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Nuclear Containment Steel Liner Corrosion Workshop: Final Summary and Recommendation Report

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Abstract

This report documents the proceedings of an expert panel workshop conducted to evaluate the mechanisms of corrosion for the steel liner in nuclear containment buildings. The U.S. Nuclear Regulatory Commission (NRC) sponsored this work which was conducted by Sandia National Laboratories. A workshop was conducted at the NRC Headquarters in Rockville, Maryland on September 2 and 3, 2010. Due to the safety function performed by the liner, the expert panel was assembled in order to address the full range of issues that may contribute to liner corrosion. This report is focused on corrosion that initiates from the outer surface of the liner, the surface that is in contact with the concrete containment building wall. Liner corrosion initiating on the outer diameter (OD) surface has been identified at several nuclear power plants, always associated with foreign material left embedded in the concrete. The potential contributing factors to liner corrosion were broken into five areas for discussion during the workshop. Those include nuclear power plant design and operation, corrosion of steel in contact with concrete, concrete aging and degradation, concrete/steel non-destructive examination (NDE), and concrete repair and corrosion mitigation. This report also includes the expert panel member's recommendations for future research.

EXECUTIVE SUMMARY

This report summarizes the proceedings and recommendations from an expert panel workshop conducted to evaluate the mechanisms of corrosion for the steel liner in nuclear containment buildings. The U.S. Nuclear Regulatory Commission (NRC) sponsored this work which was conducted by Sandia National Laboratories. A workshop was conducted at the NRC Headquarters in Rockville, Maryland on September 2 and 3, 2010. Due to the safety function performed by the steel liner for concrete containments, the expert panel was assembled in order to address a range of issues that may contribute to liner corrosion. The panel examined potential contributing factors to liner corrosion that were divided into five areas for discussion during the workshop. Those areas include nuclear power plant design and operation, corrosion of steel in contact with concrete, concrete aging and degradation, concrete/steel non-destructive examination (NDE), and concrete repair and corrosion mitigation.

The panel included Dr. Jason Petti, Dr. Dan Naus, Professor Alberto Sagüés, Professor Richard Weyers, Mr. Bryan Erler, and Dr. Neal Berke. Each of these panel members attended the workshop and contributed to this document. Two members of the Electric Power Research Institute (EPRI), Mr. Henry Stephens and Mr. Nathan Muthu, also attended and participated at the workshop.

Corrosion of containment liners has been observed on both the inside surfaces and on the outside surface that is in contact with the concrete building structure. Corrosion initiated on the interior liner surface has been observed with degraded moisture barriers or protective coatings when water has accumulated at the inner surface of the liner. Corrosion initiated on the outer surface of the liner, or the surface that is in contact with the concrete containment building wall, has been associated with foreign material left embedded in the concrete. While both interior and exterior initiated corrosion were discussed by the panel and in this report, the workshop and this summary focus on corrosion initiated at the liner/concrete interface, or outer diameter corrosion (OD-corrosion). The current known cases of through-wall corrosion of steel containment liners in domestic plants are restricted to instances of embedded foreign material in containment buildings with reinforced concrete construction. The higher density of the rebar in reinforced concrete containment may increase the probability that embedded foreign material was inadvertently left in place during original construction as compared to prestressed containments. Macrocell-accelerated localized corrosion appears to be the corrosion mechanism for OD-corrosion of steel containment liners. Corrosion is initiated by the presence of an embedded foreign material at the concrete/liner interface that may act as a crevice former and alters the local chemistry preventing passivation of the steel liner. A macrocell is formed because the local anodic area where active corrosion is occurring is coupled to a large cathodic surface that consists of multiple layers of rebar and passive sections of the liner immediately adjacent to the anodic area. Once initiated, localized corrosion can continue to propagate over a period of many years because the thick sections of concrete have sufficient water content and the ionic conductivity necessary to support the electrochemical corrosion reactions. While other mechanisms could be explored further, there is no evidence that they have contributed to OD-corrosion. Although not observed in operating plants to date, the panel identified one potential long-term degradation mechanism that could have effects on OD-corrosion. Specifically, ettringite (mineral formed during the hydration of cement) formation and dissolution coupled

with the presence of an embedded foreign material and high containment temperatures, could lead to conditions that promote corrosion of the liner.

The current state of NDE technology is not capable of effectively detecting OD-corrosion when considering the size of the containment structures and the area of the liner surface. While ultrasonic inspections can detect corrosion at point locations, there is no currently available technology for using this over large areas. Current concrete and liner repair methods are well established and are not considered an issue. Mitigation methods, mainly cathodic protection, are not considered practical for preventing liner corrosion.

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The opinions provided in this report and executive summary are those of the panel members and do not reflect the opinions or position of the NRC or NRC staff. The statements, opinions, and recommendations provided in this document are not intended to be used directly in any regulatory capacity, but are being provided to the NRC for informational purposes.

1. Introduction

This report summarizes the proceedings and recommendations from an expert panel workshop conducted to examine the issue of nuclear containment steel liner corrosion. The workshop was organized and conducted by Sandia National Laboratories and held at the U.S. Nuclear Regulatory Commission (NRC) Headquarters in Rockville, Maryland, on September 2 and 3, 2010. Due to the safety function performed by the steel liner for concrete containments, the expert panel was assembled in order to address the range of issues that may contribute to liner corrosion.

Corrosion of containment liners has been observed on both the inside surfaces and on the outside surface that is in contact with the concrete building structure. Corrosion initiated on the interior liner surface has been observed with degradation of the moisture barrier or protective coatings when water has accumulated at the inner surface of the liner. Corrosion initiated on the outer surface of the liner, or the surface that is in contact with the concrete containment building wall has been associated with foreign material left embedded in the concrete. While both interior and exterior initiated corrosion were discussed by the panel and in this report, the workshop and this summary focus on corrosion initiated at the liner/concrete interface, or outer diameter corrosion (OD-corrosion).

The potential contributing factors to liner corrosion were divided into 5 areas for discussion during the workshop. Those include nuclear power plant design and operation, corrosion of steel in contact with concrete, concrete aging and degradation, concrete/steel non-destructive examination (NDE), and concrete repair and corrosion mitigation.

The panel includes Dr. Jason Petti, Dr. Dan Naus, Professor Alberto Sagüés, Professor Richard Weyers, Bryan Erler, and Dr. Neal Berke. Each of these panel members attended the workshop and has contributed to this document. Table 1 summarizes the panel members, their affiliations, and their individual areas of expertise. Two members of the Electric Power Research Institute (EPRI), Henry Stephens and Nathan Muthu, also attended and participated at the workshop.

Table 1. Expert panel members and participants

Member	Affiliation	Expertise
Dr. Jason Petti*	Sandia National Laboratories	Containment structural integrity, degraded containment risk analysis
Dr. Dan Naus	Oak Ridge National Laboratories	Aging management, containment design and construction, NDE
Professor Alberto Sagüés	University of South Florida	Corrosion, concrete degradation
Professor Richard Weyers	Virginia Tech	Corrosion, concrete degradation and repair
Bryan Erler	Erler Engineering Ltd., ASME Board of Nuclear Codes and Standards	Containment design and construction
Dr. Neal Berke	Tourney Consulting Group (formerly of Grace Construction Products)	Corrosion, concrete aging and characterization
Henry Stephens**	EPRI	Containment design, NDE
Nathan Muthu **	EPRI	Containment liner NDE

Organized and conducted workshop (*)
Non-panel member participants (**)

The goals of the workshop and this summary report are to identify the key elements that contribute to or affect liner corrosion. These elements include examining:

- effects of construction, design, and operation of nuclear power plants on concrete defects and steel corrosion, liner corrosion mechanisms and parameters that increase susceptibility to these mechanisms,
- aging and environmental effects that contribute to degradation of concrete containment structures and corrosion of the steel liner,
- methods for evaluating aging effects and degradation of concrete,
- current methods and limitations of non-destructive examination techniques for evaluating degradation in concrete and corrosion of the liner, and
- experience with methods to mitigate concrete degradation and corrosion of the liner.

Each of these elements is addressed and organized in this report as follows. Section 2 provides a summary of the background information on containment liner corrosion. Sections 3 through 7 describe each of the five technical areas discussed during the workshop: Section 3 on nuclear power plant containment design, construction, and operation, Section 4 on corrosion of steel containment liners, Section 5 on concrete aging and degradation, Section 6 on non-destructive evaluation methods for assessing steel liners, and Section 7 on concrete repair and corrosion mitigation. Each of these sections describes the technical questions and concerns specific to each area and concludes with a short assessment on how that area addresses or affects OD-corrosion. Section 8 summarizes the panel's discussions and findings and Section 9 lists recommendations on potential areas of suggested future research. The areas of recommended future research are those identified by the panel to not only have a potentially important role in liner corrosion, but also those where a significant gap in knowledge exists. Finally, two Appendices are included. Appendix A provides the expert panel's list of recommended procedures and tests that could provide insights into the degradation mechanisms when a new case of corrosion is discovered. Appendix B includes a series of tables addressing the five technical areas that were used during the workshop to drive the discussions.

2. Background on Containment Corrosion

Currently, there are 104 operating commercial nuclear power plants in the United States. These are divided among two different plant types, boiling water reactors (BWR) and pressurized water reactors (PWR). Of the 104 plants, 35 are BWRs and 69 are PWRs. The designs of each containment building vary considerably with very few identical designs (Hessheimer and Dameron, 2006). A summary of the types of containments is provided in Dunn et al., (2010). For this workshop study, only the plants that employ a concrete containment structure with a steel liner are of interest. Therefore, 55 of the 69 PWRs and 11 of the 35 BWRs are relevant for the discussions in this summary report. The specific containments that use a steel lined concrete containment are listed in Tables 1 and 2 of Dunn et al., (2010).

In order to identify degradation, containment inspections are required as specified by American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code Section XI, Subsections IWE and IWL, as incorporated by reference in 10 CFR Part 50.55a (Title 10 of the Code of Federal Regulations). In addition to the leakage tests required during initial plant startup, periodic leak tests are also conducted throughout the life of the plant to ensure the ongoing integrity of the containment. Appendix J of 10 CFR Part 50 also requires visual inspections of the containment to search for degradation or other anomalies. Current NRC requirements, for most plants, call for an integrated leak test every 10 years (Regulatory Guide 1.163 (Rev. 0) NRC (1995), endorsement of NEI-94-01 (Rev. 0) NEI (1995)) and the inspection requirements identified in Section XI Subsections IWE and IWL of the ASME B&PV code.

Numerous cases of liner corrosion were discovered over the early lifetime of the nuclear power plant fleet. The causes of these instances of corrosion included degraded coatings, degraded moisture barrier seals, or water accumulation from various sources (Dunn et al., 2010). This led to the implementation of modifications to the inservice inspection requirements in 10 CFR Part 50 during the mid-1990s. Since these changes, 3 cases of through-wall, OD-corrosion of containment liners have been discovered between 1999 and 2009 (Dunn et al., 2010). The 3 incidents occurred at Brunswick Unit 2 in 1999, North Anna Unit 2 in 1999, and Beaver Valley Unit 1 in 2009 (NRC 2004; 2010). At Brunswick Unit 2, three areas of through-wall liner corrosion were identified. Two locations were pitting corrosion initiated on the interior surface where the protective coating had degraded. The third location was the result of corrosion initiated at the concrete/liner interface that initiated where a worker's glove that was embedded in the concrete and in contact with the steel liner. At North Anna Unit 2, one area of though-wall liner corrosion was detected that was initiated at the location where a piece of wood left embedded in the concrete. At Beaver Valley Unit 1, a region of blistered paint on the steel liner was observed during a visual examination. Upon removal and cleaning of the blistered region, a through-wall region of corrosion was revealed. As with the previous cases, a piece of wood was found after the damaged section of the liner was removed. In all cases, the areas were cleaned and repaired, and the plants returned to service.

In addition to the three cases of through-wall corrosion, a 3/16 in (4.8 mm) diameter through-wall hole was discovered in the containment liner at D.C. Cook Unit 2 in 2001 (Indiana Michigan Power Company, 2002). The hole was described by the licensee to be an improper repair of a hole drilled during construction of the containment building. During the ultrasonic inspection of the area surrounding the through-wall hole, two regions of reduced thickness were detected. One region was concluded to have been caused by water intruding through the hole. The second area of reduced liner thickness led to the discovery of a wooden-handled wire brush in contact with the liner. The wire brush was removed and the region of concrete and steel liner was repaired.

