in 2005. In 2007 and 2009, the licensee reported localized pitting and local wall thinning in the 2-X-2 liner. Wall thinning and pitting were repaired by overlay welding.

Table 4. Inservice Inspection Report Summary for BWR Plants with Steel Containment Liners

Plant	ISI IWE and/or IWL Reports	Liner Coating Degraded	Moisture Barrier Degraded	Liner Corrosion Interior	Liner Corrosion Exterior	Embedded Foreign Material	Bulging of Liner	Concrete Cracks or Damage	Concrete Voids	Exposed Rebar	Reference to Prior Assessments of the Containment Building
Brunswick 1	8	1	1	1	1	-	-	-	-	-	Naus, 1986; Ashar and Bagchi, 1995; Naus et al, 2005; Ashar, 1997, ML031050365
Brunswick 2	9	-	1	1	1	1	-	-	-	-	Naus, 1986; Ashar and Bagchi, 1995; Naus et al, 2005; NRC, 2004
Clinton 1	4	-	-	-	-	-	-	-	-	-	Naus, 1986
Grand Gulf 1	4	-	-	1	-	-	-	-	-	-	Naus, 1986
Lasalle 1	4	-	-	-	-	-	-	-	-	-	Naus, 1986
Lasalle 2	4	-	-	-	-	-	-	-	-	-	Naus, 1986
Limerick 1	5	1	-	3	-	-	-	-	-	-	Naus, 1986
Limerick 2	4	-	-	-	-	-	-	-	-	-	N/A
Nine Mile Point 2	2	1	-	1	-	-	-	-	-	-	N/A
Susquehanna 1	5	-	-	-	-	-	-	-	-	-	Naus, 1986
Susquehanna 2	3	-	-	-	-	-	-	-	-	-	Naus, 1986

2.3.2 PWR Containment Liner and Concrete Assessments

The PWR plants constructed with a steel liner in contact with a concrete structure can be subdivided into four groups based on containment building design. The majority of the plants (a total of 36) are post-tensioned concrete structures with a large dry containment. Plants with reinforced concrete construction consist of 10 reactors with a large dry containment, 7 with subatmospheric pressure containment, and 2 with an ice condenser containment structure. For each plant of interest, the licensee inservice inspection reports were collected and reviewed. Not all inspection reports were available and for some plants, no inspection reports were located in NRC's Agencywide Documents Access and Management System. The variable availability of the inservice inspection reports is documented in this inservice inspection summary along with findings significant to containment liner corrosion.

2.3.2.1 PWR Post-Tensioned Concrete Containment Buildings

Table 5 shows a summary of the information contained in the inservice inspection reports for each of the 36 plants. Concrete cracking, spalling, or damage was reported in 16 of the 36 plants with post-tensioned concrete containments. Although the plants are post-tensioned, the structure also has rebar that is usually positioned between the post-tensioned tendon conduits and the exterior concrete surface. Exposed rebar was reported at six plants. Only one plant reported the presence of concrete voids discovered in the inspections. Bulging of the containment liner was reported at one plant. Embedded foreign material was found at two plants. No containment liner corrosion that originated from the external surface was reported. Containment liner corrosion that originated on the internal surface was reported at 16 plants. In all cases, containment liner corrosion was associated with coating failures or moisture barrier degradation.

Although no incidents of corrosion originating from the external surface were reported in the 36 post-tensioned concrete plants that had a containment liner in contact with the concrete, several plants reported conditions that may potentially be significant. These include reports of embedded foreign material in the concrete, containment liner bulging, voids in the concrete, and exposed rebar.

Embedded Foreign Material in the Concrete

- At Arkansas Nuclear One Unit 1, the licensee reported that a triangular wooden wedge 1.3 x 5 x 6.3 cm [5 x 2 x 2 ½ in] was found in the containment structure at azimuth 291 deg, 37 minutes, elevation 109.7 m [360 ft] and this wedge was not removed when the original construction opening was closed. The wooded wedge was probably used to separate the form and the outer layer of rebar so that adequate concrete cover could be provided. Although the licensee determined that the wood did not compromise the structural or shielding performance requirements of the containment building, the wood was removed, the concrete was roughened and prepared, and the void was grouted flush to the surface to prevent water intrusion and potential long-term degradation. The repair was considered to be a cosmetic repair and not a structural repair of the containment building structure because the outer layer of reinforcing steel was not exposed and no other damaged material was observed in the vicinity.

- At Point Beach Unit 1, a piece of wood was found near a spare electrical penetration. The licensee reported that the wood was dry with no evidence of degradation and indicated that no concern existed for structural effects on the concrete. Based on previous industry experience with embedded wood, the licensee conducted a visual examination under the IWE inspection program and indicated that volumetric examination would be conducted on the spare electrical penetration in the area of the embedded wood. Both Point Beach Unit 1 and 2 reported exposed rebar that was determined to be a result of construction defects rather than degradation. The licensee indicated that a facade building encloses the concrete containment to protect the containment from environmental conditions. The exposed rebar was reported to have light surface corrosion that would not affect the structural strength of the containment.

Voids in the Concrete

- Oconee Unit 1 reported a lack of concrete consolidation beneath the bearing plate and a lack of bonding between the two adjacent pours at the construction joint. A void in the concrete may be connected to the crack at the construction joint. The licensee indicated that corrective actions would be taken.

Bulging of the Containment Liner

- Braidwood Unit 2 reported localized bulges and buckling at multiple locations on the containment liner. The licensee reported that no indication existed of any degradation to the liner other than it is bulged or buckled, no plate cracking or corrosion was identified, and the base metal appeared to be sound.

Exposed Rebar

- At Arkansas Nuclear One Unit 1, exposed rebar was found below the personnel airlock at elevation 118 m [387 ft 6 in]. The cause of the condition was not concrete degradation but was determined to be inattention to detail during original construction. The licensee removed the rust scale and applied an epoxy coating to protect the rebar from corrosion.

- Three Mile Island Unit 1 reported concrete cracking spalls and exposed rebar. The condition of the containment was evaluated and was determined to be acceptable as is. Reinspection of the area would be conducted to determine if active degradation was occurring.

- Turkey Point Unit 4 reported areas of exposed rebar and concrete spalling. Repairs by grouting were conducted on areas with exposed rebar and spalled areas deeper than about 6 mm [¼ in], except for one inaccessible location which was accepted as is based on an engineering disposition.

- Wolf Creek reported exposed rebar and missing concrete at the construction joint at elevation 623 m [2044 ft], below the bottom of the equipment hatch. The licensee indicated that the rebar appeared to be part of the shear ties/stirrups provided in the concrete wall. No cracks were observed in the area around the exposed rebar. No concrete repairs were reported.

2.3.2.2 PWR Reinforced Concrete Containment Buildings

The reinforced concrete containment buildings listed in Table 6 include the large dry, subatmospheric pressure and ice condenser containment designs. Cracks and concrete damage were reported in only 2 of the 19 plants. No plants reported the presence of voids in the concrete, and only one of the plants reported exposed rebar. Bulging of the liner was reported at one plant. Embedded foreign material in the concrete was reported at four plants. External corrosion of the containment liner plate was observed in four separate occasions at three plants (two separate occurrences at Beaver Valley Unit 1). Embedded foreign material in contact with the liner was identified in three of the cases of external corrosion and was determined to be a key contributing factor to penetration of the liner in two cases. Containment liner corrosion that originated on the internal surface was reported at seven plants. In all cases, the containment liner corrosion on the interior surface was associated with coating failures or moisture barrier degradation. Details of significant incidents are provided below.

Table 5. Inservice Inspection Report Summary for Post-Tensioned PWR Plants with Steel Containment Liners

Plant	ISI IWE and/or IWL Reports	Liner Coating Degraded	Moisture Barrier Degraded	Liner Corrosion Interior	Liner Corrosion Exterior	Embedded Foreign Material	Bulging of Liner	Concrete Cracks or Damage	Concrete Voids	Exposed Rebar	Reference to Prior Assessments of the Containment Building
ANO-1	4	-	-	-	-	1	-	2	-	1	N/A
ANO-2	1	-	-	-	-	-	-	1	-	-	N/A
Braidwood 1	5	-	2	2	-	-	-	1	-	-	Naus et al., 2005
Braidwood 2	6	2	4	4	-	-	1	2	-	-	N/A
Byron1	1	-	-	-	-	-	-	-	-	-	Naus, 1986
Byron 2	0	-	-	-	-	-	-	-	-	-	N/A
Callaway	2	-	-	-	-	-	-	-	-	-	Naus, 1986
Calvert Cliffs 1	1	-	1	1	-	-	-	-	-	-	Naus, 1986; NRC, 1999
Calvert Cliffs 2	1	1	1	1	-	-	-	-	-	-	Naus, 1986; NRC, 1999
Crystal River 3	5	-	-	-	-	-	-	-	-	-	Naus, 1986
Ft. Calhoun	4	-	1	-	-	-	-	2	-	-	N/A
Farley 1	1	-	-	-	-	-	-	1	-	-	Naus, 1986
Farley 2	1	-	-	-	-	-	-	-	-	-	Naus, 1986
Ginna	5	4	1	2	-	-	-	-	-	-	Naus, 1986
Millstone 2	4	-	-	-	-	-	-	-	-	-	N/A
Oconee 1	3	-	-	-	-	-	-	2	1	-	NRC, 1999
Oconee 2	3	-	1	1	-	-	-	1	-	-	Naus, 1986
Oconee 3	2	-	1	-	-	-	-	1	-	-	Naus, 1986
Palisades	3	2	1	2	-	-	-	-	-	-	Naus, 1986
Palo Verde 1	0	-	-	-	-	-	-	-	-	-	N/A
Palo Verde 2	0	-	-	-	-	-	-	-	-	-	Naus, 1986
Palo Verde 3	0	-	-	-	-	-	-	-	-	-	Naus, 1986
Point Beach 1	6	1	-	1	-	1	-	2	-	2	Ashar and Bagchi, 1995
Point Beach 2	6	2	-	2	-	-	-	2	-	2	Ashar and Bagchi, 1995
Robinson	3	3	2	3	-	-	-	-	-	-	Braverman et al., 2000
San Onofre 2	1	-	-	-	-	-	-	-	-	-	N/A
San Onofre 3	0	-	-	-	-	-	-	-	-	-	Naus, 1986
South TX 1	3	-	-	-	-	-	-	-	-	-	Naus, 1986
South TX 2	3	-	-	-	-	-	-	-	-	-	Naus, 1986
VC Summer	0	-	-	-	-	-	-	-	-	-	Naus, 1986
Three mile Is-1	4	1	3	1	-	-	-	2	-	2	Naus, 1986
Turkey Point 3	4	2	3	2	-	-	-	1	-	-	Naus, 1986; Ashar and Bagchi, 1995
Turkey Point 4	5	3	1	1	-	-	-	-	-	1	Naus, 1986; Ashar and Bagchi, 1995
Vogtle 1	5	2	1	3	-	-	-	1	-	-	N/A
Vogtle 2	4	1	1	1	-	-	-	2	-	-	N/A
Wolfe Creek	3	1	-	1	-	-	-	1	-	1	Naus, 1986

Table 6. Inservice Inspection Report Summary for Reinforced PWR Plants with Steel Containment Liners