At some PWRs, the activities surrounding the replacement of steam generators and reactor pressure vessel heads have allowed visual observation of the OD liner surface that is normally in contact with concrete enabled additional corrosion data to be collected. The vast majority of the PWR fleet has undergone at least one of the replacements. At 21 of the currently operating PWRs, these replacements were performed by cutting a hole through the concrete, rebar, and steel liner of the containment in order to create an approximately 6 m by 6 m (20 ft by 20 ft) opening. During the process for these replacements, the concrete was first hydroblasted, sawed, or jackhammer chipped away from the rebar and the steel liner, leaving them exposed. In Dunn et al. (2010), the reports of these activities were reviewed for information related to the condition of the steel liner. While the reports were not required to include details of the liner condition, at least one plant observed liner corrosion. At Beaver Valley Unit 1 in 2006, three regions of corrosion in the liner were discovered at the surface that had previously been in contact with concrete. The depth of these corroded regions varied between 1.1 and 5.8 mm (0.04 and 0.23 in). Since steel liners are constructed with between 6.4 and 10 mm (0.25 and 0.375 in) thick plates, the metal loss in these corroded regions was a significant percentage of the thickness. No clear cause was determined though the corrosion could have occurred early in the plant's life due to exposure to oxygen and water; however, any evidence of foreign material (wood) embedded in the concrete may have been destroyed during the hydroblasting process.

Recent inservice inspection reports dating back to 2000 have provided additional data on corrosion discovered in the liners of other BWR and PWR plants (Dunn et al., 2010). Of the 11 BWR plants with steel lined concrete containments, degradation of the moisture barrier causing degradation of the liner coating and liner occurred at two plants, interior liner corrosion was discovered in five cases, exterior liner corrosion leading to liner bulging was observed at one plant, and one plant reported embedded foreign material (Brunswick Unit 2 as discussed earlier). Of the 36 prestressed (or post-tensioned) concrete PWR plants (tendons internal to the concrete containment walls tensioned to induce compression in the concrete), exposed rebar were found at six plants, concrete voids were discovered at one plant, two cases of embedded foreign material were reported, and 16 plants observed internal liner surface corrosion due to degradation of the coatings or moisture barriers. Of the 19 reinforced concrete PWR plants, one case of exposed rebar was reported, one instance of bulging liner was discovered, five cases of embedded foreign material were found (three of which had through-wall corrosion as discussed earlier, North Anna Unit 2, D.C. Cook Unit 2, Beaver Valley Unit 1), and seven cases of internal surface corrosion were caused by failures of the coatings or moisture barriers. Dunn et al., (2010) includes additional details on these instances.

3. Nuclear Power Plant Containment Design, Construction, and Operation

The concrete containments for domestic PWRs and BWRs have a significant variation in the containment system and structural design. However, the liner design was similar across all 66 PWR and BWR containments of interest in this report. Due to the differences in containment designs, it is necessary to evaluate the impact that the major design considerations may have on liner degradation. The areas of interest discussed at the workshop included the system design, the containment structural design, the containment liner design, and plant operation.

3.1 Summary of Workshop Key Findings

3.1.1 Containment System Design

Achieving the required containment licensing basis is not limited to only the structure itself, but includes the overall containment system including isolation valves, bellows, sprays and chiller systems. All of these components must be effective in order to provide the licensing basis function of the containment.

There are primarily two types of systems for containments. The first is for a dry containment in which the steam from the reactor is released directly into the containment in the event of a loss of coolant accident (LOCA). The steam does not pass through any water or ice to reduce the pressure in the containment and therefore results in containments that are designed for higher pressures (0.34–0.41 MPa, 50–60 psig) and are generally larger. These containments are used for most PWRs. The second type of containment uses pressure suppression where the steam from a LOCA is passed through ice (PWR ice condenser) or water (BWR suppression pool) to condense the steam and reduce the pressure in the containment. Generally this results in smaller containments (BWR MK I and II containments). PWR ice condenser containments and BWR MK III containments, being relatively large, result in containment design pressures from 0.069–0.10 MPa (10–15 psig). The steel lined concrete BWRs range from low design pressure (0.10 MPa, 15 psi) and high volume Mark IIIs, to high design pressure (0.31–0.43 MPa, 45–62 psi) and low volume Mark Is and IIs. The lower design pressure containments require less prestressing or reinforcing steel. However, the presence of water or ice inside the containment for the BWRs and the PWR ice condensers could increase the likelihood of creating an environment conducive to inner surface liner corrosion.

One case of through-wall corrosion was at Brunswick Unit 2 which is a BWR. The other two cases of through-wall corrosion occurred at PWR containments (North Anna Unit 2 and Beaver Valley Unit 1) both of which were originally subatmospheric designs. Subatmospheric containments are operated with a slightly negative pressure within the containment, several psi below atmospheric pressure. This negative pressure could conceivably pull the liner away from the concrete creating a region for increased corrosion on the OD surface. However, this is not considered more likely that gap due to original construction. In addition, the panel concluded that the subatmospheric nature of these containments is not thought to contribute to an increased probability of liner corrosion. It is noted that the containment buildings at Beaver Valley Units 1 and 2 have been converted to atmospheric pressure operation.

3.1.2 Containment Structural Design & Construction

Both reinforced and prestressed concrete containments are designed to the same code (ASME B&PV Code Section III, Division 2) or the equivalent practice at the time. The design of these containments is controlled by the design seismic level required for the site, the containment volume and the internal pressure caused by the release of coolant and the formation of steam in a LOCA. Given a specific design pressure and containment volume, the requirements for the containment structure can be explored. The larger the diameter and height used for the containment, the higher the seismic and pressure loads on the structure. This leads to larger design forces in the containment wall which increases the required amounts of prestressing or reinforcing steel, especially near the bottom of the containment.

Dry reinforced concrete containments typically are cylinders with hemispherical domes and contain heavy reinforcing using #14 bars with a diameter of 4.3 cm (1.7 in) or #18 bars, with a diameter of 5.7 cm (2.3 in). The rebars are spaced in both the vertical and circumferential direction, in addition to diagonal bars to handle the seismic tangential shear. The concrete strength used in reinforced concrete containments was typically around 24 to 34 MPa (3500 to 5000 psi). The placement of the concrete within these heavily reinforced 1.2 to 1.5 m (4 to 5 ft) thick walls proved challenging during construction. This was mainly due to the high rebar density levels. Avoiding the formation of voids in the concrete and near the rebar was a continuing concern.

Dry prestressed concrete containments are typically cylindrical with either a hemispherical or shallow dome. Due to the high strength steel of the prestressing tendons, the amount of reinforcing steel is reduced and allows for easy concrete placement during construction. The reinforcing was typically heavier around large openings and at discontinuities such as the base mat or dome ring. However, the prestressed containments are still lightly reinforced when compared to the reinforced concrete containment. The prestressed containments typically used a maximum of #11 bars, with a diameter of 3.6 cm (1.4 in). Due to the high compressive stresses induced in the prestressed containments, concrete with a strength up to 40 MPa (6000 psi) was typically required. This made the consolidation, or removal of entrapped air, critical for the prestressed containments. However, consolidation was not considered problematic or especially difficult due to the light reinforcing steel density.

The liner acts as the inner form for the concrete during construction. Steel tie bars are mechanically attached to the liner and the outer concrete form. The outer forms are removed after concrete curing but the tie bars are embedded in the concrete may electrically connect the liner to the multiple layers of rebar. This could be an important factor in any corrosion progression.

Finally, the placement of the concrete was performed in lifts. The time between pours could have spanned several weeks. This time between pours could have increased the chance of foreign material falling on top of the previous pour and not being removed prior to the subsequent pour. This could be a factor for both reinforced and prestressed containments.

Corrosion starting from the concrete side of the liner and corroding through to the interior surface of the liner has only been discovered, to-date, as a result of foreign material being left in place during original construction. Two instances (out of 36 PWR plants) of foreign material were found in prestressed containment plants, but neither caused through-wall corrosion. In both cases, relatively small pieces of foreign material were not in contact with the liner, but were located near the outer surface of the concrete containment walls. For the 19 reinforced concrete PWR containments, four plants reported foreign material with two of these causing through-wall corrosion. Construction experience with both types of containments demonstrated that removal of construction materials prior to a new concrete pour was easier in prestressed concrete than for reinforced concrete due to the lesser congestion of rebar. This could cause an increased probability of foreign material being left in reinforced concrete containments.

In the previous section, it was stated that the negative pressure operation of subatmospheric containments was not believed to increase the likelihood of corrosion. However, the structural design may be different enough to be of significance. Specifically the rebar density and rebar distribution in the areas where foreign material was embedded could have increased the likelihood of material being left in-place during concrete placement. Two of the through-wall corrosion cases were found at subatmospheric plants and therefore the structural design of those plants could be studied further. This could possibly identify whether or not there are regions of the containment that may have been more susceptible to having foreign material embedded in the concrete.

3.1.3 Containment Liner Design

The liners of all containments have been designed in accordance with the requirements of ASME B&PV Code Section III, Division 2, or equivalent, which uses strain and deflection limit criteria rather than strength criteria. All containments basically use the same design criteria; however, there was variation in the liner anchor details, wherein some used angle and channel sections while others used welded studs. The reinforced concrete containments tended to use welded studs so the reinforcing could be closer to the liner. The prestressed concrete containments generally used angles.

The anchors were sized to assure the anchor would fail before the liner in order to prevent liner tearing, assuring continual leak tightness. Tolerances issues with the liner are not considered significant since bulges in the liner between anchors are acceptable in design and do not impact liner structural performance. The prestressed containments have increased levels of liner bulging due to the nature of the compression induced in the concrete walls. Liner bulging may be of concern in increasing the probability of corrosion due to the gap introduced between the liner and the concrete. This is discussed Section 4.

3.1.4 Operating Experience

Corrosion from the inside surface of the containment liner tends to be located in areas of water accumulation on liner sections with damaged coatings or degraded moisture barriers near the base of the dry containment where the inside concrete slab meets up against the liner. The maintenance of the liner coating and moisture barrier is critical to prevent this corrosion. In cases were internal air conditioning is used, there will be an increased likelihood of condensation on the internal liner surface. The internal surface of the liner is coated to protect against corrosion. Because the steel liner is relatively thin, the thermal gradient through the thickness of the liner is likely to be small. As a result, cooling of the liner that results in condensation on the interior surface may also lead to condensation at the liner/concrete interface.

Nuclear plants typically shut down every 18 to 24 months to refuel the reactor. Several issues surround the effects of plant outages. First, the operating temperature within the containment drops from ~60^{o}C to ambient temperature. Second, water is introduced when washing the interior containment surfaces. The drop in temperature and water introduction would increase the condensation on the liner surface. The potential effects of condensation on corrosion of the liner are discussed in Section 4.

3.2 Design, Construction, and Operation Expert Panel Assessment

Based on the cases of OD-initiated corrosion, embedded foreign material in the concrete appears to be the main driver in causing through-wall corrosion. The higher density of the rebar in reinforced concrete containment could plausibly increase the likelihood for those plants to have embedded foreign material compared to prestressed concrete containments. Focusing on reinforced concrete containments for future study may be appropriate. However, prestressed and reinforced concrete containments may both be susceptible due to material falling onto the top surface of the concrete lifts between pours. In addition, the panel concluded that there is no evidence of an increased probability of liner corrosion in subatmospheric containments. A more detailed study of the locations of discovered foreign material compared to the structural design (rebar layout) and lift locations in those areas could also be beneficial in determining the most significant contributor to this type of corrosion.

4. <u>Corrosion of Steel Containment Liners</u>

An understanding of the potential mechanisms that could lead to corrosion of the steel liner is critical to assessing the severity of this problem. The factors addressed during the workshop include general corrosion versus corrosion associated with embedded foreign material, sources of oxygen and moisture, effects of concrete cracking, plant location, and other factors that may increase the susceptibility of the liner to corrosion.

4.1 Summary of Workshop Key Findings

4.1.1 Corrosion associated with embedded foreign material

The workshop discussions focused on scenarios where foreign materials (e.g., wood or other objects) were assumed embedded in the concrete and positioned in contact with the steel liner. The background to the potential mechanism leading to corrosion is described below.

The following widely recognized observations were first recalled as background to the mechanistic discussion. Steel in contact with the highly alkaline (pH >~13), contaminant-free, concrete pore water soon develops a stable oxide/hydroxide passive film. This film lowers the rate of the anodic (corrosion) reaction to an extremely low value, on the order of a small fraction of 1 μm/year when expressed as a corrosion rate (Sagüés et al., 2003). At that rate, penetration of an 8- to 10-mm (0.3- to 0.4-in) thick liner wall would not be an engineering concern.

However, disruption of the passive film can and does take place if the pore water pH drops and becomes appreciably lower (e.g., pH<~10), or if the concrete concentration of chloride ions at the steel-concrete interface exceeds a threshold level (e.g., several hundred parts per million of the concrete density). Contaminants including other halides and sulfate ions could have a similar effect. Contaminants and pH decrease could act synergistically as well, so disruption could occur with lesser extents of either factor if they are present simultaneously.

A pH drop from initially high values is often observed as result of carbonation by reaction of the concrete pore water with atmospheric carbon dioxide, resulting in a carbonation front slowly penetrating into the concrete, starting from its outer surface. When the carbonation front reaches the steel, passivity breakdown takes place (Bertolini et al., 2004). However, carbonation will only penetrate up to 10 cm (4 in) over a long period of time (100 yrs) as discussed in Section 5.1.2.

Chloride contamination often originates from external salt sources (e.g., seawater, deicing salts) that create a high concentration of chloride ions on the external concrete surface. Chloride transport inward ensues by diffusion through the pore network of the concrete or through cracks, eventually resulting in the threshold value being reached at the steel location and consequent passivity breakdown (Benturi et al., 1997). Although current standards place chloride limits on concrete, chloride limits for concrete were not included in ACI 318 during the construction of many of the nuclear plants in the US, possibly resulting in an internal source of chlorides.

Passivity breakdown by either mechanism does not necessarily involve external sources or slow development. If low pH or sufficient contamination are initially present in parts of the concrete structure in contact with the steel, the passive regime can be absent from original construction on the steel at those locations.

Where the passive regime is disrupted or not established, the iron dissolution reaction, is summarized as

$$Fe \rightarrow Fe^{2+} + 2e^- \qquad \text{Eq. 1}$$

and proceeds at a rate that may be described by a form of Butler-Volmer kinetics (Macdonald, 1977, Kranc and Sagüés, 1994)

$$i_a = i_{oa}\, a_{Fe} \exp{(E-E_{oa})/\beta_a} \qquad \text{Eq. 2}$$

where i_a is the rate of the anodic reaction (given here as a current density), i_{oa} is a standard exchange current density, a_{Fe} is the activity of the metal undergoing oxidation, E describes the local potential, E_{oa} indicates the standard redox potential for the Fe oxidation reaction, and β_a is the Tafel slope for the anodic reaction. It is further assumed that E is sufficiently above E_{oa} to ignore the reverse, Fe-reduction reaction. In the regime of validity of Eq. 2, the rate increases exponentially with the value of the local potential and no transport limitation takes place since a_{Fe} is nominally constant. The total anodic current must be balanced by a cathodic process, which for steel in concrete is usually oxygen reduction that can be summarized as

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \qquad \text{Eq.3}$$

This reaction can take place in any surrounding regions where the steel retains its passive condition because passive films on steel can be efficient electronic semiconductors. The local rate of oxygen reduction (i_c) also approximately follows Butler-Volmer kinetics

$$i_c = i_{oc}\, a_{O2} \exp (E_{oc}-E)/\beta_c \qquad \text{Eq. 4}$$

where i_{oc}, E_{oc} and β_c are the corresponding kinetic parameters for the cathodic reaction analog to those introduced for Eq. 2, and a_{O2} is the activity of oxygen in the concrete at the steel concrete interface. Since a_{O2} is nearly proportional to the oxygen concentration, the cathodic reaction rate is subject to transport limitations reflecting the extent to which oxygen was present initially in the medium and how efficiently it can be replenished by transport from the outside. Furthermore, the corrosion rate at the anode is controlled by the relative size of the cathodic and anodic regions and the extent to which they are conductively coupled through the intervening concrete. In principle, a situation with a relatively small anodic region, low resistivity concrete, and a large passive steel surface not severely oxygen-starved, could lead to high local corrosion rates and early local failure of a steel component.

4.1.2 Foreign material corrosion example

The principles introduced in the previous section are applied here using parameters that are typical for a reinforced concrete containment with a steel liner. The through-wall liner corrosion cases associated with the presence of foreign materials (e.g., wood, leather) were interpreted to indicate that the steel in contact with the foreign material was not in the passive condition. The most likely explanation is that the local pH at the steel liner/foreign material interface was below the value necessary to sustain passivity. That value is not a fixed quantity as it depends, among other factors, on the concentration of aggressive species. For example, in the case of chloride contamination, the pH necessary to sustain passivity increases with the log of the chloride content as illustrated in Figure 1 for the case of model solutions (Li, 2001). Figure 1 shows this passivity breakdown for concrete reinforcing steel (two surface conditions) in model pore water solutions of various pH. The $[Cl^-]/[OH^-] = 1$ line is calculated for 25°C, assuming an OH^- ion activity coefficient of 0.7. Extrapolation of the experimental trend suggests that even residual levels of chloride contamination in the pore water (e.g., 10^{-3} M) could result in passivity breakdown if the pH fell by as little as one or two units below the usual range encountered in concrete (usual pH >~13). It is noted that a chloride concentration of 10^{-3} M in the pore water could, after adjusting for typical chloride binding effects, be easily exceeded by the normally acceptable background levels of chloride content in commercially produced concrete (Wang et al., 2005). The expectation of steel activation with only modest pH drop still holds even after assuming a more conservative derating trend (the 1:1 line in Figure 1).

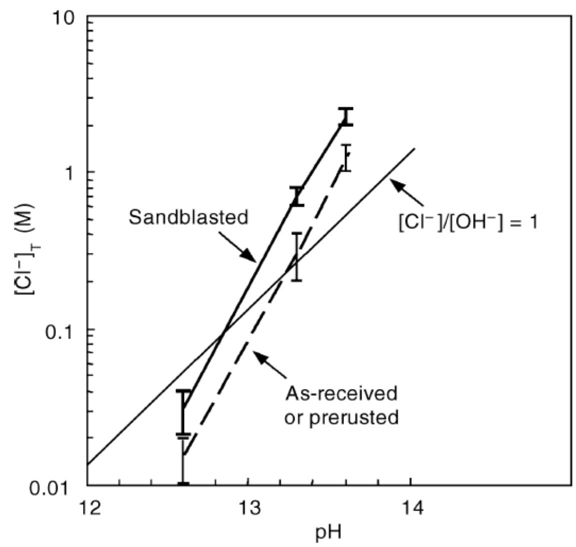

Figure 1 - Threshold chloride ion concentration at room temperature (Li and Sagüés, 2001)

For a hypothetical example, a piece of wood was assumed to be left unintentionally embedded in the concrete and positioned in contact with the steel liner. As was typical in plant construction, the concrete is assumed to have a relatively low compressive strength (e.g., 24 MPa, 3,500 psi) which would imply a mixture proportion with a relatively high water-to-cement (w/c) ratio (e.g., >~0.5). At that ratio, the cement hydration process does not consume all the mix water. Therefore, the pore network after hardening is expected to be saturated with water. Given the very thick concrete walls in contact with the liner, desiccation by evaporation on the outer surface would be expected to be a very slow process, so high relative humidity could be retained at the liner depth for several decades or longer.

In the above scenario, the embedded wood is exposed to that high humidity, which would penetrate the wood pores by a combination of vapor transport and capillary absorption processes. Moist wood by itself tends to have low pH (e.g., from neutral to as low as 3 (Winandy and Rowell, 2005)). In the case of Beaver Valley, the pH of the wood was reported to be 3.7 (FirstEnergy, 2009). The wood pore water at the interface with the surrounding concrete is likely to eventually develop by interdiffusion a composition and pH comparable to that of the concrete pore water. However, deeper into the wood body such a process should be correspondingly slower, roughly in proportion to the square of the distance from the interface under ideal diffusional transport. Thus, it is quite likely that a region on the liner surface, comparable in size to the footprint of the wood piece, would retain a pH low enough to sustain an active surface condition for a considerable length of time.

Once active corrosion initiates in that region, the local pH may remain autocatalytically depressed analogous to the case of pitting corrosion phenomena (Jones, 1996). The local anodic reaction releases Fe^{2+} ions that hydrolyze, often in association with Cl^- ions that preferentially migrate to the anode to maintain charge balance. Hydrolysis results in net consumption of OH^- ions which lowers or assists in keeping low the local pH, thus facilitating preservation of the active condition.

If the cathodic reaction locus were limited to that of the anodic location, the corrosion rate might experience a relatively rapid decrease with time as the oxygen in the immediate neighborhood of the anode became depleted, given the low effective diffusivity of oxygen in nearly water-saturated concrete (Kranc and Sagüés, 1994). The oxygen depletion could however become insignificant or very slow if the cathodic reaction were to be spread over a much larger area. An idealized representation of that situation is shown in Figure 2, where active corrosion is taking place at the footprint of the foreign material and the arrows represent the ionic macrocell[1] current flow. This occurs first through the foreign material and then the concrete and the surrounding passive steel surface. That surface includes both the surrounding outer (concrete-side) liner face, and all the embedded rebar, only part of which is shown for clarity.

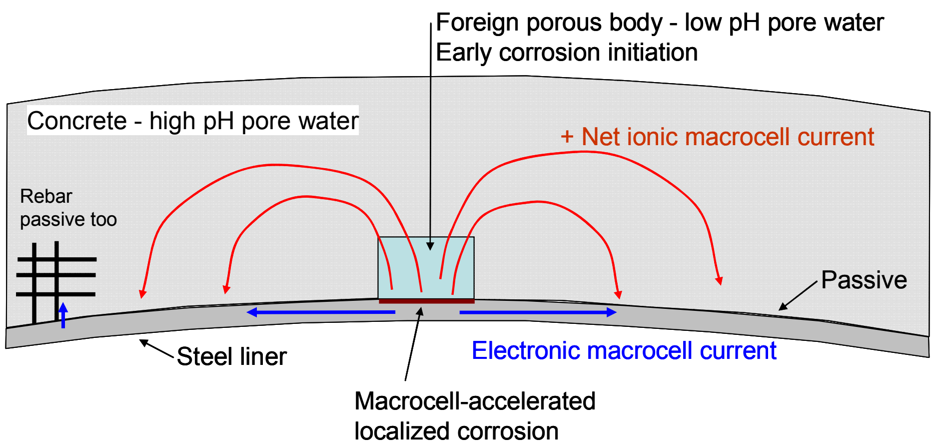

Figure 2 - Idealized corrosion scenario

Since the conductance of the metallic path is many orders of magnitude greater than that for the electrolyte, any ohmic limitation to the extent of macrocell coupling lays with the electrolyte. Because of the high rebar placement density and the small dimension of the active spot compared to that of the rest of the liner, much of the passive steel assembly is expected to be experiencing relatively little polarization. The anodic reaction may be polarized more given the smaller anode size, but the actual polarization extents for either reaction are not known at present. In the absence of other information, a nominal amount $\Delta E = 0.25$ V was assumed to describe the difference between both polarized potentials, which acts on the effective circuit resistance to drive the macrocell current. This value was conservatively chosen to be about half of the potential difference common between uncoupled passive steel and active steel in chloride-contaminated concrete (Kranc and Sagüés, 1994).

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[1] An ionic corrosion macrocell current flows through the electrolyte between predominantly anodic and cathodic zones of a metal surface. A corresponding electronic macrocell current flows between both zones through the metal thus completing the electrochemical circuit. All else being constant, the macrocell current is lower when the ohmic resistance of the circuit is large. (Kranc and Sagüés, 1994)

The resistance of the electrolytic path is not known either, but judicious parametric choices can be made by first assuming resistivity values representative of very low, medium and high concrete resistivity in field structures (1, 10 and 100 kΩ-cm respectively (Bertolini et al., 2004)) and by considering for simplicity that both the foreign material and the surrounding concrete have the same resistivity. Second, the geometry of the system is abstracted to be that of an anodic disk placed on an isolating plane in contact with an electrolyte which has a remotely placed cathode of infinite dimensions. In effect, this assumption states that the cathodic region operates at a very small current density but over a very large area. This is an extrapolation consistent with the previous considerations on the relative extents and locus of each reaction. With such geometry, the effective resistance of the ohmic path (R) is finite and equal to (Oltra and Keddam, 1988)

$$R = \rho / 4r \qquad \text{Eq. 5}$$

where ρ is the resistivity of the medium and r is the radius of the disk anode. Assuming for simplicity that the macrocell current density at the anode is approximately constant over its surface and that the amount of cathodic reaction at the anode is small compared to that on the larger passive steel cathodic region, the corrosion current density i_{corr} at the anode is given by

$$i_{corr} = \Delta E / R\ S = 4\ \Delta E / \pi\ r\ \rho \qquad \text{Eq. 6}$$

where $S = \pi\ r^2$ is the area of the disk anode. To bracket the range of observed liner penetration corrosion incidents, the value of r was assigned representative parametric values of 1 cm, 3 cm and 10 cm. The corrosion current density was converted into an equivalent steel corrosion rate (one-sided, starting from the concrete-liner interface) by simple Faradaic conversion assuming formation of Fe^{2+} ions. This yields ~12 µm/y of steel penetration for a corrosion current density of 1 $\mu A/cm^2$ (Jones, 1996).