Plant	ISI IWE and/or IWL Reports	Liner Coating Degraded	Moisture Barrier Degraded	Liner Corrosion Interior	Liner Corrosion Exterior	Embedded Foreign Material	Bulging of Liner	Concrete Cracks or Damage	Concrete Voids	Exposed Rebar	Reference to Prior Assessments of the Containment Building
D.C. Cook 1	6	3	1	4	-	1	-	-	-	-	Naus, 1986
D.C. Cook 2	7	4	-	2	1	1	-	-	-	-	Naus, 1986
Beaver Valley 1	4	-	1	-	2	1	-	-	-	-	Naus, 1986
Beaver Valley 2	4	1	-	1	-	-	-	-	-	-	N/A
Millstone 3	1	-	-	-	-	-	-	-	-	-	N/A
North Anna 1	2	-	-	-	-	1	-	-	-	-	N/A
North Anna 2	2	-	-	-	1	1	-	-	-	-	Naus, 1986
Surry 1	1	-	-	-	-	-	-	-	-	-	Naus, 1986
Surry 2	1	-	-	-	-	-	-	-	-	-	N/A
Comanche Peak 1	2	-	-	-	-	-	-	-	-	-	Naus, 1986
Comanche Peak 2	1	-	-	-	-	-	-	-	-	-	Naus, 1986
Diablo Canyon 1	5	-	-	-	-	-	-	-	-	-	Ashar and Bagchi, 1995
Diablo Canyon 2	6	1	-	-	-	-	-	-	-	-	Ashar and Bagchi, 1995
Indian Point 2	2	1	1	1	-	-	-	1	-	1	Naus, 1986
Indian Point 3	2	1	1	-	-	-	-	-	-	-	N/A
Salem 1	3	1	1	1	-	-	-	-	-	-	N/A
Salem 2	5	1	-	2	-	-	-	1	-	-	Naus, 1986
Seabrook	5	-	-	-	-	-	-	-	-	-	Naus, 1986
Shearon Harris 1	4	2	-	1	-	-	1	-	-	-	N/A

Embedded Foreign Material

- At North Anna Unit 1 in 2001, six pieces of wood were discovered embedded in the concrete dome. Two of the pieces were very small and easily removed with no concrete repairs necessary. The third piece was removed leaving a hole that was about 3.8 x 3.8 x 1 cm [$1^1/_2$ x $1^1/_2$ x $^3/_4$ in] deep. No concrete repair was required. The fourth piece was removed and resulted in a hole in the concrete surface that was about 8.8 x 5.7 x 2 cm [3 ½ x 2 ¼ x 2 in] maximum depth. Reinforcing steel bars were not exposed. The area was repaired with grout. The fifth piece was removed, resulting in a hole in the concrete surface that was about 5 x 3.8 x 5.7 cm [2 x 1 ½ x 2 ¼ in] maximum depth. Reinforcing steel bars were not exposed. The area was repaired with grout. The sixth piece was 3.8 x 3.8 cm [1 ½ x 1 ½ in] and extended through the concrete dome to the steel liner. The wood was removed and the liner was cleaned and examined using UT and showed no indication of metal loss. The concrete surface within the hole was examined and no reinforcing steel bars were exposed. The area was repaired with grout.

- In 2002, Indiana Michigan Power Company indicated three pieces of wood and one piece of plastic were found embedded in the concrete of the D.C Cook Unit 1 containment building (Indiana Michigan Power Company, 2002). The licensee reported that all of the items were shallowly embedded in the concrete and that the areas around these items did not indicate any significant leaching or any other distress conditions. Based on the size of the pieces, the licensee determined that the structural integrity of the containment was unaffected by the presence of these foreign materials.

Containment Liner Bulging

- At Shearon Harris Unit 1 in 2000, bulging of the liner under the transfer canal was observed. The licensee reported that, when tapped with a hammer, the bulged areas sound hollow but sound solid within a few feet where welded studs are embedded in the concrete. Also, many areas that are not bulged also sounded hollow when tapped and then sounded solid within a few feet. Because the bulged areas sounded the same as the other areas, no further action was taken.

Exposed Rebar

- At Indian Point Unit 2 in 2001, concrete inspections revealed several areas with spalling and exposed cadweld splices and reinforcing bars. Some corrosion was exhibited for all cases where rebar and or cadwelds were exposed to the environment as a result of concrete spalling. However, no flaking or aggressive corrosion processes were observed. The licensee reported that none of the indications were structural concerns for the containment structure. The licensee also indicated that all of the observations/findings would be monitored as required by the IWL portion of ASME code to document and track any potential changes to the observations noted.

2.4 Previous Assessments and Containment Operating Experience

The degradation of concrete and steel containment structures has been reviewed and assessed in several previous reports (Naus, 1986; Ashar and Bagchi, 1995; Naus et al., 1996; Naus, 2007; Braverman et al., 2000). In addition, the effects of corrosion damage on the structural capacity of the containment structures have been evaluated (Spencer et al., 2006; Cherry and Smith, 2001).

NUREG/CR-4652 (Naus, 1986) included a review of concrete structures where problems were encountered. The problems were attributed to either faulty design or errors in construction. In addition, NUREG/CR-4652 contains an annotated listing of problem areas associated with concrete containments in light water reactors. By far, the most common problem was the presence of voids and honeycombing (voids in concrete caused by the mortar not filling the spaces between the coarse aggregate particles). Cracking and spalling was the second most common problem followed by defective material.

NUREG-1522 (Ashar and Bagchi, 1995) reported observations obtained during NRC inspections at several operating nuclear power plants. They reported that most of the degradations of the steel shell and steel liners of reinforced and prestressed concrete containments are associated with the presence of high humidity or water. Improved coatings, liberal corrosion allowance, state-of-the-art methods for remotely monitoring corrosion, and use of impressed current corrosion protection system for sites susceptible to degradation would help alleviate the problems encountered in the operating reactors. Bulging of liner plate sections were observed at several plants.

NUREG/CR-6679 (Braverman et al., 2000) summarized instances of degradation obtained from Licensee Event Reports (LERs), NRC generic correspondences, NUREG reports, and other documents. Degradation of containment was identified as the fourth most commonly observed occurrences for passive structures and components following piping, steam generators, and reactor pressure vessels. Liner degradation accounted for 11 percent of the degradation occurrences for all structural steel passive structures and components and 30 percent of the degradation occurrences for all containment subcomponents. For concrete, the most common degradation mode observed was cracking, which was five times more frequent than spalling. Corrosion was the second most common degradation mode for all metal structures and second only to stress corrosion cracking.

NUREG/CR-6927 (Naus, 2007) provides detailed information on concrete and steel degradation that has been reported for US nuclear power plants. Most of these occurrences were previously reported by NUREG/CR-6679 (Braverman et al., 2000), NUREG-1522 (Ashar and Bagchi, 1995), and NUREG/CR-4652 (Naus, 1986). Operating experience with corrosion of the containment liners includes corrosion as a result of coating degradation, moisture barrier degradation and embedded foreign materials. It should be noted that coating and moisture barrier degradation also have been identified in containment designs that utilize a freestanding steel containment vessel rather than a containment liner.

2.4.1 Corrosion with Coating or Moisture Barrier Degradation in BWRs

- In 1980, Oyster Creek discovered water in the gap between the reactor drywell liner and the concrete shield. The water was believed to originate from refueling water leaking from the bellows at the drywell to cavity seal. The seal was repaired and a gasket was replaced in 1986. UT measurements also made in 1986 indicated that 60 of 143 areas in the drywell liner had a reduction in thickness of more than 6.3 mm [1/4 in] from the drawing thickness of 2.93 cm [1.154 in]. The most severe corrosion was found in the sand bed region at a nominal elevation of 3.4 m [11 ft 3 in]. The highest corrosion rate determined was 0.89 ± 0.17 mm/yr [35.2 ± 6.8 mpy]. In the spherical portion of the drywell liner above the sand bed region, the highest corrosion rate determined was 0.12 ± 0.04 mm/yr [4.6 ± 1.6 mpy] at a nominal elevation of 15.5 m [51 ft] (Ashar and Bagchi, 1995). The drywell liner was cleaned, repaired (as necessary), and recoated using a submersible coating.

- In 1988, Nine Mile Point Unit 1 (free standing steel comtainment) was found to have corrosion on the uncoated inside surface of the torus shell. Independent measurements indicated several instances where the thickness was at or below the minimum specified wall thickness (Ashar and Bagchi, 1995).

- In January 1993 Brunswick Units 1 and 2 were found to have corrosion of the drywell liner. The liner was corroded at various spots at the junction of the base floor and the liner. The sealing material along the circumference at the junction of the drywell wall and the bottom floor had significantly degraded from water accumulation at the junction. The liner plate was found to have pitting that had penetrated as much as 50 percent of the original material thickness. The licensee repaired the pitted liner plate areas and resealed the entire gap at the junction with dense silicone elastomer prior to restarting (Ashar and Bagchi, 1995).

- Cooper (free standing steel containment) had more than 150 corrosion pits on the inside surface of the torus observed during previous inspections conducted by the licensee. Signs of corrosion on the external surface of the torus shell were apparently caused by water that leaked from above the torus and ran down the torus shell wall. Coating degradation was also found inside the Mark I containment structure (Ashar and Bagchi, 1995).

- In 1997, NRC inspections at Brunswick Units 1 and 2 found significant corrosion due to moisture barrier degradation. Extensive pitting, up to 50 percent of the thickness of the liner plate, was located in the area of the moisture barrier. For both units, the licensee repaired the liner plates by welding the pitted areas. The moisture barrier was resealed, the liner plates were replaced and inspected in accordance with ASME Section III Division 2, and the entire area was recoated (NRC, 1997b).

- In November 2001, Dresden Unit 2 was found to have an area of missing coating and primer encircling the drywell shell adjacent to the basement floor. The area was 5 to 10 cm [2 to 4 in] wide. In this area, the base metal of the drywell shell was found to be corroded. The degraded area was found to be within the corrosion allowance based on UT and visual examinations. The shell coating was repaired in this area (NRC, 2004).

2.4.2 Corrosion with Coating or Moisture Barrier Degradation in PWRs

- Robinson Unit 2 and Beaver Valley Unit 1 had areas of bulging and spot corrosion of the liner plate and degradation of the liner coatings. Surface cracking of concrete and deterioration of earlier patched concrete was observed (Ashar and Bagchi, 1995).

- In August 1989, McGuire Unit 2 reported significant coating damage and base metal corrosion on the outer surface of the steel shell that was limited to 9.1 m [30 ft] circumferential sections no higher than 25 mm [1 in] above the annulus floors. The steel shells have a nominal thickness near the annulus floor of 25.4 mm [1 in]. The average depth of the corrosion is 2.5 mm [100 mils] with pits of up to 3.2 mm [125 mils]. Corrosion that is up to 7.6 mm [30 mils] deep also was found in areas below the level of the annulus floor on the Unit 2 shell where concrete was removed to expose the shell surface. This below-floor corrosion was due to a lack of sealant at the interface between the shell and the annulus floor (Ashar and Bagchi, 1995).

- In September 1989, Catawba Units 1 and 2 were found to have coating damage and base metal corrosion on the outer surfaces of the steel shells at the intersection of the shell and the concrete annulus floor. The damage was limited to a circumference of 4.6 m [15 ft], a height of 2.5 cm [1 in] above the annulus floor and an average depth of 7.6 mm [30 mils]. The cause was believed to be attack by boric acid coolant that had leaked from instrument line compression fittings and condensed, and collected on the annulus floor (Ashar and Bagchi, 1995).

- In April 1990, McGuire Unit 1 was found to have degradation of the steel containment consisting of general coating failures and localized pits up to 1.1 mm [45 mils] deep. In some areas, the diameter of the localized pits ranged from 0.63 to 2.54 cm [0.25 to 1 in]. In other locations, clusters of pits were reported that measured to be up to 2.5 cm [1 in] wide and 5.0 cm [2 in] long. The corrosion was located on the inside surface at the floor level between the upper and the lower containment compartments in the vicinity of the ice condenser in a 51-mm [2-inch] floor gap filled with cork that interfaces with the coated steel containment. The cork contained moisture that may have originated from the ice condenser or from condensation. The minimum thickness of the worst pitted area was greater than the required minimum thickness (Ashar and Bagchi, 1995).