The projected corrosion rates for various idealized scenario parameter combinations and the previously assumed nominal macrocell driving potential difference of ΔE = 0.25 V are summarized in Figure 3. Consistent with the assumptions and the expected severity of having increasing cathode to anode area ratios, faster corrosion is projected for the smallest anode radius cases. The value of corrosion rate highlighted is for full wall penetration of a representative 1-cm thick liner over a service time of 30 years, assuming a rate constant with time. That condition, representative of the reported field failures, is achieved for all anode sizes if the lowest resistivity case (1 kΩ-cm) is considered. Such a condition is reasonable in water-saturated concrete scenarios. Even when assuming a value as high as 10 kΩ-cm, corrosion penetration within the service life range of interest appears plausible if small anodes were to develop. It is noted also that the value of ΔE=0.25 V was conservatively chosen and the effect would be stronger if the driving potential were higher.

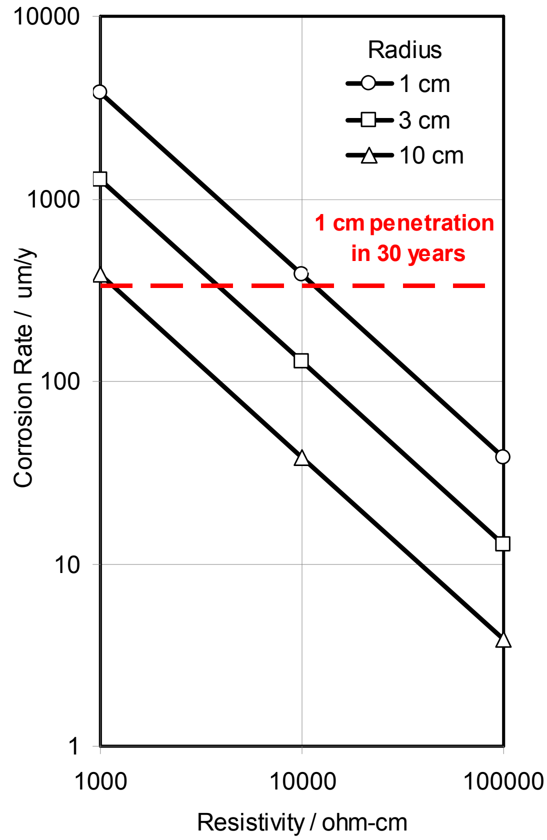

Figure 3 - Projected steel liner penetration rates (one-sided, starting from the concrete-liner interface)

The above scenario and semiquantitative calculations are only a simple exploratory approach to an otherwise complicated system. Detailed modeling taking into account polarization functions with appropriate coupling with oxygen transport (e.g., Kranc and Sagüés, 1994) could be conducted for verification and expansion of the conclusions. Nevertheless, the analysis supports the plausibility of a scenario where foreign materials in the type of concrete and reinforcement surrounding the liner serves as a corrosion initiation center, and the low resistivity of the concrete enables the development of strong macrocell coupling between an anode and a large cathode. That large cathode area, and the projection of substantial corrosion rates even when assuming a moderate macrocell driving potential, support the expectation that oxygen availability is not a strong limiting factor in the observed wastage.

4.1.3 Construction materials and defects

The general discussion above considered the case of wood as the foreign material. In principle, any other material that would locally hinder the stability of a passive film on the liner surface, and would have a size or geometric arrangement that creates a stable adverse environment, could have comparable effects. In addition to foreign material that is inadvertently left in place during construction, material may also be intentionally contained within the cast concrete such as spacers or thermal insulation. This material may also disrupt the passivity of the carbon steel in concrete and lead to corrosion (NRC, 2010). Beyond considering foreign objects and construction materials, voids or separations between the liner surface and the immediately adjacent concrete could also be examined to determine if that condition could sustain a locally active region. In the absence of a high initial chloride content in the concrete, it was concluded that any local loss of passivity at the voids would not be sustained in the long term. That expectation agrees with the lack of observation to date of corrosion related to liner plate buckling, which is commonly observed and could result in local separation of the liner and the concrete. Concrete carbonation at a metal-concrete void could result in sustained local corrosion (as it has been observed in some post tensioned tendon anchorages with bleed water voids) but the likelihood of carbonation at such depths from the external surface is considered to be very low (also discussed in Section 5.1.2).

4.1.4 Containment liner temperature

The high service temperature (on the order of 60^{o}C) could be a concern since this may, over long periods of time, promote or enhance the risk of ettringite decomposition (normally starting at temperatures above 70^{o}C), potentially releasing sulfate, or local release of bound chlorides, all of which could facilitate the onset of local corrosion (Collepardi, 2006). In addition, the operating Pourbaix diagram for iron at high temperatures within the operating range shows a smaller zone of stable passivity at 60°C than at 25^{o}C, where much of the experience on corrosion of steel in concrete originates (Townsend, 1969). However, while these potential adverse factors may have been contributors to passivity breakdown in the observed incidents, there is no indication at present that they were the main initiating cause. The effect of temperature on the containment structure is also addressed in Section 5.

During periodic shutdowns, the temperature of the liner may cool down from temperatures near 60°C to ambient temperature which could lead to added water condensation. Water used for cleaning on the interior liner surfaces may reduce liner temperature and promote condensation at the concrete liner interface. As discussed earlier, the high water to cement ratio used in construction and the concrete wall thickness likely results in abundant water available in the concrete microstructure under operating conditions. Consequently, condensation at the concrete/liner interface during refueling outages may not have a significant effect on the probability of, or propagation rates for OD-corrosion.

4.1.5 Containment liner welds

The containment liner is constructed using many plates of low alloy steel (typically A516 grade 60) that are welded together. Because the composition of weld filler metals used is slightly different from the steel liner base metal, corrosion of the welds or the adjacent base metal must be considered. Factors that may influence the possibility of localized corrosion in the vicinity of the welds are the composition of the steel and filler metals, cold work from forming and grinding, and parameters used in the welding process. However, there is no evidence to-date to indicate that the welds joining liner plates present an important preferential site for sustained localized corrosion. None of the reviewed inspection reports showed any increase in corrosion at liner welds, including reports from steam generator and pressure vessel head replacements where a temporary opening in containment exposed large sections of the liner. In addition, Figure 7 from Dunn et al. (2010) showed a corrosion patch at Beaver Valley Unit 1 that extended from one side of a weld to the other. There is no indication of preferential attack in the weld metal.

4.1.6 Containment concrete cracking

Concrete carbonation in sound concrete takes place to a depth approximately proportional to the square root of time of exposure. This uses a proportionality constant that is quite small (Bertolini et al., 2004) so progression through the thick concrete wall would take an extremely long time. Carbonation does progress faster along cracks that remain open (Jana and Erlin, 2007). Therefore, cracks in the concrete wall could be a potential concern in that respect. However, concrete cracking penetrating from the external surface of the containment to the liner was deemed unlikely in view of the extensive amount of reinforcement used. Autogenous healing would be expected to occur as well and act as a mitigating factor that would prevent continued preferential carbonation from cracks (Neville, 2002). Thus, carbonation of the concrete to the liner depth is considered to be highly unlikely (also discussed in Section 5.1.2). Since cracking could reach the depth of the initial rebar layers, there is a potential for that rebar being galvanically coupled to a macrocell increasing the oxygen concentration, and therefore, the corrosion rate. However, the effect is most likely small due to the large area of the cathode. Chloride ingress is similar to carbonation progression and is not likely to progress far enough through the containment walls to be an issue for OD-corrosion.

4.1.7 Plant geographical location effects

Plant location was not considered to be important factor for liner OD-corrosion. Chloride penetration from the outside would take an extremely long time to reach significant concentrations to disrupt the passivity of the liner that is in contract with the alkaline concrete environment. Accelerated transport of chlorides to the concrete/liner interface through cracks in the concrete is not considered to be relevant owing to the limited depth of cracking in the reinforced structure and autogenous healing of cracks (Neville, 2002). Conditions at the time of construction may have created greater risk of chloride contamination of the liner surface in marine sites, but it is assumed that appropriate cleaning procedures were implemented prior to concrete casting. However, this does not preclude the eventual development of rebar corrosion and associated cracking and spalling on the outside of the concrete wall due to external chloride contamination. Chloride-induced deterioration of the outer reinforcement layers is likely to occur and be identified well before chloride migration to the concrete/liner interface.

One area that may influence the corrosion of the liner would be in the case of a plant located near high ground water, especially in a marine environment. This could lead to ingress of water with elevated chloride concentrations into the concrete/liner interface, leading to localized corrosion. However, it is likely that any issues related to the marine environment ground water would be observed at multiple locations throughout the plant prior to being an issue at the concrete/liner interface.

4.1.8 Regions of the liner that are more susceptible to liner corrosion

In the absence of foreign materials, no potentially preferential zones were identified except for penetrations (which are numerous) and cold joints between concrete lifts. Penetrations in the containment usually have denser rebar distributions to compensate structurally. Even in general, the containment walls include a dense array of reinforcement with opportunities for poor consolidation and voids which may serve as preferential sites for corrosion initiation, especially if bleed water (excess water in the concrete) would accumulate (Wang et al., 2005). Instances of corrosion associated with those zones remain to be documented.

4.2 Liner Corrosion Expert Panel Assessment

Macrocell-accelerated localized corrosion that is initiated where foreign materials embedded in the concrete are in contact with containment liner appears to be the most likely mechanism for OD-corrosion. There have been 8 cases of foreign materials found in concrete containment structure with 3 plants experiencing through-wall corrosion that is directly attributable to foreign materials located at the concrete/liner interface. Foreign materials used in construction are typically wood used in forms and to position reinforcement prior to concrete placement. Wood naturally has an acidic pH that can alter the local chemistry and disrupt the passivity of the carbon steel. The macrocell created in the low resistivity concrete by a relatively small anodic area that is coupled to a large cathodic surface drives localized corrosion propagation leading to liner penetration. While other mechanisms could be explored further, there is no evidence that they have contributed to OD-corrosion.

5. Concrete Aging and Degradation

This section addresses the influence of specific concrete degradation mechanisms on the corrosion of the containment liner. Issues addressed include external ingress of chloride, carbonation, delayed ettringite formation, and expansive reactions (e.g., alkali-silica reaction). Other degradation mechanisms were deemed to be too remote to have an influence on the corrosion of the steel liner.

5.1 Summary of Workshop Key Findings

5.1.1 Concrete degradation and durability factors

Factors that influence concrete durability are related to constituent materials, construction processes, physical properties of the hardened concrete, nature of exposure conditions, and loading types and frequency (Scholer, 1956). The sum of individual influences results in over 170 items that may have an influence on the degradation of concrete. These items were known at the time of construction of the US fleet of nuclear power plants. Design methodologies addressed mechanical and thermal loading conditions; concrete specifications addressed constituent materials, construction processes, the hardened concrete properties, and the nature of exposure conditions, both internal and external.

Although concrete degradation mechanisms were known at the time of construction of nuclear power plants, the understanding of these mechanisms was not as developed in that era as they are today (Weyers et al., 1989). Examples include alkali-silica reaction, delayed ettringite formation, and corrosion of steel in concrete as carbonation, chloride, and the synergistics of carbonation/chloride-induced corrosion. In addition to the mechanisms, the understanding of the kinetics of the reactions, and thus service life performance, was in its infancy at the time of plant design and construction.

Almost all concrete degradation mechanisms include water; and the presence of water in the bulk concrete is influenced by its permeability. Concrete permeability is related to the water to cement ratio (w/c) of the concrete, curing conditions (time, temperature and moisture), and consolidation. Some regions can develop localized conditions of higher gas and water permeabilities such as cold joints.