- In April 1992, Robinson Unit 2 was observed to have discoloration of the vertical portion of the containment liner indicating possible corrosion of the liner at an insulation joint (Ashar and Bagchi, 1995).

- In June 1992, Trojan (not operating) and Beaver Valley Unit 1 were found to have peeling coatings and areas of liner corrosion (Ashar and Bagchi, 1995).

- In December 1996, H.B. Robinson Unit 2 was found to have degraded caulking and insulation sheathing panels during a containment walkdown. The vertical portion of the containment liner at Robinson is protected by a polyvinyl chloride insulation material and a metal sheathing material. The licensee determined that a portion of this insulation sheathing material was loose and that some of the caulking between the sheathing panels was deteriorated. After examination during subsequent refueling outages, they determined that the protective coating for the containment liner was degraded and that while some corrosion of the containment liner had occurred, the liner still met design requirements (Braverman et al., 2000).

- In February and March 1998, D.C. Cook identified corrosion (pitting) of the containment liner at the moisture barrier seal areas of both units. At Unit 1, the licensee identified more than 60 areas in which the thickness (1 cm [$^3/_8$ in] nominally) of the steel liner plate had been reduced below the minimum design thickness value of (0.6 cm [0.25 inch]) (NRC, 2004).

- In October 1999, the Palisades Plant discovered that a floor-to-liner moisture barrier seal had never been installed and used a thin metal blade as a probe to confirm the presence of moisture in the crevice. Subsequently, a borescope was used to identify areas of liner corrosion, and it was determined that the corrosion had not yet appreciably degraded the liner in this area. Consequently, a new liner-to-floor moisture barrier seal was installed (NRC, 2004).

- In May 2002 at the Sequoyah Nuclear Plant Unit 2 (freestanding steel containment vessel surrounded by a reinforced concrete shield building), NRC identified areas of the steel containment vessel with degraded coatings and rust. One of the floor drains was clogged in the annulus area (1.5m [5 feet] wide) between the containment vessel and the reinforced concrete shield building. Localized water ponding at the clogged drain had come in contact with a section of the steel containment vessel causing deterioration of the coatings and rusting (NRC, 2004).

- In July 2002 at Davis-Besse (freestanding containment vessel with a concrete shield building), corrosion was identified where the containment meets the floor. Davis-Besse subsequently performed UT examinations to confirm that the freestanding metal containment had not been corroded below the minimum design thickness. Davis-Besse subsequently installed a moisture barrier at the containment-to-floor junction to prevent moisture intrusion (NRC, 2004).

- In fall 2003 at Surry Unit 2, NRC inspectors found degraded coatings and rust on the containment liner at the junction of the metal liner and interior concrete floor. The inspectors also discovered that the moisture barrier at the junction between the metal liner plate and interior concrete floor was degraded (NRC, 2004).

2.5 NRC Communications

Corrosion of containment liners has been observed in several operating reactors, and NRC has issued multiple information notices summarized as follows:

<u>Information Notice 86-99 Supplement 1 – Degradation of Steel Containments</u>. Alerted addressees to additional information about the discovery of significant corrosion on the external surface of the carbon steel drywell in the sand bed region of the Oyster Creek plant. The BWR Owners Group was also surveying its members to determine whether other plants are experiencing water leakage into the drywell gap and possible corrosion of the exterior surfaces in the sand bed region as well as in the spherical and cylindrical parts of the drywell.

<u>Information Notice 89-79 – Degraded Coatings and Corrosion of Steel Containment Vessels</u>. Alerted addressees to the discovery of severely degraded coatings and corrosion of steel ice condenser containment vessels that were caused by boric acid and collected condensation in the annular space

between the steel shell and the surrounding concrete shield building. Coating damage and base metal corrosion were found at McGuire Units 1 & 2 and at Catawba Units 1 & 2

Information Notice 89-79 Supplement 1 – Degraded Coatings and Corrosion of Steel Containment Vessels. Alerted addressees to additional information concerning the corrosion of containment vessels. The detection of corroded steel plate material in the drywells and wet wells of BWR plants and corroded steel containments of PWR plants led to the concern that degradation caused by corrosion may be generic to all types of containments.

Information Notice 97-19 – Liner Plate Corrosion in Concrete Containments. Alerted addressees to occurrences of corrosion in the liner plates of reinforced and pre-stressed concrete containments and to detrimental effects such corrosion could have on containment reliability. In January 1993, an NRC inspector pointed out corrosion of the drywell liner at Brunswick Unit 2. The liner was corroded at various spots at the junction of the base floor and the liner. A subsequent examination of Brunswick Unit 1 showed similar corrosion. In June 1992, peeled coating and spots of liner corrosion were observed at Trojan (not operating) and at Beaver Valley Unit 1. Minor corrosion also was observed at Salem Unit 2 in 1993. Discoloration of the vertical portion of the containment liner was observed at an insulation joint at Robinson Unit 2 in 1992.

Information Notice 97-13 – Deficient Conditions Associated with Protective Coatings at Nuclear Power Plants. Alerted addressees about several instances in which protective coatings have not been properly applied, maintained, or qualified. In November 1996, 40 percent to 50 percent of the concrete floor coatings at Zion Unit 2 (not operating) showed extensive failure as a result of mechanical damage and wear. In addition, about 5 percent of the coating associated with the concrete wall and liner plate was degraded.

Information Notice 04-09 – Corrosion of Steel Containment and Containment Liner. Alerted addressees to recent occurrences of corrosion in freestanding metallic containments and in liner plates of reinforced and prestressed concrete containments. Specific information was provided for eight plants. Factors identified as significant included coating and moisture barrier degradation, water accumulation and embedded foreign materials.

Information Notice 2010-12 – Containment Liner Corrosion. Alerted addressees to recent occurrences of corrosion of containment liners when the liners were in contact with objects or materials that can trap water and with acidic conditions. Specific information was provided on the 2009 Beaver Valley Unit 1 incident where through-wall corrosion occurred as a result of foreign material in the concrete. Information also was provided on the penetration sleeve corrosion at Brunswick Unit 1 caused by moisture trapped in felt intentionally wrapped around the on the outside of the sleeve. The felt was used to allow thermal expansion. Corrosion of the liner at inaccessible locations under insulation at Salem unit 2 discovered in 2009 was also included.

3. Data Analysis and Trends

Corrosion of containment liners that are usually coated on the interior surface occurs at three locations: (1) the liner interior at the concrete basemat/liner interface, which is usually protected with a moisture barrier, (2) at areas where the coating has been damaged or degraded and (3) the external liner surface, which is designed to be in contact with concrete. Several factors also may influence the corrosion of the liner at each location.

Corrosion of the liner on the interior surface is affected by the condition of the coating, the presence of attachments and penetrations, whether insulation is used on the interior surfaces, and the plant design. Coating damage by abrasion or degradation as a result of age and thermal cycling or water absorption can lead to conditions where the underlying steel is directly exposed, or as a result of the formation of coating delaminations and blisters that may eventually rupture. Insulation can act as a crevice former and trap moisture between the insulation and the steel. The PWR ice condenser design has an additional source of moisture, wherein the borated ice racks may cause condensation on the containment liner, leading to corrosion where the coating is compromised.

At the concrete basemat/liner interface, the condition of the moisture barrier is the main factor that affects corrosion of the liner. Plant design also has a significant influence on corrosion at the basemat/liner interface. Significant corrosion-related metal loss, which has been observed at ice condenser plants with a freestanding steel containment vessel surrounded by a concrete shield building, was found to be the result of the combination of moisture barrier degradation with condensation and/or accumulation of borated water from reactor cavity, and service water leaks in PWRs (Asher and Bagchi, 1995).

On the external surface of the liner, the main factor that appears to affect corrosion is construction-related events. Cases of through-wall corrosion have been attributed to the presence of foreign material in the concrete as a result of inadequate practices/housekeeping at the time of the original construction. Aging-related degradation such as cracking, carbonation, and chloride ingress also could affect the performance of concrete structures including containment buildings. Containment design and operation also could be a contributing factor.

The information obtained from the inservice inspection reports summarized in Tables 4, 5 and 6, indicates that liner corrosion from the interior surface has been observed at many plants. Factors that are significant for the corrosion of the containment liner on the interior surfaces are known and have been identified in previous NRC information notices. Because the objective of this report is an analysis of steel containment liner corrosion that initiated at the concrete/steel interface surface that is normally in contact with the concrete containment structure, the subsequent sections discuss the factors that could contribute to these incidents.

3.1 Corrosion Rates

Table 7 shows a summary of the incidents where corrosion was observed on the external surface of the liner. Plant age at the time of the incident was determined by the time between the first operation and the corrosion-related incident. Based on the age of the plants and the thickness of the liner, the average corrosion rate can be determined to be in the range of 0.29 to 0.50 mm/yr [11 to 19 mpy]. It should be noted that the average rate is not representative of the actual corrosion process that likely occurred over a period of many years. It is possible that the corrosion rate varied considerably perhaps by several orders of magnitude during the period from construction to discovery.

Although not representative, the average corrosion rate for the liner corrosion penetration incidents does allow comparison to both measured atmospheric corrosion rates and the range of observed localized corrosion rates for steel. Localized corrosion rates as a result of differential aeration or differential pH can be in excess of 3 mm/yr [120 mpy] (Matsushima, 2000a). Atmospheric corrosion rates for steel are dependent on the type of environment. Rural atmospheres are the most benign, and the corrosion rate of steel is in the range of 0.005 to 0.02 mm/yr [0.2 to 0.8 mpy]. The corrosion rate of steel in industrial environments has been reported to be in the range of 0.01 to 0.05 mm/yr [0.4 to 2 mpy]. In marine environments, which are much more aggressive owing to the presence of chloride salts and increased time of wetness from precipitation and elevated humidity, the atmospheric corrosion rate of carbon steel corrosion rate is typically 0.03 to 0.08 mm/year [1.2 to 3.2 mpy] (Matsushima, 2000b).

3.2 Construction Defects

The International Atomic Energy Agency (IAEA) survey (IAEA, 1998) identified cracking and corrosion as the most reported degradation effects for concrete and steel materials. About 30 percent of these instances were attributed to design or construction deficiencies. Examples of problems listed in the IAEA report include low 28-day compressive strengths, voids under the prestressing tendon-bearing plates resulting from improper concrete placement; cracking of prestressing tendon anchorheads due to stress corrosion or embrittlement; and containment dome delaminations due to low-quality aggregate materials and the absence of radial steel reinforcement or unbalanced prestressing forces. Other construction-related problems have included occurrence of excessive voids in the concrete, contaminated concrete, cold joints in cadwelds used to connect rebar sections, materials out of specification, exposure to freezing temperatures during concrete curing, misplaced steel reinforcement, prestressing system buttonhead deficiencies, and water-contaminated corrosion inhibitors. A variety of construction defects have previously been identified at U.S. nuclear power plants (Naus, 1986).

Table 8 contains a list of the original construction contractors for the 104 operating domestic nuclear power plants. Of the 21 original contractors, 15 built plants that utilize a steel containment liner in contact with concrete. The number of plants constructed by each of these 15 contractors varies from 1 to 22. Most contractors built only one or two types of PWR and/or one type of boiling-water reactor (BWR). All eight known cases of embedded foreign material in the concrete occurred at plants built with only four companies as the primary construction contractor.

All domestic plants with incidents of corrosion penetration of the liner were between 19 and 33 years old based on the time period between construction permit issuance and when plant first criticality. In addition, all of the incidents where foreign material was left embedded in the concrete and exterior corrosion of the liner occurred were in plants for which the construction permit was issued between 1967 and 1971. During this period, the construction permits for about 50 nuclear power plants were issued, and 30 of these power plants were designs that use a steel containment liner.

3.2.1 Embedded Foreign Material

The effects of embedded foreign material in the concrete on the steel containment liner are likely dependent on a variety of factors, including the composition, size, and location of the foreign material. Carbon steel is passivated when exposed to an alkaline environment without the presence of aggressive contaminants such as chlorides. Foreign materials that are in contact with the steel liner can alter the local chemistry and conditions at the exterior surface of the liner. Wood, which has been identified as contributing to the steel containment liner exterior corrosion incidents at D.C. Cook Unit 2, Brunswick Unit 2, North Anna Unit 2 and Beaver Valley Unit 1, is naturally acidic (Gibson and Watt, 2010) and also may trap moisture necessary for corrosion reactions. In addition, wood may contain and release chemicals used to prevent rotting and pest infestation that may reduce the local pH and promote corrosion of the steel. If the wood has a moisture content greater than about 30 percent, microbial degradation of the wood can occur. Wood-rotting microorganisms require iron and manganese for metabolic processes, and some microorganisms have metal chelating agents to obtain these elements from their surroundings (Morris, 2000). The metabolic byproducts also can be acidic and can disrupt the passivity of carbon steel in contact with rotting wood.

Table 7. Summary of Containment Liner Penetration and External Corrosion Events

Plant	Year of incident	Plant age at time of incident	Construction	Liner/metal thickness	Corrosion penetration	Average corrosion rate	Observations
Barsebeck-2 BWR Sweden	1993	16	Reinforced concrete	7 mm 0.275”	7 mm 0.275”	0.44 mm/yr [17 mpy]	Void in the concrete from initial construction and water accumulation
Brunswick 2 BWR Mark 1 GE 4	1999	24	Reinforced concrete	8 mm 0.312”	8 mm 0.312”	0.33 mm/yr [13 mpy]	Foreign material in concrete. Coating damage
North Anna-2 PWR W-3LP	1999	19	Reinforced concrete Subatmospheric	10 mm 0.375”	10 mm 0.375”	0.5 mm/yr [20 mpy]	Foreign material in concrete
D.C. Cook PWR W-4LP	2000	22	Reinforced concrete Ice condenser	10 mm 0.375”	1.8-4.8 mm 0.072-0.188”	0.08-0.22 mm/yr [3.2-8.5 mpy]	Foreign material in concrete. Penetration was likely manmade
Beaver Valley-1 PWR W-3LP	2006	30	Reinforced concrete Subatmospheric	10 mm 0.375”	1.1 - 5.8 mm 0.045 - 0.227 in	0.04 - 0.19 mm/yr [1.5 – 7.5 mpy]	Concrete pH < 11
	2009	33	Reinforced concrete Subatmospheric	10 mm 0.375”	10 mm 0.375”	0.29 mm/yr [11 mpy]	Foreign material in concrete

Table 8. Listing of Original Construction Contractors for Domestic Nuclear Power Plants and Observed Incidents of Embedded Foreign Materials and Exterior Corrosion of the Containment Liner

Original Construction Contractor	Nuclear Power Plants		Nuclear Power Plant Type and Containment Designs that Have a Steel Containment Liner						Incidents (NPPs w/ a steel liner)			
									BWR		PWR	
	Total	w/ Steel liner	BWR R-DW R-WW	BWR R-DW PT-WW	PWR PT Dry	PWR R Dry	PWR R ICE	PWR R Sub Atm	Foreign material	Exterior corrosion of liner	Foreign material	Exterior corrosion of liner
American Electric Power (AEP)	2	2	0	0	0	0	2	0	-	-	2	1
Burns and Roe (B&R)	2	0	-	-	-	-	-	-	-	-	-	-
Babcock and Wilcox (B&W)	1	0	-	-	-	-	-	-	-	-	-	-
Baldwin (BALD)	1	1	1	0	0	0	0	0	0	0	0	0
Bechtel (BECH)	29	22	5	0	17	0	0	0	0	0	2	0
Brown and Root (BRRT)	4	4	2	0	0	2	0	0	1	1	0	0
Commonwealth Edison (CWE)	6	6	0	2	4	0	0	0	0	0	0	0
Daniel International (DANI)	6	5	0	0	4	1	0	0	-	-	0	0
Duke Power Company (DUKE)	7	3	0	0	3	0	0	0	-	-	0	-
Ebasco (EBSO)	7	3	0	0	3	0	0	0	-	-	0	0
Gibbs, Hill, Durham, and Richardson (GDHR)	1	1	0	0	1	0	0	0	-	-	0	0
Georgia Power Company (GPC)	4	2	0	0	2	0	0	0	-	-	0	0
J.A. Jones (JONES)	1	1	0	0	1	0	0	0	-	-	0	0
Kaiser Engineers (KAIS)	1	0	-	-	-	-	-	-	-	-	-	-
Northern States Power (NSP)	2	0	-	-	-	-	-	-	-	-	-	-
Pacific Gas and Electric (PG&E)	2	2	0	0	0	2	0	0	-	-	0	0
Pioneer Services and Engineering (PSE)	1	0	-	-	-	-	-	-	-	-	-	-
Stone and Webster (S&W)	11	8	1	0	0	0	0	7	0	0	3	2
Tennessee Valley Authority (TVA)	6	0	-	-	-		-	-	-	-	-	-
United Engineers and Constructors (UE&C)	8	4	0	0	1	3	0	0	-	-	0	0
Westinghouse Development Corporation (WDCO)	2	2	0	0	0	2	0	0	-	-	0	0

NPP: Nuclear power plant
BWR: Boiling-water reactor
PWR: Pressurized-water reactor
DW: Drywell
WW: Wetwell

R: Reinforced concrete
PT: Post-tensioned concrete
Dry: Large dry containment
ICE: Ice condenser containment
Sub Atm: Sub-atmospheric containment

A workman's leather glove was reported to be found in the concrete in contact with the through-wall corrosion at Brunswick Unit 2 along with pieces of wood. The effect of the glove is unclear. Although, tanning agents used in the production of leather and the presence of chloride from perspiration may promote corrosion of steel, no analysis of the glove removed from the concrete was available for review.

In addition to disrupting the concrete/steel interface and the possible introduction of contaminates that may promote corrosion of steel, the most significant effect of a foreign material in the concrete and in contact with the steel liner is the possibility of crevice corrosion. When an aqueous phase is present, the local environment in the crevice created between steel and the wood is significantly different from the environment where the steel is in contact with the concrete. In the crevice, the corrosion of iron occurs and generates Fe^{2+} cations and described in Equation 1.

$$\mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2\mathrm{e}^{-} \quad \text{(Eq. 1)}$$

These cations are then hydrolyzed in the aqueous environment and form $Fe(OH)_2$ (solid) and H^+ anions as shown in Equations 2 and 3 (Isaacs, 1990).

$$\mathrm{Fe}^{2+} + \mathrm{H_2O} \rightarrow \mathrm{Fe(OH)}^{+} + \mathrm{H}^{+} \quad \text{(Eq. 2)}$$

$$\mathrm{Fe(OH)}^{+} + \mathrm{H_2O} \rightarrow \mathrm{Fe(OH)_2} + \mathrm{H}^{+} \quad \text{(Eq. 3)}$$

Anions with high mobility diffuse into the crevice to maintain electroneutrality. Chloride ions are have high mobility and are often present in many systems either as a natural species or a contaminant. The result is a crevice environment that is acidic and concentrated in chloride ions that significantly increases the corrosion rate of the steel. Outside of the crevice, the steel is in contact with the concrete. Reduction reactions such as the reduction of oxygen (Equation 4) occur on the steel outside the crevice.

$$\mathrm{O_2} + 2\mathrm{H_2O} + 4\mathrm{e}^{-} \rightarrow 4\mathrm{OH}^{-} \quad \text{(Eq. 4)}$$

The reduction reactions complete the electrochemical circuit necessary to support the anodic reactions inside the crevice (Wallwork and Harris, 1974; Isaacs, 1990).

3.2.2 Voids

Voids in the concrete have been identified in several plants in the United States. These defects typically occur as a result of incomplete consolidation of the concrete and the entrapment of air. Voids can vary in size and shape, and water may accumulate in such voids. These defects may be locations where water accumulates. If in equilibrium with the concrete, the pH of the water in the voids would be expected to be alkaline and therefore impart passivity to the steel. The addition of chlorides could be detrimental to the passive film and promote pitting corrosion. The only reported case of corrosion penetration from voids was at the Baresbeck-2 BWR in Sweden. It is unclear from the report whether any water was collected for analysis. The average corrosion rate of 0.44 mm/yr [17 mpy] suggests localized corrosion was the cause of failure. After the discovery of localized corrosion at Beaver Valley-1 in 2006, voids were speculated as having a possible role of voids in the localized corrosion of the steel liner (FirstEnergy, 2006). However, positive determination of the presence of voids was not confirmed. Voids and unconsolidated concrete also were identified during plant construction and were repaired by the addition of grout (Naus, 1986).

3.2.3 Liner Bulging

Liner bulging and, more generally, separation of the liner from the concrete can affect large areas on the order of square meters. To date, no corrosion-related failures have been initiated at locations where liner bulging is known to have existed. The effect of bulging or separation of the liner from the concrete may have similar effects on the liner as large voids. Accumulation or ponding of water may be possible in these areas. If the water chemistry is modified by the concrete, alkaline conditions and passivity of the carbon steel liner can be expected. The introduction of chloride ions or carbonation of the concrete may result in conditions where corrosion of the liner may preferentially occur at areas of separation or bulging.

3.3 Plant Type, Design, and Operation

There are a number of differences and variations to the designs of the containment buildings for the 104 operating nuclear U.S. power plants. For containment buildings using a steel containment liner, a rough breakdown of the designs is as follows:

- BWR reinforced drywell reinforced wetwell.
- BWR reinforced drywell post-tensioned wetwell.
- PWR reinforced ice condenser containment.
- PWR reinforced subatmospheric containment.
- PWR reinforced large dry containment.
- PWR post-tensioned large dry containment.

It is unclear if the differences in the design and operation have any effect on the probability for imbedded reinforcement and containment liner corrosion. One design variation that may be important is whether the containment used reinforced or post-tensioned concrete. In a reinforced concrete containment structure, multiple layers of rebar must be positioned during construction. For post-tensioned structures, there are 1-, 2-, and 3-dimensional post-tensioned designs. An important difference between reinforced and post-tensioned containment buildings is the amount and location of the reinforcement or post-tensioning systems. Reinforced containments may have rebar located closer to the liner than the post-tensioning conduits.

Aside from reinforcement design, post-tensioned containment buildings are designed to have the concrete in compression. This is accomplished by numerous post-tensioning tendons that encircle the containment building.. Tendons also are positioned vertically and are located in the containment dome. Any cracks that develop in the concrete containment structure are likely to remain tight as a result of the compressive stresses on the concrete. This may limit the depths to which the crack propagates and also may limit the ingress of moisture. The depth of carbonation is known to be a function of crack width.

Subatmospheric containments are designed to operate at a slightly reduced atmospheric pressure. It is not clear if the operating pressure is significant to promote bulging of the liner or promote migration of moisture toward the liner during operation. Of the nine ice condenser plants, seven are constructed with containments that have a concrete shield building with a freestanding steel cylinder. Only D.C. Cook Units 1 and 2 are constructed with a steel liner in contact with the concrete. The ice condenser plants have large borated ice racks that are designed to condense steam during a loss-of-coolant accident. It is unclear if this design might promote condensation on the interior and exterior surfaces. Condensation on the exterior surface would result in liquid water in contact with the steel/concrete interface.

4. Containment Material Degradation Mechanisms

Environmentally-induced degradation of concrete structures is recognized as a significance issue for aging infrastructure including bridges, highways, and buildings. Although the relationship between environmentally-induced degradation and the containment liner corrosion events that are known to date are not clear, aging and degradation of the concrete containment structures needs to be considered as about two-thirds of the current fleet of domestic nuclear power plants (NPPs) have received license extensions to operate beyond 40 years. Background information on environmentally-induced degradation mechanisms that may be significant for NPP containment structures is included in this section along with a discussion of factors that affect these degradation mechanisms.