The water content of the concrete containment from the time the concrete is placed would be influenced by the concrete's initial water content, cement hydration, permeability, path length, and temperature gradient across the concrete vessel wall. At placement, the concrete is completely saturated and concrete pore water is in contact with the steel liner. The high pH of the pore water passivates the steel liner and the reinforcing steel. As hydration of the cement progresses, the free moisture content of the concrete decreases. The w/c of the concrete used in the construction of the containment structure was likely to be 0.5 or greater, as the specified concrete strength was in the range of 24–28 MPa (3500–4000 psi) at 28 days. Thus, for all practical purposes, hydration of the cement was completed in about a year. The moisture content of the concrete was then near saturation with drying taking place on the external surface. During operation, the interior temperature of the containment building is at or less than 60°C (140°F) with relative humidities (RH) from 20 to 85% (Hookham and Shah, 1994). It is reasonable to assume that the steel liner would maintain the same temperature as the interior of the containment building. Thus, the concrete is exposed to a continuous heat source on the interior surface and varying heat and moisture conditions on the exterior surface. The interior surface heating decreases during maintenance outages as the containment temperature drops to ambient conditions.

Studies conducted by McDonald (1975) and Nilsson and Johansson (2006) demonstrate that the moisture movement in concrete is slow and sufficient free moisture remains in the containment vessel concrete to participate in concrete degradation modes such as corrosion of steel and alkali silica reaction. McDonald (1975) used a pie-shaped geometry representing the flow path through a cylindrical wall. The concrete section was 2.74 m (9 ft) in length and heated on one surface with the other end exposed to the atmosphere. A temperature of 44°C (111°F) was maintained for one year following a 17 month period after casting. After the one year heating period, the moisture content at both ends was 15% less than the average interior moisture content which remained constant. The average moisture content was about 0.21 g/cm^3 (13 lbs/ft^3) (3.4% by weight, 21% by volume), whereas the ends were about 0.18 g/cm^3 (11 lbs/ft^3) (2.9% by weight, 18% by volume). It was concluded that moisture movement is slow and not significant at temperatures at or less than 44°C (111°F) for thick-walled concrete pressure vessels.

Nilsson and Johansson (2006) reported relative humidity (RH) measurements at two locations in the Barsebäck containment building. The containment cross-section is unique, 300 mm (12 in) thick outer layer, steel liner, and then a 800 mm (31.5 in) thick layer of concrete. The RH at the drying surface was between 40 and 60% and exceeded 80% at location about 750 mm (30 in) from the drying surface after 30 years in service.

5.1.2 Carbonation, chloride ingress, and concrete cracks and spalls

Steel-lined nuclear reactor containment vessels consist of approximately 1.2 m (4 ft) of reinforced concrete, lined on the interior with an 8- to 10-mm thick continuous steel plating. Both carbonation and chloride ingress are controlled by diffusion. Under the worst conditions (e.g., high concrete w/c ratio, high environmental CO_2 or chloride), penetration depths even at cracks, cold joints, and form tie locations most likely would not exceed 10 cm (4 in) in 100 years (Broomfield, 2007).

Structural degradation mechanisms such as cracking or spalling either do not affect the liner, or would be detected and repaired prior to affecting liner corrosion. These and other mechanisms are not likely to have an influence on the corrosion of the steel liner.

5.1.3 Concrete reactions and phase stability

As addressed in Section 5.1.2, very slow diffusion rates result in essentially no effect on liner corrosion as the result of carbonation or chloride ingress. However, a possible time-related mechanism could be related to delayed ettringite formation and deformation as a result of the increased volume of the reaction products. In concrete with hydration at temperatures below 70^{o}C, the following reactions will take place to form ettringite:

$$Ca(OH)_2 + SO_3 = CaSO_4 \bullet H_2O \qquad \text{Eq. 7}$$

$$Ca_4Al_2O_3 \bullet SO_4 \bullet 12H_2O + 2CaSO_4 + 20H_2O = Ca_6 \bullet Al_2O_3 \bullet 3SO_4 \bullet 32H_2O \text{ (ettringite)} \qquad \text{Eq. 8}$$

Ettringite that forms during concrete hydration is normal and usually does not have any negative effects. However, if casting temperatures are high and the concrete temperature remains high for several hours after setting, ettringite will not form. In mass concrete, typically with section thicknesses greater than 0.9 m (3 ft), the heat of hydration can rise above 70^{o}C (158^{o}F), thus preventing the formation of ettringite. Later, after the concrete cools, delayed ettringite will form if sufficient moisture is present. As this is an expansive reaction, cracking can occur at those locations. There have been cases in other industries of mass concrete or large precast heat cured sections that were severely cracked due to high casting/curing temperatures. However, this has not been reported at any nuclear plant to-date. Cracking as a result of delayed ettringite formation could promote corrosion of steel in concrete if the pH drops or the cracks formed leads to chloride ingress (not likely at the depths of the liner).

The other possibility, as noted in Section 4, is that ettringite that formed would be converted back to the original phases releasing sulfate. The dissolution of ettringite will result in $CaSO_4$ formation. $CaSO_4$ is not very soluble at high pH, but could become soluble if the pH is reduced. At that point, sulfate ions even in the parts-per-million (ppm) range can contribute to localized corrosion. The main factors controlling dissolution are temperature and pH. Extended time at temperatures above 70^{o}C can cause ettringite to dissolve. Lowering of the pH can do the same. A slight drop in pH at high temperatures can cause an increase in sulfate concentration. A significant drop in pH can cause ettringite to dissolve even at lower temperatures resulting in free sulfate as it becomes more soluble at lower pH. As noted, simple dissolution is not necessarily a problem as long as the pH remains high. In the location of localized corrosion, the pH will drop leading to an enhanced attack as sulfate ions become soluble.

Embedded materials can lead to a reduction in pH with a localized increase in sulfate solubility producing more corrosion than expected. Experiments would be required in order to estimate the actual increases in corrosion rate that could be expected under these conditions.

On a separate issue, long periods of time can result in a possible depletion of the oxygen levels near the liner at some locations. This could result in a loss of passivity with corrosion occurring without expansive products. Hydrolysis could occur causing a decrease in pH. This is a very long-term process, in most cases in excess of 30 years. If the reinforcing bars are in electrical contact with the liner, it could be providing a large cathode to drive corrosion in an oxygen depleted zone. Long-term effects may be a function of specific conditions at a given plant. Whether or not conditions at different plants vary enough to affect these long-term effects is not known but could be studied.

Other long-term degradation mechanisms, such as alkali-silica reaction that also has expansive reaction products may result in the bulging of the steel liner. However, the confinement of the steel liner, reinforcing steel, and/or prestressing forces may prevent expansion. As mentioned earlier, the bulging of the liner is not uncommon from prestressing forces regardless of any expansive mechanism in the concrete. With that said, alkali-silica reaction is not considered to be a issue for OD-corrosion since it would be observed at other plant locations prior to being an issue for liner corrosion.

5.1.4 Concrete chemistry and additives

Other than flyash and chloride that may have been included in the original construction materials, the original concrete constituents would have little to no effect on the corrosion of the steel liner. Chemically bound chloride may be released by carbonation and thus initiate corrosion at pH values between 9 and 11 (Broomfield, 2007). Likewise, flyash may reduce the pH of the concrete resulting in lower chloride threshold values. However, this influence would be offset by the lower permeability of flyash concrete. Any adverse effects of concrete construction material would manifest themselves on the outside surface of the containment building before occurring at the liner concrete interface.

5.2 Concrete Aging and Degradation Expert Panel Assessment

As described in Section 5.1.3, potential long-term concrete degradation mechanisms could be a concern and have effects on OD-corrosion. Specifically, the reduced ettringite stability and the release of sulfate at reduced pH values that are expected with embedded foreign material as well as oxygen depletion could be studied in more detail. Other concrete degradation mechanisms were determined to be either not critical, not likely (e.g., carbonation and chloride ingress discussed in Section 5.1.2), or would be visible at locations other than the liner/concrete interface prior to being a concern for OD-corrosion.

6. Non-Destructive Evaluation Methods for Assessing Steel Liners

Nondestructive examination is the primary method used to locate and evaluate the significance of indications of containment liner degradation. Selection of the appropriate method depends on the type and nature of the degradation, the component geometry, type and circumstances of inspection, and cost and availability. The issues and NDE techniques related to liner corrosion detection are addressed in this section.

6.1 Summary of Workshop Key Findings

6.1.1 Adequacy of ASME Section XI, IWE examination

Inspection requirements, acceptance standards, and evaluation criteria for Class MC pressure retaining components and metallic liners for Class CC pressure retaining components are provided in Section XI, Subsection IWE of the ASME B&PV Code. The full scope of Subsection IWE includes steel containment shells and their integral attachments; containment hatches and airlocks; seals, gaskets, moisture barriers, and pressure-retaining bolting. Examination categories are specified in Subsection IWE with the parameters monitored or inspected dependent on the particular examination category (e.g., Category E-A covers metallic surfaces and Category E-C addresses containment surfaces requiring augmented examinations). The primary in-service inspection method specified in Subsection IWE is visual examination (e.g., general visual, VT-3, VT-1). Limited volumetric examination (e.g., ultrasonic thickness measurement) and surface examination (e.g., liquid penetrant) may also be necessary in some cases. The scope and frequency of examinations specified in 10 CFR 50.55a and Subsection IWE ensure that aging effects would be detected before they would compromise the design-basis requirement. Furthermore, 10 CFR 50.55a(b)(2)(ix) specifies additional requirements for inaccessible areas when conditions exist in accessible areas that could indicate the presence of or result in degradation to such inaccessible areas. ASME Section XI, Subsection IWE examinations are primarily visual based so they are not considered to be capable of detecting OD-corrosion until it progresses sufficiently to result in a coating blister or rust staining that is visible on the inside surface of the liner. Visual inspection techniques and effectiveness is discussed in more detail in Section 6.1.3.

6.1.2 NDE techniques

Current in-service testing programs at operating nuclear power plants rely on nondestructive testing to detect the presence of service-induced degradation that may lead to loss of pressure boundary or structural integrity. Nondestructive examination methods for metallic materials primarily involve surface and volumetric inspections to detect the presence of degradation (i.e., loss of section due to corrosion or presence of cracking). Rules for surface and volumetric examinations of containment pressure boundary components are provided in Section XI, Subsection IWA of the ASME B&PV Code. Examination types identified in the

Code for performing in-service inspections include visual, surface (i.e., magnetic particle, liquid penetrant, eddy current, and ultrasonic), and volumetric (i.e., radiographic, ultrasonic, eddy current, and acoustic emission). Alternative techniques, combinations of techniques, and newly developed techniques are permitted provided the results are considered to be equivalent or superior to those of the specified technique. Acceptance standards are defined in Article IWE-3000 of the ASME Code. The two most common techniques used to examine the containment liner are visual and ultrasonic and are described in the following two sections.

6.1.3 Effectiveness of visual examinations

Visual and optical testing involves inspectors visually looking for defects. Visual inspection is one of the most common and least expensive methods for evaluating the condition of a liner (e.g., presence of surface flaws, discontinuities, or corrosion). It is generally the first inspection that is performed as part of an evaluation process and is beneficial for performing gross defect detection and identifying areas for more detailed examination. Visual inspections can identify where degradation is most likely to occur, and when degradation has commenced (e.g., rust staining or coating cracks). Once a suspect area is identified, all surface debris and protective coatings are removed so that the area can be inspected in more detail.

Visual examinations can be performed either with the unaided eye or optical magnifiers. Without material or component removal, visual inspections are limited to accessible areas. In situations where access is limited or normal visual acuity is not sufficient, examination may require the use of visual aids such as supplemental illumination, flexible or rigid borescopes, image sensors, or magnifying systems. Mechanical aids may also be required as part of the visual inspection. Mechanical aides may include: measuring rules and tapes, calipers and micrometers, square and angle measuring devices, thread, pitch, and thickness gages, and plumb lines. The effectiveness of a visual inspection is dependent on the experience and competence of the person performing the inspections. As discussed earlier, visual inspections will identify corrosion occurrence from liner OD-corrosion only after it has progressed sufficiently to result in a coating blister or rust staining that is visible on the inside surface of the liner. Liner bulges would be identified through visual inspections, but occurrence of liner bulges would likely be from sources other than corrosion (e.g., prestressed containment with internal heating that expands the liner between anchorage locations).

Since no correlation has been identified between surface degradation and through-wall dimension, volumetric nondestructive methods (e.g., ultrasonic testing) may be needed to fully characterize the extent of corrosion or cracks detected by visual testing methods in order to determine a component’s structural integrity or leaktightness.

6.1.4 Effectiveness of ultrasonic testing

Ultrasonic testing uses sound waves of short wavelength and high frequency (e.g., 0.5 to 20 MHz) to detect and evaluate surface and subsurface flaws, for material characterization, and to measure remaining material thickness. Ultrasonic inspection techniques are commonly divided into three primary classifications: (1) normal beam and angle beam (relates to the angle that the sound energy enters the test article), (2) pulse-echo and through transmission (relates to whether reflected or transmitted energy is used), and (3) contact and immersion (relates to the method of coupling the transducer, and hence the transmitted energy, to the test article). A transducer, driven by a pulsar that produces a high voltage electrical pulse, generates high frequency ultrasonic energy that is introduced into the material under investigation and propagates in the form of a series of pulses of extremely short duration. During the time interval between transmissions the transducer can detect reflected signals. As the sound wave propagates through a material it continually loses a part of its energy because of scattering and internal friction effects within the material. Attenuation losses, together with beam divergence, account for the major limitation on the depth of penetration that can be achieved for component inspection. The extent of attenuation increases with an increase in frequency. Changing the frequency when the sound velocity is fixed will change the wavelength of the sound that in turn affects the probability of flaw detection (i.e., discontinuity should be larger than one-half the wavelength for detection). The ability to locate small discontinuities and resolution generally increase with an increase in frequency. Since conventional piezoelectric transducers typically operate at frequencies of 500 kHz or more, the corresponding inspection range is relatively short (a few meters) because of a high wave attenuation in that frequency range. Although piezoelectric transducers are most frequently used to generate the sound waves, the sound waves may also result from other sources such as laser-generated ultrasound, electromagnetic acoustic transducers, and magnetostrictive sensors. Phased array probes consisting of a transducer assembly having from 16 to 256 small individual elements that may be arranged in a strip (linear array), a ring (annular array), or a circular matrix (circular array), can be used for volumetric inspections.

Advantages of ultrasonic methods are high sensitivity permitting detection of small flaws, thickness measurements can be provided, and access to only one surface is required to detect degradation. Although detection of OD initiated liner corrosion through application of ultrasonic methods to determine areas of reduced liner section is possible, its primary application would probably be to quantify the extent of liner thinning in areas of known corrosion since its application is time consuming (i.e., point-by-point inspection). The method at present does not provide sufficient global inspection capabilities to scan relatively large areas of the liner to identify areas of reduced thickness (i.e., concrete in tight contact with the liner significantly contributes to signal attenuation).

6.1.5 Other techniques for assessing liner OD-corrosion

Although no completely suitable technique for inspection of inaccessible portions of a containment liner has been demonstrated to date, several techniques have been investigated that exhibit potential (e.g., electromagnetic acoustic transducers, magnetostrictive sensors, multimode guided waves, and electrochemical techniques). A summary of several of the activities associated with these techniques is provided below with a more detailed discussion provided in the references provided.

Electromagnetic acoustic transducers (EMATs) were evaluated relative to detection of corrosion in Mark I containment vessels (Maxfield and Kuramoto, 1988). Simulated corrosion-like defects (12.7-mm wide by 101.6-mm long by 11.4-mm deep, 0.5-in wide by 4.0-in long by 0.45-in deep) were milled into a 2.1 m wide by 4.9 m long by 25.4 mm thick

(6.9 ft wide by 16.1 ft long by .01 in thick) plate at a distance of 0.6 m (1.97 ft) from one end. Pulse-echo and through-transmission modes were evaluated; however no concrete was adjacent to the plate surfaces during these tests. In the pulse-echo mode a sharp flaw (e.g., pit type) at least halfway through the plate thickness could be detected at distances up to 4.6 m (15 ft), however, defect sizing could not be done and detection of general corrosion was thought to be difficult. In the through-transmission mode the authors estimated that deep corrosion damage (> 75% of plate thickness) could be detected at distances to 15 m (49 ft) or more, but the location could not be precisely determined.

Two studies have been conducted to investigate the feasibility of applying magnetostrictive sensor technology to inspection of plate-type materials and to evaluate its potential for detecting and locating thickness reductions in the containment metallic pressure boundary resulting from corrosion (Kwun, 1999; Kwun and Kim, 2000). In the first study, initial modeling studies to demonstrate that the technique had potential to achieve long-range inspection in plates backed on both sides by concrete were followed by an experimental investigation. A carbon steel plate approximately 6.35 mm thick by 1.23 m wide by 6.11 m long (0.25 in thick by 4.0 ft wide by 20.0 ft long) was used as the test article. A notch approximately 3 mm deep by 6 mm wide by 10 cm long (0.12 in deep by 0.24 in wide by 3.9 in long) was machined into the plate at a distance of 4.06 m (13.3 ft) from the probe end of the plate. Subsequent tests extended the notch length to 20 cm (7.9 in) and 30 cm (11.8 in). Results indicated that guided waves have potential for performing global, long-range inspections of plates and plate-like structures, and should work well for inspection of plates backed by concrete on either one or both sides.

In the second study, two carbon steel plates 1.22 m wide by 6.11 m long by 6.35 mm thick (4.0 ft wide by 20.0 ft long by 0.25 in thick) were used as test articles to evaluate the affects of concrete on wave attenuation and to investigate long-range inspection capability. For tests with concrete on both sides of the plate, an approximately 152 mm (5.98 in) thick layer of concrete was cast and cured that measured about 1.22×2.44 m^2 (4.0×8.0 ft^2) covering about 40% of the plate length. A notch 102 mm (4.02 in) long extending halfway through the plate was located approximately 3.2 m (10.5 ft) from the probes. In addition to the effect of concrete, the effects of several construction features were also evaluated. It was found that when the concrete was bonded to the plate surface, the concrete increased the guided wave attenuation significantly, severely limiting the inspection capability of the guided waves, except for the A0 wave mode at a fairly low frequency (below approximately 25 kHz) which could be used for detection of relatively large defects within a few meters of the magnetostrictive sensor probe. It was also found that when the concrete was in physical contact to but debonded from the plate surface, the concrete showed no measurable effects on the guided wave attenuation and, therefore, its inspection capability. Since the concrete in the potentially damaged areas of the metallic pressure boundaries is probably detached from the steel surface, the guided waves are expected to have good applicability in practice. Other construction features related to the metallic pressure boundary such as welds, sealants, and paint were found to have no significant impact on long-range inspection capability.

A limited experimental investigation and an analytical study were conducted to demonstrate the feasibility of using multimode guided waves for identification and location of thickness reductions in the metallic pressure boundary of nuclear power plant containments (Li and Rose, 2001; Pelts et al., 1996). Experimental studies utilized plates 914 mm long by 203 mm wide by 25 mm thick (36 in long by 8 in wide by 1 in thick) that contained flaws 4 mm (0.16 in) deep that were either rectangular, rounded, or "V" shaped, or rectangular flaws of different depth (8 or 12 mm deep, 0.31 or 0.47 in deep). Some of plates were embedded in concrete with or without a bond existing between the concrete and plate. Results indicated that both shear-horizontal and Lamb wave modes can be used for inspection of steel containment structures, with both being somewhat insensitive to the concrete boundary for specific velocity and frequency values. Strong benefits of using shear-horizontal waves via an EMAT transducer were demonstrated with an overall improved signal-to-noise ratio, practically no interference from the concrete interface and the potential for non-contact testing. In the analytical study the boundary element method was used to study the interaction of various guided wave packets of energy with various corrosion boundaries in a structure (e.g., elliptical-shaped scatterers with a variation in defect depth and length values). Theoretical and experimental data on the scattering of shear-horizontal waves were obtained, indicating the potential for solving the classification problem. Results have application in establishing data acquisition and analysis guidelines for development of test protocol and the quantification algorithm development program.

Non-destructive electrochemical techniques where applied to two nuclear power plant liners (Martínez et al., 2008). The measurements were made directly over the concrete slab above the liner plate. The slab, which varied in thickness above the liner (0.5 to 0.8 m, 1.6 to 2.6 ft), contained two carbon steel rebar meshes. Corrosion potential measurements were made to locate areas where metal embedded in concrete had become depassivated and thus potentially able to corrode. Corrosion rate measurements provided information on the instantaneous rate of the liner corrosion. Resistivity measurements of the concrete were made to indicate the risk of corrosion. Passivity verification measurements indicated the state of passivity of a metallic component embedded in concrete (i.e., qualitative determination of whether the metal is well protected, moderately protected, or unprotected). It was concluded from the study that non-destructive electrochemical techniques appear to be an appropriate tool for evaluation of corrosion of metal liners embedded in concrete. However, the large amount of instrumentation and high level of maintenance required, as well as the limited amount of area that could be monitored with a single system, limit the practicality of this method. Additional complications center around possible modifications to the structure, compromised electrode stability due to elevated temperature and radiation exposure, and possible frequent maintenance and replacement.

Although several of the techniques summarized above exhibit potential for identifying corrosion of liner materials in inaccessible areas (e.g., liner OD-corrosion), none of these techniques is developed for field application to detect corrosion.

6.1.6 Issues with the size of the containment and using only sampling to find corrosion

Depending on the design, concrete containments can be on the order of 30 to 40 m in diameter by 50 to 60 m high by 0.9 to 1.4 m thick (98 to 131 ft in diameter by 164 to 197 ft high by 3.0 to 4.6 ft thick). The inside surface of the concrete containments is lined by relatively thin steel plate (e.g., 8 to 10 mm thick, 0.31 to 0.39 in thick) joined by welding and attached to the concrete through studs or angle sections. Depending on whether the containment design is reinforced concrete or a combination of reinforced and prestressed concrete, the walls and dome of the containment can contain significant amounts of steel reinforcement. Conducting non-destructive examinations using existing capabilities (i.e., ultrasonic inspections) to identify areas of the liner exhibiting loss of section due to corrosion generally involves setting up a grid and making thickness measurements (e.g., ASME Section XI, Subsection IWE notes that grids not exceeding one foot square shall be used and minimum wall thickness within each grid determined). As a result of the large surface area involved, and difficulties in making measurements in areas with limited or no accessibility, the likelihood of identifying OD liner corrosion using sampling is very small. Based on present capabilities, the most effective application of ultrasonic inspections would be for thickness determinations in suspect areas (i.e., areas exhibiting coating blisters or rust staining) to identify the extent of liner thinning. As discussed in the previous sections, no other NDE techniques are developed sufficiently to be effective in examining the vast area of liner surface in existing containments.

6.1.7 Challenges with examining containment from outer concrete wall

Examining the liner from the outer concrete wall of the containment presents significant difficulties. Wall thicknesses can be in excess of one meter, the containments have high steel reinforcement density, there can be a number of penetrations or cast-in-place items, and accessibility may be limited due to presence of other components. At the current state-of-the art, no techniques are known that have the ability to detect liner corrosion from the outer concrete wall.

6.2 NDE Expert Panel Assessment

The current state of NDE technology is not capable of effectively detecting OD-corrosion prior to through-wall penetration when considering the size of the containment structures and the area of the liner surface. While ultrasonic inspections can detect corrosion at point or small area locations, there is no current technology for using this over large areas. It is possible that some type of crawler technology could be employed in combination with a NDE technique, but this could result in damage to the coatings on the liner. Development of other techniques in this area may result in an appropriate method that could cover larger areas; however, no technology currently exists.

7. Concrete Repair and Corrosion Mitigation

Repair objectives are to restore a component's integrity, arrest the mechanism(s) producing distress, and ensure (as far as possible) that causes of distress will not reoccur. Provided that the cause(s) of distress is arrested, available repair procedures are effective in reestablishing the integrity of the concrete and/or liner. Mitigation methods to prevent corrosion such as cathodic protection as also discussed in this section.

7.1 Summary of Workshop Key Findings

7.1.1 Repair techniques for liner corrosion (liner and damaged concrete)

According to requirements provided in 10 CFR 50, Appendix J, evidence of structural deterioration that could affect the structural integrity or leak-tightness of metal and concrete containments must be corrected before the containment can be returned to service. Corrective actions that are taken must be performed in accordance with the repair procedures, nondestructive examinations, and testing specified in applicable Codes including those editions and addenda of ASME B&PV Code Section XI that have been adopted by the NRC. The Owner is responsible for preparing Repair/Replacement Plans that list all editions, addenda, and Code cases that are applicable to a particular repair or replacement.

Requirements contained in the ASME B&PV Code note that containment pressure boundary components with flaws, discontinuities, or areas of degradation that do not meet acceptance standards may not be returned to service unless:

- the unacceptable flaws, discontinuities, or areas of degradation are removed to the extent necessary to meet the acceptance standards;
- a repair involving welding is performed such that existing design requirements are met; or
- the component or portion of the component containing the unacceptable flaws or areas of degradation is replaced.