The containment structures of interest are constructed using either reinforced or prestressed post-tensioned concrete in contact with a steel containment liner. Under normal conditions, the steel embedded in the concrete is covered with a passivating oxide layer that is stabilized by the alkaline concrete pore water environment. Consequently, the passivated steel has a very low corrosion rate. Degradation of the concrete can lead to conditions where the corrosion rate of the embedded steel is significantly increased. Cracks in the concrete can act as pathways for the ingress of water and aggressive species that can alter the pH of the concrete or disrupt the passive oxide film on the embedded steel. The inclusion or introduction of chloride can lead to breakdown of the passive film and the initiation of localized corrosion. Carbonation of concrete reduces the pH of the concrete pore water and promotes dissolution of the protective, passivating oxide film. Once initiated, active corrosion of the embedded steel results in the formation of corrosion products that have a significantly larger volume than the steel. The increased volume causes stresses in the concrete sufficient to promote cracking of the concrete. This provides additional pathways for the transport of aggressive species and ingress of water from the outside environment and thereby exacerbates the degradation of the concrete and the corrosion of the embedded steel reinforcement bar.

<u>Testing and Examination Methods</u>

NUREG/CR-6424 (Naus et al., 1996) and IAEA-TECDOC-1025 (IAEA, 1998) reviewed commonly used evaluation procedures to assess concrete properties and physical condition and rebar conditions. Methods commonly utilized to assess concrete and reinforcing steel are:

Concrete non-destructive inspection

- Visual examination.
- Ultrasonic (UT) pulse echo testing.
- Acoustic or stress wave reflection/refraction.
- Audio or acoustic impact echo.
- Radiographic testing.
- Penetrating radar.
- Infrared thermography.

Concrete destructive methods

- Core sample extraction and examination.
- Petrography.
- Surface hardness.
- Probe penetration methods.
- Pullout tests.
- Mix composition analyses.
- Chloride ion content testing.
- Carbonation depth testing.

Embedded steel assessment testing

- Magnetic cover tests.
- Four electrode concrete resistivity testing.
- Electrochemical potential measurements.
- Polarization resistance.

Containment liner assessment methods

- Integrated and local leakage rate tests.
- Visual examination.
- UT testing.
- Magnetic particle testing.
- Penetrant testing.

Although numerous techniques have been used to assess the condition of concrete structures, each method has limitations in terms of capability, resolution, or implementation. For containment structures, visual examination is the most commonly used inspection method because it is versatile and relatively easy to implement. Followup examination of suspect areas are typically conducted using UT or sounding methods.

4.1 Concrete Cracking

Cracking of concrete can result from a variety of causes. The American Concrete Institute has provided guidance on the causes, assessment, and repair methods for cracks in concrete structures (American Concrete Institute, 2009a). Concrete cracking can be broadly divided into two categories: (1) cracks that occur before curing (i.e., plastic concrete) and (2) cracks that occur after curing (Naus et al., 1996; Krauss and Naus, 1998). Before curing, concrete may crack as a result of freezing, plastic shrinkage, plastic settlement, or movement of forms or the subgrade. After curing, cracking can occur because of structural issues or because of physical, chemical or thermal processes. The following sections provide summaries of descriptions of cracking mechanisms that may be relevant to containment structures..

4.1.1 Plastic Cracking

Cracking in plastic concrete is often caused by plastic shrinkage or settlement.

- Plastic shrinkage cracking occurs when moisture evaporates from the surface of freshly placed concrete at a rate faster than it is replaced by bleed water from the concrete interior. Rapid drying causes the surface of the concrete to shrink and undergo tensile stress due to the restraint of the underlying concrete. This tensile stress causes shallow cracks in either a parallel arrangement or a random polygonal pattern.

- Settlement cracking occurs when concrete components continue to consolidate and shrink after initial placement. The plastic concrete may be locally restrained by the reinforcing steel bars, a previous concrete placement, or formwork. This local restraint may result in voids, cracks, or both, adjacent to the restraining element.

4.1.2 Hardened Concrete Cracking

In hardened concrete, cracking can be caused by drying, thermal stresses, chemical reactions, weathering, corrosion of embedded reinforcement, poor construction practices and designs, and construction overloads.

- Drying shrinkage is caused by the loss of moisture from the cement paste constituent. Aggregate particles provide internal restraint that reduces the magnitude of this volume loss. The combination of shrinkage and restraint causes tensile stresses to develop and, when the tensile strength of the material is exceeded, the concrete cracks.

- Thermal stresses are produced as a result of temperature differences within a concrete structure. This may be caused by portions of the structure losing heat of hydration at different rates or by weather conditions locally cooling or heating one portion of the structure to a different temperature or at a different rate than another portion of the structure. These temperature differences result in differential volume changes leading to tensile stresses that can exceed the concrete strength.

- Materials used to make the concrete or materials that come into contact with the concrete after it has hardened may react chemically to produce an environment conducive to cracking. Concrete may crack with time as the result of expansive reactions between an aggregate component that contains active silica and alkalis derived from cement hydration, admixtures, or external sources. Three common chemical reactions that can lead to cracking are sulfate attack, delayed ettringite formation, and alkali-aggregrate reactions.

  - Sulfate attack of concrete is caused by exposure of concrete products or structures to an excessive amount of sulfate from internal or external sources. Magnesium, sodium, calcium, and potassium sulfates react with the calcium hydroxide and, if enough water is present, result in expansion and irregular cracking of the concrete.

  - Delayed ettringite formation by reaction of internal or external sulfate with anhydrous or hydrated calcium aluminates can result in expansion and cracking.

  - Alkali-aggregate reactions leading to loss of strength, stiffness, and durability of concrete can result from chemical reactions involving alkali ions from the portland cement, calcium and hydroxyl ions, and some siliceous constituents in aggregates. Reactions of these constituents can form a calcium alkali-silicate gel. This gel absorbs pore solution water and expands, which can disrupt the concrete

- Weathering, including freezing and thawing, wetting and drying, and heating and cooling can result in concrete cracking. The volume increase caused by the formation of ice may impart stresses to the concrete sufficient to cause cracking. Similarly, differential stresses as a result of wetting and drying and heating and cooling also can lead to stresses that promote cracking.

- Poor construction practices such as adding water to concrete to increase workability can lead to cracking. The water-to-cementious-material ratio is calculated to control the quality of the resulting concrete. Adding additional water will increase the w/cm ratio, which has the effect of reducing strength, increasing settlement, increasing porosity, and increasing drying shrinkage.

- Construction overloads may be more severe than those experienced in service and may occur when the concrete is most susceptible to damage resulting in permanent cracks. Precast members, such as beams and panels, are most frequently subject to this abuse, but cast-in-place concrete also can be affected

4.1.3 Concrete Repair

Multiple repair methods are available to mitigate concrete degradation. Cracking and spalling are the most significant degradation modes for containment structures. ACI 224.1R-07 contains descriptions of the methods available for repairing cracks (American Concrete Institute, 2009a). NUREG/CR-6424 (Naus et al., 1996) and IAEA-TECDOC-1025 (IAEA, 1998) include a general guide for repairing concrete cracking and spalling, and contain a comparison of the properties of patching materials. The repair method chosen depends on many factors including the nature of the crack, whether the crack and structure are actively moving and the type of structure. Repair methods for cracks are typically applicable to cracks that result from settlement of structural effects. Generally, cracks causing leaks in water-retaining or other storage structures should be repaired. For cracks exposed to a moist or corrosive environment, crack repair and sealing may be required to minimize future deterioration due to the corrosion of reinforcement. Results of a survey conducted by the International Atomic Energy Agency (IAEA) (IAEA, 1998) reveal that epoxy injection, routing and sealing, and the use of flexible sealants are the most commonly used crack repair methods

Repair of spalling is typically done with concrete replacement. Small areas of shallow spalling may not require repair. The determination of whether repair is required must consider the minimum acceptable cover depth for rebar and the size of the spalled area. Results of the IAEA survey indicate that concrete replacement drypacking and sealers are the most commonly used spalling repair methods.

4.2 Concrete Degradation and Corrosion

Corrosion of rebar usually does not occur in concrete because of a tightly adhering protective oxide coating that is stable in the highly alkaline (high pH) concrete environment. Reinforcing steel may corrode, however, if the alkalinity of the concrete is reduced through chloride ingress or carbonation, which can destroy the protective oxide coating. Corrosion of the steel produces iron oxides and hydroxides that have a volume much greater than the volume of the original metallic iron. This increase in volume causes high radial bursting stresses around reinforcing bars and results in local radial cracks (American Concrete Institute, 2009b). These splitting cracks can propagate along the bar, resulting in the formation of longitudinal cracks or spalling of the concrete. Cracks provide easy access for ingress of additional oxygen, moisture, and chlorides that leads to further corrosion.

4.2.1 Carbonation of Mature Concrete

Carbonation of concrete refers to the transport of atmospheric carbon dioxide into mature concrete and its subsequent reaction with the alkaline cement material by the following reaction (Equation 5):

$$\mathrm{CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O} \qquad \text{(Eq. 5)}$$

In sound concrete, CO_2 penetration along with its carbonation reaction with cement material proceeds through the concrete cover (the thickness of the concrete between the rebar and the surface) as an even front. Behind the carbonation front, the consumption of alkaline $Ca(OH)_2$ by Eq. 1 reduces the pH of the pore water system in the concrete from 12.5-13.0 to 8.5-9.0 (American Concrete Institute, 2009b) where the passivating film on the steel rebar becomes unstable. Ingress of atmospheric CO_2 into concrete is driven primarily by diffusion, and thus the rate of carbonation is dependent on the rate of diffusion. The time required for the carbonation front to proceed through the concrete cover to the steel rebar can be estimated by Equation 6.

$$t = \left(\frac{d}{k}\right)^2 \qquad \text{(Eq. 6)}$$

where *t* is the time for carbonation to reach the reinforcement bar, *d* is the concrete cover thickness, and *k* is a permeability factor dependent on the concrete grade (IAEA, 2002). The rate of carbonation is relatively slow, on the order of 0.04 in [1 mm] per year in good quality mature concrete (Vaysburd et al.,1997).

Penetration through a concrete cover to the reinforcing steel bars is expected to occur on the order of tens of years. However, CO_2 will transport more rapidly in environments with higher atmospheric CO_2 content. For example, areas of heavy industry may contain up to 100 times the natural concentration of

0.03 percent CO_2 (American Concrete Institute, 2009b). The ingress of gases is higher at low relative humidity values, but the reaction between the gas and the cement paste takes place in solution; therefore, the reaction rate is higher at high humidity values. Therefore, the most aggressive environment for concrete paste neutralization is alternate wet and dry cycles and high temperatures. Under constant conditions, an ambient relative humidity of 60 percent has been the most favorable for carbonation. The absence of chlorides, age, and high porosity associated with high water to cement ratio also will increase the carbonation rate (American Concrete Institute 2009b; Broomfield, 2000).

Previously existing cracks in the structure resulting from such causes as direct loading of the structure or due to chemical or physical causes can allow the rapid penetration of carbon dioxide to the steel reinforcement (Naus, 2007) by means of localized carbonation rather than a slow carbonation front. Subsequent corrosion initiation will occur sooner in cracked concrete than in sound concrete. Crack width also plays a role in determining time to corrosion. If the crack width is greater than 0.15 – 0.2 mm [0.006 – 0.008 in], the carbonation front will penetrate a 30 – 50 mm [1.2 – 2.0 in] cover and reach the steel rebar within 60 years (Braveman et al., 2000).