These three conditions are intended to ensure that metal and concrete containment pressure boundary components remain free from defects during their entire service life. A less prescriptive condition for continued service has been developed and included in requirements provided in Section XI, Subsection IWE-3000 of the ASME B&PV Code. These requirements state that containments with pressure boundary components that contain flaws, discontinuities, or areas of degradation that do not meet acceptance standards may be permitted to remain in service provided an engineering evaluation reveals that the flaws, discontinuities, or areas of degradation have no affect on structural integrity or leak-tight integrity.

Corrosion damage of liners observed to date has primarily been either the result of embedded foreign material (e.g., wood) in contact with the liner resulting in OD-corrosion or inside-initiated corrosion resulting from coating failures or moisture barrier degradation. The OD-corrosion repair has consisted of removal of the damaged liner section and embedded foreign material, grouting the resulting void, and replacing the liner plate section. Figure 4 illustrates repair methods that have been proposed for OD-corrosion (Oland and Naus, 1998).

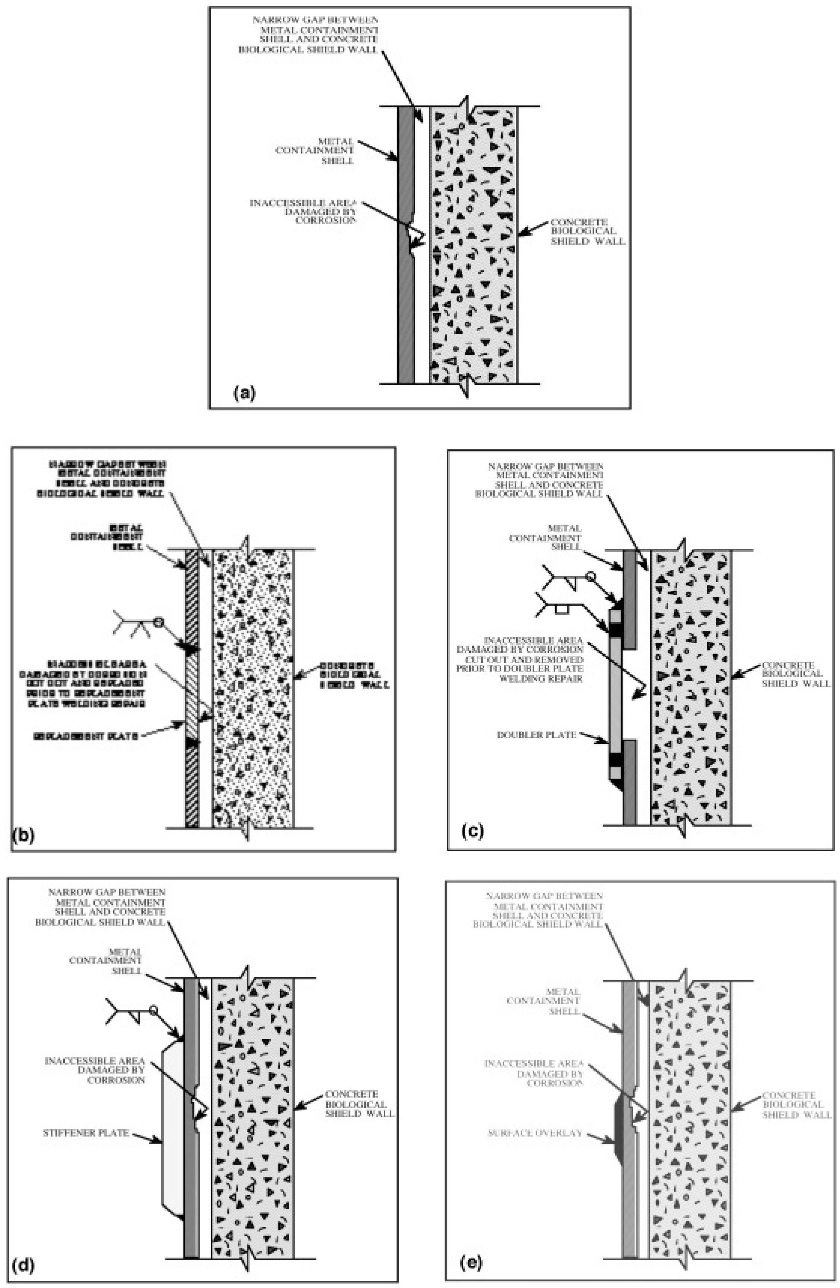

Figure 4 - Examples of repair procedures for outside-initiated corrosion: (a) liner exhibiting excessive loss of section, (b) replacement plate welding procedure, (c) doubler-plate welding procedure, (d) stiffener plate welding procedure, and (e) surface overlay welding procedure (Oland and Naus, 1998).

Where coating failures have occurred and the liner section has not been reduced, the corrosion products were removed from the liner and the coating replaced. Moisture barrier degradation at the interface between the liner and concrete (e.g., location where liner becomes embedded in floor of containment) has occurred at several plants. Generally, where section loss has been minimal the repair procedure has involved removal of the damaged moisture barrier, inspection, removal of corrosion products, recoating of the liner, and replacement of the moisture barrier. In some cases corrosion at this location has been significant enough that the concrete had to be removed at the interface, the liner cleaned, liner section thickness reestablished through a weld overlay procedure, concrete replaced with a mortar, and the moisture barrier reinstalled. Figure 5 provides an illustration of this repair procedure (Oland and Naus, 1998). Provided that the cause(s) of distress is arrested, available repair procedures such as described above are effective in reestablishing the integrity of the liner.

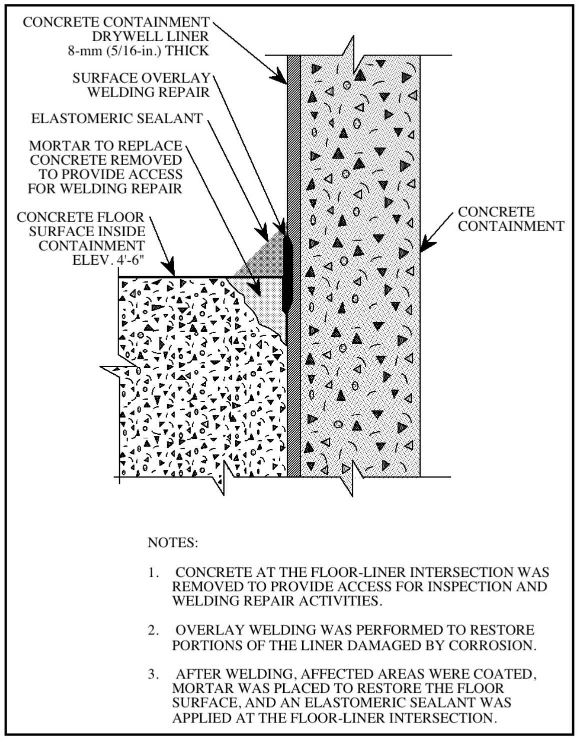

Figure 5 - Example of repair procedure for liner corrosion due to moisture barrier degradation (Oland and Naus, 1998).

7.1.2 Effectiveness and appropriateness of corrosion mitigation methods and repairs

Surface coatings and barriers are used to prevent corrosion of the inner liner surface. However, coatings are not always applied to the external surfaces of the liner that will be in contact with the concrete. Surface coatings on the external surface of the containment walls are used at some plants to protect the structure from contaminants. Surface coatings on the exterior of the containment concrete walls will only protect the concrete's outer surface. Sealers, coatings, and membranes that have been used for external coatings are explored in Naus et al. (1996). As discussed earlier, there is sufficient water in the concrete and ingress of corrosive species to the concrete/liner interface are not likely to occur through normal and extended operation periods (e.g., 100 years as stated in Section 5.1.2). Therefore, an exterior coating applied to the containment building concrete is not likely to help prevent OD-corrosion of the containment liner.

Cathodic protection is the only technique capable of totally reversing the chemical and electrical phenomena causing corrosion. Cathodic protection is a method that reduces or eliminates corrosion by making the metal a cathode by means of either attaching an anode or impressing a counterbalancing current.

Sacrificial anode cathodic protection systems rely on a metal that is naturally anodic to the structure being protected in the environment of interest. Three metals, magnesium, zinc, and aluminum, are commonly used as sacrificial anodes. The voltage difference between sacrificial anodes and cathodes is limited to about one volt or less depending on the anode material and the specific environment (NACE, 1984). This limitation reduces the current distribution pattern along the cathode and makes sacrificial anode cathodic protection systems less suited for use in freshwater applications and low-conductivity environments such as concrete.

Impressed current cathodic protection systems work on the principle that current flowing onto any metal shifts its normal potential in the negative direction if correct amounts of current can be impressed on the surface to be protected. The impressed current cathodic systems rely on an external electrical power source to provide the required direct current. With their necessary array of electrical components, these systems are more complex than sacrificial anode cathodic protection systems and they may create stray current corrosion in nearby structures. Impressed current systems can have significantly increased current output capacity that enables protection over a larger area compared with sacrificial anode systems.

The effectiveness of cathodic protection systems to mitigate liner corrosion is questionable because of the large quantity of steel contained in a reinforced concrete containment and the requirement for an electrolyte. If improperly operated, cathodic protection systems can produce hydrogen ions having the potential for hydrogen embrittlement. While the use of cathodic protection systems for prestressing cables, reinforcing, and the liner has been reported in recent license application renewals (R.E. Ginna, 2002, Turkey Point, 2000), the effectiveness of cathodic protection for preventing liner corrosion has yet to be demonstrated.

7.1.3 Current concrete repair techniques and durability

Reinforced concrete structures can start to deteriorate due to exposure to the environment (e.g., temperature, moisture, and cyclic loading) almost from the time of construction. The rate of deterioration is dependent on the component's structural design, materials selection, quality of construction, curing, and aggressiveness of its environmental exposure. Termination of a component's service life occurs when it can no longer meet its functional and performance requirements. Results provided through periodic application of in-service inspection techniques as part of a condition assessment program can be used to develop and implement a remedial action prior to the structure achieving an unacceptable level of performance. Depending on the degree of deterioration and the residual strength of the structure, the function of a remedial measures activity may be structural, protective, cosmetic, or any combination of these.

The first step in any repair activity is a thorough assessment of the damaged structure or component including evaluation of the (1) cause of deterioration, (2) extent of deterioration, and (3) effect of deterioration on the functional and performance requirements of the structure or component. From this information a remedial measures strategy is developed based on the consequence of damage (e.g., affect of degradation on structural safety), time requirements for implementation (e.g., shutdown requirements, immediate or future safety concern), economic aspects (e.g., partial or complete repair), and residual service life requirements (e.g., desired residual service life will influence action taken) (Price et al., 1993). Basic remedial measures options include (1) no active intervention, (2) more frequent inspections or conduct of specific studies, (3) if safety margins are presently acceptable, take action to prevent deterioration from getting worse, (4) carry out repairs to restore deteriorated or damaged parts of structure to a satisfactory condition, and (5) demolish and rebuild all or part of structure. Quite often options (3) and (4) are considered jointly.

Deterioration of reinforced concrete often results in cracking, spalling, or delamination. Corrosion resulting from either carbonation or the presence of chlorides is the dominant type of distress that impacts reinforced concrete structures. After identifying that a crack is of sufficient size to require repair, it is important to determine if the crack is dormant or active (i.e., mechanism still operating). Dormant cracks can be resin injected using epoxy or high molecular weight methacrylate (HMWM). Active cracks must be treated as if they are control joints and require special treatment, especially if fluid leakage is involved. Surface preparation is critical to a successful spall repair. The concrete substrate must be sound and the exposed surface dry and free of oil, grease, and loose particles. The most appropriate materials for patching are those that are closest in composition to the material to be patched. Usually this means Portland cement concrete for large patches or Portland cement mortar for small ones; however, non-Portland cement binders have been used successfully. By patching with a cementitious material, the final thermal and structural properties of the repair will be similar to the base concrete. Where the repairs are exposed to aggressive fluids the chemical composition of the fluids should be known and the repair materials must be compatible. Delaminations can be repaired by removal and replacement of the delaminated concrete. In areas where removal of concrete is not required, the delaminated area can be repaired by injection of epoxy or HMWM. Proper surface preparation, batching, mixing, placing, and curing are all important for long-term durability of concrete repairs. Basic repair solutions for corrosion-damaged reinforced concrete include: (1) realkalization by either direct replacement of contaminated concrete with new concrete, use of a cementitious material overlay, or application of electrochemical means to accelerate diffusion of alkalis into carbonated concrete; (2) limiting the corrosion rate by changing the environment (e.g., drying) to reduce the electrolytic conductivity; (3) steel reinforcement coating (e.g., epoxy); (4) chloride extraction by passing an electric current (DC) from an anode attached to the concrete surface through the concrete to the reinforcement (chloride ions migrate to anode); and (5) cathodic protection. More detailed information on typical remedial measures for NPP concrete structures is available in several references: (ACI, 2007; ACI, 2008; Emmons, 1993; U.S. Bureau of Reclamation, 1996; U.S Army Corps of Engineers, 1992).