4.2.2 Corrosion as a Result of Concrete Carbonation

Carbonation results in a decrease in pH of the pore solution along the carbonation front to values as low as 8.5. The passive film protecting the steel rebar is pH dependent and becomes unstable as pH decreases from about pH 12.5 (Pourbaix, 1974). Therefore, as the carbonation front reaches the steel reinforcement bar, large surface areas of the reinforcement bar are depassivated. Corrosion resulting from depassivation occurs as general oxidation over the entire surface of the steel rebar. It also is observed that corrosion of the rebar is more severe at areas that are nearest to the outer surface of the concrete because the carbonation front contacts the outer rebar surface first (Braveman et al., 2000).

4.2.3 Chloride Introduced During the Construction Phase

Chloride is commonly added to concrete as a curing accelerant, generally in the form of $CaCl_2$. The addition of $CaCl_2$ will shorten curing, but the presence of $CaCl_2$ can make the pore water environment more corrosive to steel reinforcement bars. Dissolved $CaCl_2$ in the initial concrete pore water base chemistry raises the conductivity of the pore solution, which can accelerate the electrochemical corrosion process (American Concrete Institute, 2009b). Calcium cations precipitate hydroxide ions to form $Ca(OH)_2$, lowering the pH of the pore water (Caseres, 2002). In addition to affecting the pore water chemistry, chloride ions attack reinforcement bars directly by interacting with the protective passive oxide layer on the steel. As a result, the presence of chloride-based curing additives can cause an initial high rate of corrosion during the curing phase. In addition, accelerated curing can result in a more porous concrete matrix that is more susceptible to carbonation or transport of environmental chloride after the concrete is fully mature. For all of these reasons, chloride additives have generally not been used as accelerants for many concrete structures, including nuclear containments.

In concrete mixtures without chloride-containing curing accelerants, chlorides may still initially be present in the concrete mixture as impurities in the aggregate component of the concrete. Chloride can be introduced as chloride containing water in the concrete mix, inadequately washed aggregates, or deposition and ingress of marine salts or chlorides from chemical processing (Naus, 2007). Aggregate chlorides are bound within the calcium aluminate matrix and are therefore unavailable to initiate corrosion during the initial curing stages. These chlorides remain immobilized in mature concrete as long as the pore water remains alkaline and are not considered a major contributor to initial corrosion. However, if pH of the pore water in matured concrete is lowered by external factors such as penetration of environmental chloride or carbonation, these initially bound chlorides will be released, raising the concentration of chloride in the mature pore water system (Clifton, 1991).

4.2.4 Chloride Transport Into Mature Concrete

After curing, mature concrete can be exposed to chloride from the environment. Chloride ions are typically present in the environment at all nuclear sites. The most common sources of environmental chloride are seawater and saltwater spray in marine environments and deicing salts in colder climates. Chloride ions also can be present in ground water and potable water systems, albeit at lower concentrations. Because of its high mobility, high solubility, and ability to destabilize the passive film on many engineering alloy systems, chloride contamination is a common cause of corrosion damage. Structures impacted from these chloride sources are generally infrastructure components such as dock piers, bridges, and building foundations. For nuclear containment applications, appreciable amounts of chloride distributed throughout the structure are expected only in containment structures located near seashores (Clifton, 1991) where atmospheric chloride may gain ingress to mature concrete. Environmental chloride can transport through concrete by a variety of mechanisms.

- Diffusion: Mass-Transfer of Chloride Ions Driven by a Chloride Concentration Gradient. Diffusion occurs in saturated media such as seawater or air and acts in either steady-state or non-steady-state processes (Cement Concrete and Aggregates Australia, 2009). If the concrete contains species that can bind chloride, such as calcium aluminates, then the diffusion process is slowed until the chloride sink is exhausted.

- Permeability, Migration, Adsorption. Permeability refers to transport of chloride through concrete while under pressure, migration refers to transport of chloride in electrically charged media, and adsorption refers to chloride that is sorbed onto the outer surface layers within the concrete but is not transported into the bulk structure. These modes of transport are generally not active in concrete nuclear containment structures.

- Capillary Suction. Surface tension within capillaries will transport liquids on the surface of concrete into the interior of the concrete. In an interconnected pore system, chlorides dissolved in the liquids will also transport into concrete by capillary suction more rapidly than by diffusion alone. At the same time, chlorides that gained ingress by capillary suction are drawn deeper into the concrete by diffusion.

For most nuclear applications, environmental chloride is transported into concrete by a mixed mode of diffusion and capillary suction. The rates of both diffusion and capillary suction are dependent on properties of the concrete, especially on the structure of the pore system. Larger and more interconnected pores allow for greater rates of diffusion and capillary adsorption and suction. Pore structure in the mature concrete is influenced by the ratio of water/cement material (w/cm). For example, as w/cm increases from 0.4 to 0.7, the effective diffusion coefficient rises by a factor of at least 5, depending on the type of concrete. In contrast, a lower w/cm ratio will decrease the connectivity of the pore system, slowing or stopping capillary suction. Concrete under tension will facilitate chloride diffusion due to microcracks at the interface between cement paste and aggregate. Curing procedure also affects porosity, although the effect is not as pronounced. Curing concrete for 3 days as opposed to no curing can decrease porosity from 12 to 10 percent at depths of 10 mm (Cement Concrete and Aggregates Australia, 2009).

4.2.5 Chloride Binding and the Critical Chloride Content

Not all the chlorides present in the concrete contribute to steel corrosion. Chloride is incorporated into the crystal structure of tricalcium aluminate in the cement phase to form Friedel's Salt which is stable at high pH, as shown in Equation 7.

$$CaCl_2 + 3CaO \cdot Al_2O_3 + 10H_2O \rightarrow 3CaO \cdot CaCl_2 + 10H_2O \quad \text{(Friedel's salt)} \qquad \text{(Eq. 7)}$$

Reactions with similar aggregates such as tetracalcium aluminoferrite (C4AF) also will isolate chloride from the pore water system so that it is no longer available to initiate corrosion. Chlorides also can become physically trapped either by adsorption or in unconnected pores (Caseres, 2002). The fraction of total chlorides available in the pore solution to cause breakdown of the passive film on steel is a function of a number of parameters including aggregate content, pH, the water cement ratio, and whether the chloride was added to the mixture or penetrated into the hardened concrete.

To initiate corrosion of steel rebar; (i.e., initiate breakdown of the passive film), chloride must be present at a certain critical threshold concentration in the pore water within the concrete ratio. Figure 9 shows the factors affecting critical chloride threshold (American Concrete Institute 2009b) in which the critical chloride concentration to cement ratio is plotted as a function of relative humidity in the environment.

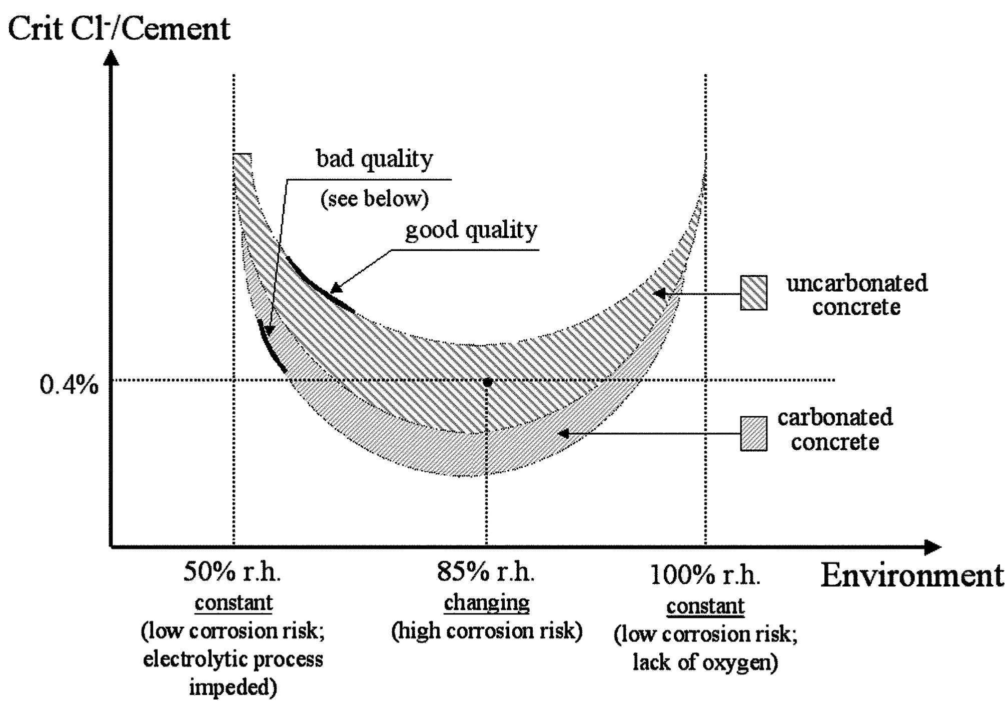

Figure 9. Effect of Relative Humidity on the Critical Chloride Concentration in Concrete (American Concrete Institute, 2009b).

The shaded areas represent the range of acceptable critical chloride content. "Quality" refers to the quality of the concrete cover. As shown in Figure 9, a threshold content of 0.4 percent Cl^- by weight is used as a general guide for acceptable concrete by the International Federation for Structural Concrete. In the United States, the critical chloride threshold value is about 0.25 percent Cl^- by weight. The breakdown of the passive film is dependent on effective chloride content as well as on the ratio of Cl^-/OH^-. At a typical mature concrete pH of 12.5 to 13, the passive film on steel rebar begins to break down at Cl^-/OH^- ratios higher than ~0.3. If the pH is lowered (e.g., by a carbonation front), the chloride threshold sufficient for corrosion initiation is lowered greatly (American Concrete Institute, 2009b).

Enhanced corrosion of the steel reinforcing bars can result when a carbonation front acts in concert with chloride. The decrease in pore water pH due to carbonation enhances the initiation of corrosion by chloride. As the pH of the pore water is lowered by the carbonation front, chloride previously bound in aggregates as chloroaluminates is released as free chloride. Therefore, chloride tends to accumulate at the carbonation front (American Concrete Institute, 2009b). In addition, because chloride activity is influenced by Cl^-/OH^- ratio, chloride is more likely to initiate corrosion at a lower pH. For example, the threshold chloride concentration for corrosion initiation was measured to be 8,000 ppm at pH 13.2 while the threshold chloride concentration for corrosion initiation at pH 11.6 was measured ~70 ppm (Clifton, 1991).

The synergy between carbonation and chloride content is reflected in the International Federation for Structural Concrete shown in Figure 9. In noncarbonated concrete, a general guideline is Cl^- 0.4 percent by weight is considered acceptable. For carbonated concrete, the entire acceptable region occurs at lower critical chloride content threshold, with a general guideline of ~0.2 percent Cl^- by weight (American Concrete Institute, 2009b).

4.2.6 Corrosion as a Result of Chloride

When chloride is present as an accelerant or aggregate contaminant, the initial high rate of corrosion gradually decreases as the concrete matures and the aggregate component of concrete reacts with the cement paste and establishes a more alkaline environment in the pore system. The alkaline environment restabilizes the passive layer on the steel rebar (American Concrete Institute, 2009b).

In mature concrete, the ingress of chloride is detrimental because chloride can disrupt the passive oxide film on the steel surface and promote localized attack such as pitting corrosion. Although the actual mechanism of breakdown of the passive film by chlorides is not known, once the passive film is ruptured and active corrosion is initiated, the corrosion reaction proceeds autocatalytically as follows. Corrosion of metallic iron produces soluble ferrous ions, which in turn are hydrolyzed to iron hydroxides. The hydrolysis reaction consumes anions (OH^-) so that the active corrosion site becomes both locally acidic and positively charged. The active site attracts anions to maintain charge balance. Chloride ions are then drawn to the active site because they have a high solubility and high mobility and are often the most available anion. The chloride and ferrous ions react to form a soluble complex that diffuses away from the acidic corrosion site. When the complex reaches the more alkaline bulk solution it breaks down, precipitating an insoluble iron hydroxide and liberating the chloride to return to the corrosion site and attack the passive layer on the reinforcing steel bar (American Concrete Institute, 2009b).

The initial precipitated iron hydroxide has a low state of oxidation and tends to react further with oxygen to form higher oxide corrosion products. These corrosion products have a larger specific volume than the steel from which they were formed (American Concrete Institute, 2009b). The increase in volume causes internal stresses within the concrete that may be sufficient to cause cracking and spalling of the concrete cover.

4.3 Corrosion Assessment, Mitigation, and Prevention

Assessment methods are commonly practiced to determine the extent of environmental degradation and corrosion-related damage to reinforced concrete structures. Because carbonation and chloride ingress are significant environmental processes that contribute to the corrosion of embedded steel, evaluation methods have been developed to characterize the chloride concentrations and degree of concrete carbonation.

4.3.1 Measurement of Chemical Alteration and Corrosion Rates in Concrete

Carbonation of concrete can be determined by testing with a phenolphthalein solution for alkalinity. Tests for carbonation depth are performed by drilling to expose fresh concrete or by obtaining a core sample. Chloride concentration measurements are more difficult and require the extraction of liquid from the concrete sample. Once extracted, chloride concentration can be measured using an ion-selective electrode or a titration method (Broomfield, 2000).

Assessments to determine the corrosion of steel in concrete may be conducted using either indirect or direct methods. Concrete resistivity is often measured to assess the possible corrosion activity for embedded steel. The resistivity measurement is conducted using a four-probe resistivity cell similar to that used to conduct soil resistivity measurements. Resistivity measurements are useful to identify areas where high corrosion rates may exist but should be supported with direct measurements. Table 9 includes a general interpretation of resistivity measurements (Broomfield, 2000).

Table 9. Concrete Resistivity and the Relative Corrosion Rate of Steel

Concrete Resistivity	Steel Corrosion Assessment
> 20 kohm cm	Low corrosion rate
10 – 20 kohm cm	Low to moderate corrosion rate
5 – 10 kohm cm	High corrosion rate
< 5 kohm cm	Very high corrosion rate

Electrochemical potential measurements for the steel also are an indirect method for assessing the corrosivity of concrete. These measurements are relatively simple but require an electrical connection through the concrete to the embedded steel. Because steel will be passivated under normal conditions, the electrochemical potential of steel in concrete should be in a range where the passive oxide is stable. Generally, the potential range for passivated steel in concrete is expected to be above -200 mV vs. a copper/copper sulfate electrode (CSE) or correspondingly above -140 mV vs. a saturated calomel electrode (SCE). If the steel is actively corroding, then the oxide film is not stable and the potential will be below -350 mV vs. CSE (-290 mV vs. SCE).

Other DC and AC electrochemical measurement techniques also have been used. Electrochemical impedance spectroscopy is an AC technique that may be used to determine corrosion rates. Although the AC technique has some advantages, it also requires more complex equipment and analytical methods. DC measurements are typically performed using the polarization resistance method where the corrosion rate or corrosion current density, I_{corr}, is inversely proportional to the resistance of the steel to anodic polarization. To accurately determine the corrosion rate using this method, the steel surface area from which I_{corr} is measured must be controlled using specialized test equipment that incorporates a guard ring. With the use of a guard ring, the following criteria are generally used to assess corrosion rates using polarization resistance as shown in Table 10 (Broomfield, 2000).

Table 10. Relative Corrosion Rate of Steel in Concrete Determined by Polarization Resistance Testing

Corrosion current density, I_{corr}	Steel Corrosion Assessment
< 0.2 μA/cm^2	Passive condition
0.1 to 0.5 μA/cm^2	Low to moderate corrosion rate
0.5 to 1.0 μA/cm^2	Moderate to high corrosion rate
> 1 μA/cm^2	High corrosion rate

The use of electrochemical methods to measure corrosion rate also requires knowledge of concrete cover depth. Electrochemical measurements are generally not acceptable for deep concrete cover depths because the concrete resistance becomes too high. Similarly, the technique is not applicable for high concrete resistance values, however the corrosion rate in highly resistive concrete is expected to be low.

4.3.2 Corrosion Damage Assessment

Corrosion of embedded steel produces high-volume corrosion products and high stresses in the surrounding concrete, leading to physical damage that may include delaminations, spalling, or cracking. The most common damage assessment method is visual examination, which is used to identify and size cracks and extent of spalling. In addition, visual examination may also be used to determine areas where efflorescence has occurred and to identify rust staining of concrete.

More sophisticated techniques are required to detect delamination caused by rebar corrosion. Delaminations create an interface that affects the speed at which the sound travels and thus the time in which an echo is detected. The delamination interface is probed by sounding methods using a calibrated striking hammer and sound-detection equipment. The known thickness of the concrete can then be compared to the results of the sounding measurements to determine if delamination has occurred. Other nondestructive techniques such as UT measurements and adapted ground-penetrating radar measurements have been used to detect and size delaminations and to determine the depth and position of rebar. Drilling core samples is a destructive technique, but this method can be use to verify nondestructive assessment, particularly when repairs are anticipated.

Descriptions and assessments of methods to evaluate concrete and corrosion of steel in concrete have been extensively reviewed, and further assessment is beyond the scope of this report. The reader is referred to the numerous available references on the subject that are specific to NPPs (Naus, 1986; Naus et al., 1996; IAEA, 1998; IAEA, 2002; IAEA, 2005; Naus et al 1996; Naus et al., 2005).

4.3.3 Corrosion Prevention and Mitigation

A wide number of corrosion prevention and mitigation methods have been used for concrete structures. For both prestressed and reinforced concrete structures, coatings and sealers that limit the penetration of moisture and contaminants may be applied to the surface. Concrete overlays with low permeability have also been developed. Corrosion inhibitors and water displacing grease has been used in the tendon sheaths of post-tensioned structures. For reinforced structures, a number of corrosion protection methods have been used including corrosion-resistant rebar, coated rebar, corrosion inhibitor in addition to concrete mixtures and the use of cathodic protection.

Sealers are liquids applied to the surface of hardened concrete to either prevent or decrease the penetration of liquid or gases, especially to limit the ingress of water, carbon dioxide, chlorides, or aggressive species (Naus et al., 1996). Sealers may include boiled linseed oil, sodium or potassium silicates, stearates, silicones, asphaltic emulsion, and cementitious formulations. Sealers are commonly applied to bridge decks to prevent chloride ion ingress associated with the use of deicing salts. Sealer formulations for bridge decks include polyurethanes, methyl methacrylates, certain epoxy formulations, relatively low molecular weight siloxane oligomers, and silanes. Coatings and membranes are usually thicker than sealers and generally do not penetrate the concrete. Coating types include epoxy resins, polyester resins, acrylics, vinyls, polyurethanes, and cementitious materials. Membrane types include liquid applied acrylics, urethanes, neoprenes, vinyls, rubberized asphalts, silicones, and preformed membranes such as rubberized asphalts, neoprenes, and butyl rubbers, hypalons, vinyls, and ethylene propylene diene (Naus et al.,1996). Polymer, latex, and silica-fume containing concrete overlays have been developed to significantly reduce chloride ion penetration. Overlays are generally applied in much greater thickness compared to either sealers or coatings. Polymer injection has also been shown to lower chloride ion permeability; however, this technology is currently regarded as experimental (American Concrete Institute, 2009b).

Rebar coatings have been applied to protect the reinforcement in concrete structures in aggressive environments. Three types of coatings have been applied. Epoxy coatings are designed to protect the rebar from corrosion using a non conductive coating that prevents moisture and contaminants from contacting the underlying steel. Numerous issues have been observed including the exposure of steel where the rebar is cut and the degradation of the coating that results in isolated areas where the steel is exposed (American Concrete Institute 2009b). Sacrificial metal coatings such as galvanized zinc coatings have been used in some marine applications. Because zinc will corrode in concrete exposed to aggressive environments, the application of galvanized coatings can be expected to only delay rather than prevent the onset of rebar corrosion induced damage to the concrete structure (American Concrete Institute 2009b). Protective metal coatings such as nickel and copper are designed to prevent corrosion by the use of a corrosion-resistant metal layer that prevents exposure of the rebar to the concrete. Defects in the coatings lead to isolated regions where the steel is exposed and in contact with the more noble metal. As a result of the unfavorable small anode (steel) and large cathode (metal coating), galvanic corrosion of the steel occurs at an accelerated rate. Rebar produced with a composite structure incorporating a thick stainless steel outer layer with a carbon steel interior has been developed to reduce the use of costly corrosion resistant metals but still provide enhanced corrosion resistance.

Cathodic protection of reinforced steel structures is usually limited to high-value structures in corrosive environments such as bridges in marine atmospheres. The approach to cathodic protection is similar to other steel engineered structures such as pipelines and offshore marine platforms. Both imposed current and sacrificial anode systems have been used. The cathodic current density necessary to maintain a passive layer on the reinforcing steel before the reinforced concrete is contaminated with chlorides; is relatively low. Typical operating current densities range between 0.2 and 2.0 mA/m^2 (0.02 – 0.2 mA/ft^2) for new reinforced concrete structures. For existing salt-contaminated structures, operating current densities range between 2 to 20 mA/m^2 [0.2 – 2 mA/ft^2] (American Concrete Institute, 2009b).

4.4 Plant Location

As previously described, aging of concrete can result in physical and chemical changes that may significantly affect the corrosion of reinforcement and the steel containment liner. Carbonation may lead to accelerated corrosion rates for the steel as a result of decreased passive film stability at pH values below 10. Corrosion of the steel reinforcement and the liner may also be affected by chloride ingress. However, because of the thickness of the concrete shield building, the time necessary for carbonation and chloride ingress to occur is expected to be very long. Cracking and either carbonation or chloride ingress may be postulated as a mechanism for degradation although the combined effects are only likely over extended operational periods.

Location may be important for aging affects. Concrete cracking as a result of freeze and thaw cycles are much more likely in northern regions. An assessment of the environmental effects on the corrosion of steel in concrete is limited and difficult to apply to operating NPPs. It is known that the application of deicing salts, particularly in the northeast and the upper Midwest States contributes to the corrosion of reinforced bridges and highway structures. Similarly, the chloride ingress into concrete structures in brackish waters in the southern United States and in coastal regions is a known problem. Long-term environmental effects on steel in concrete and steel containment liners may be similar to the known effects for atmospheric exposure of steel with the obvious exception that the process will be slowed by the thickness and chemistry of the concrete. Atmospheric corrosion rates are dependent on the time of wetness from both high humidity and precipitation, chloride concentration, and sulfur dioxide concentration (Matsushima, 2000b; Tullmin and Roberge, 2000). Sulfur dioxide is an atmospheric pollutant from industrial processes and also a significant contributor to acid rain. Chloride concentration is typically controlled by distance to an ocean or gulf.

The National Atmospheric Deposition Program has monitoring stations through the United States and measures the deposition of chloride, sulfate, precipitation pH, and cumulative precipitation. Deposition maps for these monitored parameters from 2008 are shown in Figures 10 to 13. Precipitation is greatest in the eastern United States and in the upper northwest. Figure 11 shows hydrogen ion concentration measured as pH. Acidic pH values below 5 are concentrated in the Midwest, Mid Atlantic, and New England States. This is primarily due to industrial pollutants such as sulfur dioxide. A deposition map for sulfur dioxide is not available, but Figure 12 shows the deposition of sulfate. In general, the sulfate deposition is similar to the pattern for acidic precipitation. Figure 13 shows chloride deposition. Clearly the highest concentration of chloride is along the coastal regions.

The corrosion of the containment liner and the rebar at Beaver Valley 1 in 2006 was attributed in part to atmospheric exposure during construction. Among the aging related degradation mechanisms reported as a result of the IAEA survey were chloride ingress of seawater intake structures, water ingress through cracks, and contamination of corrosion inhibitors. At Beaver Valley Unit 1 in 2006, analysis of the concrete pH showed values in the range of 10.62 to 10.67. Although significantly lower than 12.5 expected for concrete, carbonation of the concrete was not identified as a contributing factor for the corrosion of the liner. Some chlorides (0.56 ppm) were also identified in the Beaver Valley Unit 1 concrete samples. Analysis was not able to definitively determine the role of chloride in the corrosion (FirstEnergy, 2009). However, the low chloride concentrations observed in Beaver Valley 1 are not likely to be significant given that previous studies have indicated that chloride concentration for pitting is generally at or above 10 ppm (Szklarska-Smialowska, 1986).

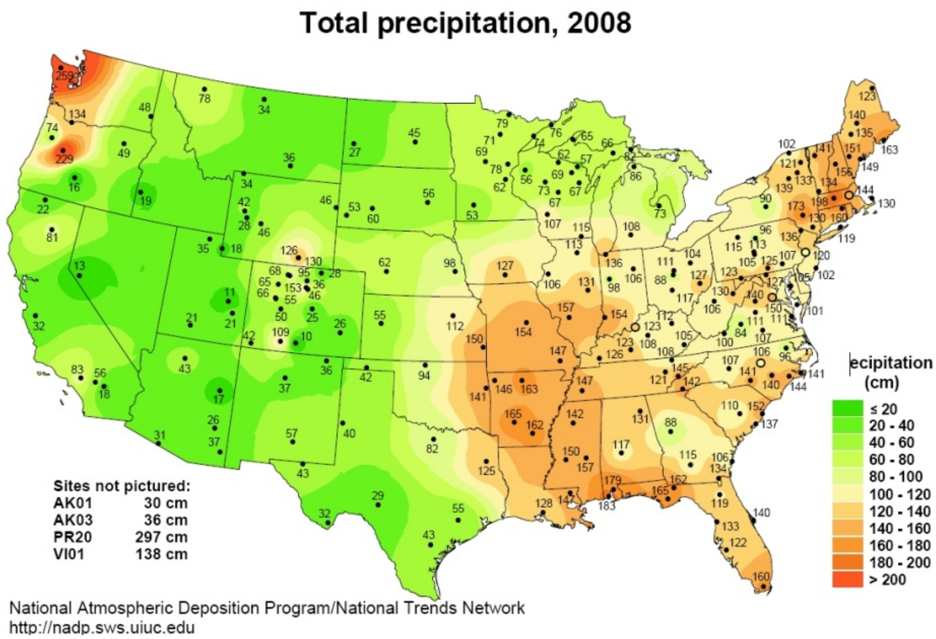

Figure 10. Precipitation Total for the United States in 2008.

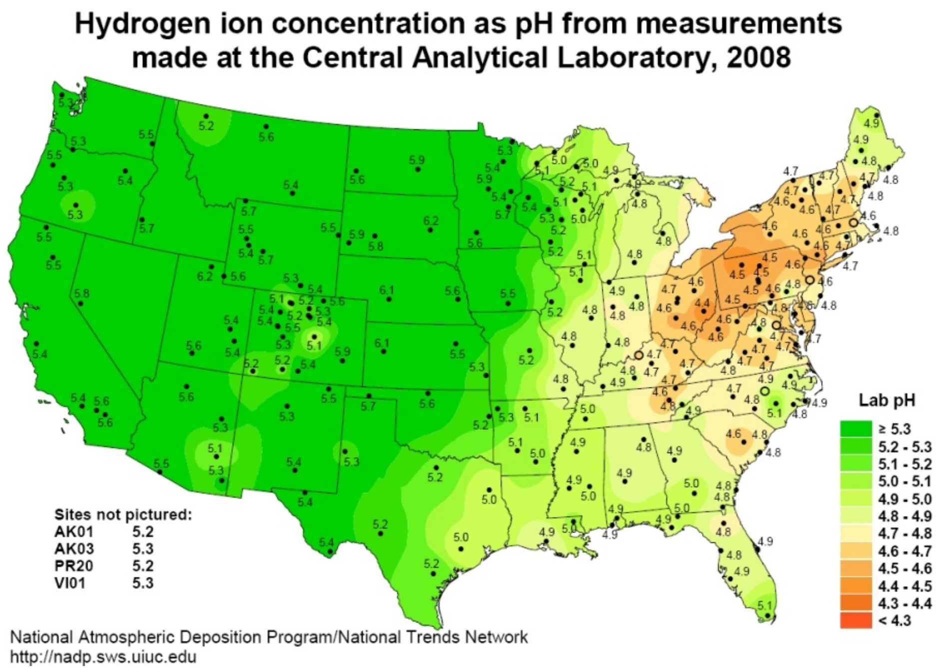

Figure 11. Hydrogen Ion Concentration in Precipitation as pH Measurements for the United States in 2008.

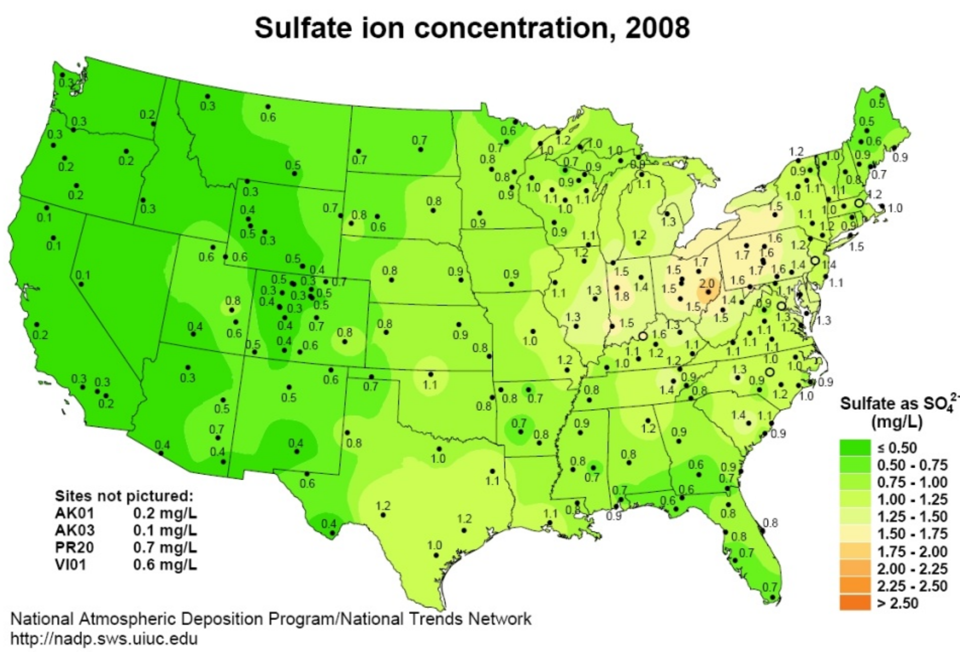

Figure 12. Sulfate Ion Concentration in Precipitation for the United States in 2008.

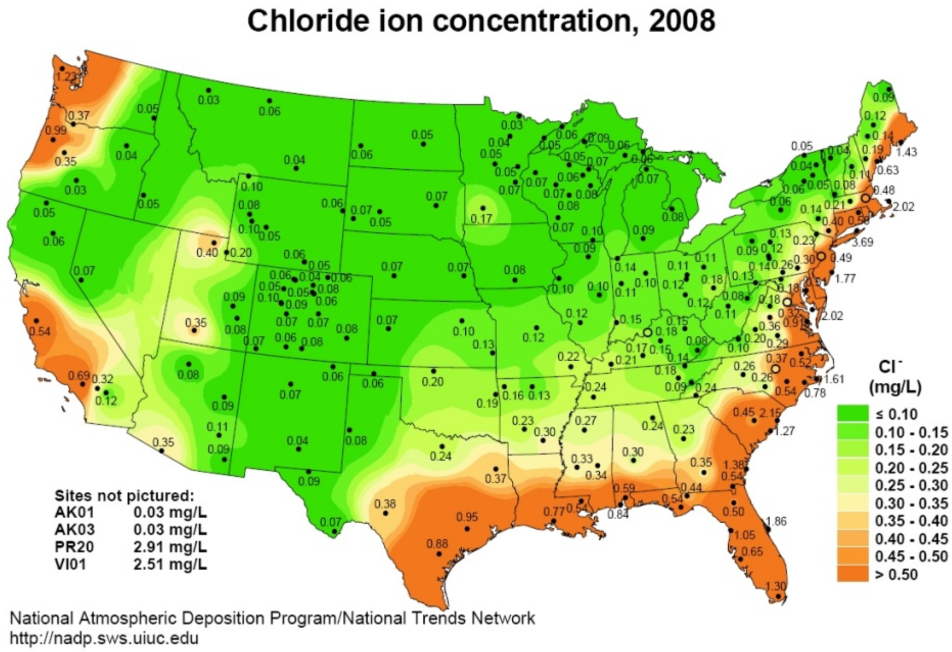

Figure 13. Chloride Ion Concentration in Precipitation for the United States in 2008.

5. Summary

The focus of this work was to evaluate the corrosion of the steel containment liner that has initiated from the exterior surface that is in contact with the concrete containment structure. Available information on corrosion-related degradation of steel containment liners used with reinforced or prestressed post-tensioned concrete containment structures was reviewed. The following summary is based on the review of the available information from compiled from a variety of sources including NRC inspection reports, licensee inservice inspection reports, operational experience, and NRC informational notices.

- Sixty-six nuclear power plants in the United States have containment buildings constructed with carbon steel liners in contact with concrete. This includes a total of 55 pressurized-water reactors (PWRs) and 11 boiling-water reactors (BWRs). Of PWRs, 19 plants are reinforced concrete construction and 36 are post-tensioned concrete. For the BWRs, all 11 plants have reinforced drywells; 9 plants also have reinforced wetwells and 2 have post-tensioned wetwells.

- Instances of containment liner corrosion initiated from the outside surface at the concrete/steel liner interface have been observed at four U.S. plants. All four plants were reinforced concrete construction. In most cases, corrosion at the concrete/liner interface was initiated where foreign material was embedded in the concrete and in contact with the liner. Through-wall corrosion of the containment liner has been observed at three plants.

- Four additional cases exist where foreign material was found to be embedded in the concrete containment structure. In all four cases, the foreign material was wood that was used during the original construction. In one of these cases, a wood piece extended all the way though the concrete and was in contact with the containment liner; however, no measurable corrosion of the liner occurred.

- Of the eight NPPs with embedded foreign material, six NPPs were reinforced concrete construction with and three were subatmospheric plants. The eight known cases of embedded foreign material in the concrete occurred at plants built by four companies as the primary construction contractor.

- Significant corrosion of a containment penetration sleeve was caused by moisture trapped in felt intentionally wrapped around the on the outside of the sleeve to allow thermal expansion.

- Foreign materials such as wood and worker's gloves or organic materials such as felt have been shown to promote the corrosion the steel liner. Wood is naturally acidic and may disrupt the passivitiy of carbon steel. In addition, these materials may retain moisture, promote crevice corrosion, and be the source of acidic decomposition products.

- International operating experience suggests that the presence of voids in the concrete adjacent to the containment liner also may promote corrosion. Voids in the concrete and liner bulges, where the liner is physically separated from the concrete, have been observed several U.S. NPPs.

- It is unclear if differences in plant design and operation affect the susceptibility to corrosion of containment liners that is initiated at the liner/concrete interface.

- Although not the main focus of this study, liner corrosion initiating on the inside surface of containment liners due to degraded or damaged coatings and water collection behind moisture barriers occurs more frequently than corrosion at the liner/concrete interface. NRC-required inspections have resulted in early detection and mitigation of damaged coatings and moisture barriers.

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