7.1.4 Issues related to PWR component replacement

As of December 2010, 21 PWRs have replaced steam generators and/or the reactor pressure vessel head that required making a temporary opening in containment buildings constructed using either reinforced or post-tensioned concrete with a steel liner (Dunn et al., 2010).

Typically these openings have been in the vertical portions of the containment building, but temporary openings have also been made in the containment dome. Initially the openings were made through a combination of core drilling and sawing or jackhammer chipping; however, more recently high-pressure water (hydroblasting) has been used to remove the concrete. With respect to the containment liner, one issue is related to the potential for corrosion occurrence, or contamination by potentially corrosive materials (e.g., chlorides), while the liner is removed in preparation for the component replacement (e.g., steam generators or the reactor pressure vessel head). Also, residual stresses resulting from the reinstallation of the liner after PWR component replacement will occur. Finally, cold joints are created during these replacements. Depending on how these joints are finished and how the concrete/rebar repair is performed, these regions could provide pathways for corrosive contaminants. Additional information on how these replacements/repairs are performed could aid in determining the likelihood of these items contributing to future corrosion of the liner.

7.2 Repair and Mitigation Expert Panel Assessment

Current concrete and liner repair methods are well established and are not considered an issue. Mitigation methods, mainly cathodic protection, are not considered practical in preventing liner corrosion. The process of replacing steam generators and/or reactor pressure vessel heads could have some potential effects on future OD-corrosion of the liner. These could potentially arise from introduction of corrosive material during replacement or ingress of material through cold joints. However, additional details on this process could indicate that these issues have been considered and accounted for during the replacement process.

8. Summary

The following is a summary of the expert panel discussions on OD-corrosion of containment liners.

- Plant design and construction may influence the susceptibility to OD-corrosion due to differences in the probability of foreign material being embedded in the concrete. In particular, the higher rebar density of reinforced concrete structures may result in a greater probability that foreign materials are inadvertently embedded in the concrete compared to prestressed concrete structures.
- The operation of subatmospheric containments was not believed to increase the likelihood of OD-corrosion. Instances of OD-corrosion in subatmospheric containments are associated with embedded foreign material.
- Macrocell-accelerated localized corrosion appears to be the mechanism for OD-corrosion of containment liners. Corrosion was initiated by foreign materials located at the concrete/liner interface that were inadvertently embedded in the concrete during original construction. Concrete has sufficient water content and ionic conductivity to support electrochemical corrosion reactions. Cathodic areas, including the concrete rebar and passive sections of the liner, are electrically coupled to the anodic area of the liner where corrosion proceeds. The resulting macrocell created by the large

cathodic area that is coupled to the anodic site and contained in low resistivity concrete can drive localized corrosion propagation through the liner thickness.

- While other corrosion mechanisms could be explored further, there is no evidence that they have contributed to existing cases of through-wall corrosion.
- Potential long term concrete degradation mechanisms, such as delayed ettringite formation and dissolution in combination with the presence of a foreign body, may affect OD-corrosion and could be studied in greater detail.
- Concrete degradation mechanisms, such as carbonation, and chloride ingress from the external environment, were determined to be insignificant to liner corrosion. Additionally there is no evidence that corrosion has been caused by the selection of construction materials, concrete additives, or concrete contamination.
- Large scale screening of containment liners for small areas of OD-corrosion is not feasible with currently available NDE techniques. Development of NDE techniques to allow large areas of the liner to be inspected for OD-corrosion may be possible with future advances in technology.
- Current concrete and liner repair methods are well established and are not considered an issue. However, access holes cut into the containment building during steam generator replacement outages could affect future liner corrosion if corrosive material is introduced or contaminants are allowed to ingress at cold joints in the concrete.
- Mitigation methods (e.g., cathodic protection) may not be effective in this application.

9. Recommendations for Future Research

This report summarizes the expert panel member opinions regarding the issues related to mechanisms, inspection methods, and repairs for OD-corrosion of steel containment liners. The technical areas addressed include nuclear power plant design and operation, corrosion of steel in contact with concrete, concrete aging and degradation, concrete/steel non-destructive examination, and concrete repair and corrosion mitigation. For each of these areas, the expert panel member's assessments have also been provided. In participating in the workshop and developing this summary report, a number of items were identified that the panel recommends for future research or study. These items are those that the panel determined to be either of high importance or of potentially high importance. The panel recommended further study for items of potentially high importance only if the knowledge gap with respect to OD-corrosion was judged to be high.

Nuclear Plant Design and Operation

Since the potential for liner corrosion due to embedded foreign material may be greater for reinforced concrete containments due to the higher rebar density, focusing on those containments for future study may be appropriate. Also, a more detailed study could be conducted on the cases of embedded foreign material to date. This study could include an examination of the construction practices and procedures with respect to the locations of the embedded material to look for trends. Foreign material may be more likely to be located at higher density rebar locations (e.g., around penetrations) or at cold joints (e.g., concrete lift layers).

Liner Corrosion

Detailed modeling of corrosion initiation and propagation could be conducted to capture the complexity of the system, beyond the simplified analysis presented here in Section 4. The model could at a minimum include accurate accounting for polarization at the anodic and cathodic regions and include the effect of oxygen transport and availability. The model would be able to quantify alternative scenarios where the effect of parameters describing concrete quality, water content, wall dimensions, rebar placement, temperature and its fluctuations and related variables, are evaluated.

Added usefulness and confidence on model projections could be achieved by a subsequent or concurrent experimental investigation. Experiments aimed at replicating the observed damage conditions could be conducted with steel plates in contact with concrete that has embedded debris representative of that found at the sites. The experiments would determine/confirm under which conditions a sustained corrosion regime can be supported at the debris/steel interface, including required factors such as debris size, composition, transport properties, temperature, moisture content and native chloride content of the concrete.

Concrete Aging and Degradation

Investigation of the possibility of sulfate-induced corrosion of the steel liner from delayed ettringite formation and dissolution may be warranted. Potentially as part of the testing and analysis work for liner corrosion in the previous section, additional work on steel plate exposed to similar concretes could be conducted to determine the severity of both temperature and the other possible concrete degradation reactions on steel corrosion in the absence of chlorides or carbonation.

NDE

A technique is desired that can be applied remotely to inspect and determine the overall condition of large areas of the containment liner in a cost- and performance-effective manner. Limited research indicates that several techniques (e.g., electromagnetic acoustic transducers, magnetostrictive sensors, and multimode guide waves) exhibit potential for detection of liner corrosion. Further investigation of these techniques could be pursued with respect to detection capability and signal processing (e.g., defect sizing). The most promising of these techniques could be evaluated and validated through “mock-ups” of containment cross-sections containing simulated flaws representing general and pitting corrosion. Also, decommissioned plants (e.g., Zion Nuclear Power Plant) provide an opportunity to evaluate potential non-destructive evaluation techniques and validate results.

Concrete Repair and Corrosion Mitigation

Procedures are available for repair of containment liners and concrete. The overall effectiveness of remedial measures for reinforced concrete materials is one area where additional information would be useful. Very little data and information are available relative to the durability and effectiveness of repairs that have been made to nuclear power plant concrete structures.

Appendix A: New Liner Corrosion Recommendations

This appendix outlines the procedures the panel recommends be taken in the event that a new case of liner corrosion is found in an operating nuclear power plant containment liner. ASTM G161-00 (2007), Standard Guide for Corrosion-Related Failure Analysis, provides thorough listings and general procedures that could be implemented. The procedures listed in this Appendix include specific items related to containment liner corrosion in order to obtain data from the event that could potentially aid in determining the causes and processes. These items are only recommendations from the expert panel. Any actual required procedures would be determined by the NRC or the individual plants.

Table 2. New Corrosion Case Recommended Procedures and Tests

Test/Information Desired	Expected Insights/Comments
Steel liner thickness measurements in the surrounding region using UT or other appropriate method.	This item has been performed in cases of corrosion to date and would be expected for future cases. Thickness measurements of the surrounding liner provide the extent of the damage to the liner.
Prior to clean-up or repair, place reference electrode on exposed medium and measure potential against steel. Also measure pH of exposed medium.	Potential difference and pH are key parameters is assessing the corrosion progression.
Breakdown of the chemical composition of the steel plating through the thickness in the affected area	This would provide details to help determine how the corrosion process proceeded for the specific case.
Testing of any contaminants at the corrosion site, type, pH, sulfates	Contaminant inventories would indicate the environment and causes of the corrosion.
Extract samples of the foreign object, if any. Test for chemical composition and pore water pH	Data on the foreign object composition and pH will allow for proper characterization of the corrosion process. Avoiding contamination and drying of the sample are critical.
Concrete pH and moisture content at the liner/concrete interface, take cores of concrete if feasible	The pH and moisture again would provide data on the environment and aid in developing conclusions on the corrosion progression.
Measurements of the void space between the concrete and the liner in the surrounding region	The distance or void between the liner and the concrete may affect the corrosion progress; therefore, measurements of the gap between them in the region of corrosion would be beneficial.
Temperature at the concrete/liner interface (normal operating and outage)	The temperature of the liner and concrete during operation and outages is critical in modeling the corrosion processes effectively.

Appendix B: Phenomenon/Process Tables

In the preparation for the workshop, a series a phenomenon/process tables were assembled to provide an initial set of questions that span the 5 technical areas of concern. The expert panel discussed these questions and added additional issues during the course of the meeting. The following sections provide these questions and some brief comments on each with an importance and knowledge gap ranking (L-Low, M-Medium, H-High). These rankings are the opinions of the panel members and not the NRC or NRC staff. Each of these questions/issues is explored in more detail in the text of this report. The relevant text section is provided in parenthesis next to each phenomenon.

NPP Containment structure design, construction, and operation

Questions/Issues:

1. Would either a post-tensioned containment or a reinforced containment be more susceptible to containment liner corrosion?
2. Are sub-atmospheric containments more susceptible than large dry containments?
3. Is there a particular time at which the liner is more susceptible to corrosion, for example during an outage or during prolonged operation of air conditioners in humid climates?
4. Could containment liner corrosion susceptibility be a function of, construction practices or inadequate quality assurance practices?

Table 3. NPP Containment structure design, construction, and operation - Phenomenon/Process Table

<table>
<tr><th>question number(s)</th><th>phenomenon/process (sections discussed)</th><th>importance ranking (H/M/L)</th><th>knowledge gap (H/M/L)</th></tr>
<tr><td>1</td><td>Rebar density (3.1.1)</td><td>H</td><td>M</td></tr>
<tr><td colspan="4">comment: Reinforced concrete containments have more rebar "congestion" than post-tensioned containments which could lead to higher probabilities of foreign material remaining during concrete placement.</td></tr>
<tr><td>1</td><td>Liner buckling (3.1.2)</td><td>M</td><td>M</td></tr>
<tr><td colspan="4">comment: Post-tensioned containments have more substantial buckling of the liner than Reinforced containments, providing a gap between the steel liner and the concrete to enable water accumulation.</td></tr>
<tr><td>2</td><td>Subatmospheric operation/design (3.1.1, 3.1.2)</td><td>L</td><td>L</td></tr>
<tr><td colspan="4">comment: Reduced operating pressure not considered an issue. Design issues should be considered under rebar density concern.</td></tr>
<tr><td>3</td><td>Outages causing temperature changes in the containment (3.1.4)</td><td>M</td><td>M</td></tr>
<tr><td colspan="4">comment: Could affect condensation.</td></tr>
<tr><td>3</td><td>Air conditioning causing condensation inside containment (3.1.4)</td><td>M</td><td>M</td></tr>
<tr><td colspan="4">comment: Condensation on the inside liner surface could cause condensation on the liner/concrete interface (Outer diameter corrosion)</td></tr>
<tr><td>4</td><td>Dimensional tolerance issues with liner placement (3.1.3)</td><td>L</td><td>L</td></tr>
<tr><td colspan="4">comment: Tolerance issues with the liner not considered a significant issue beyond the liner buckling issue.</td></tr>
</table>

Corrosion of steel containment liners

Questions/Issues:

1. What is(are) the mechanism(s) for corrosion of steel containment liners?
2. What factors or parameters that may increase the containment liner susceptibility to this mechanism(s)?
3. Is a foreign object a necessary precursor for corrosion?
4. Is oxygen needed for corrosion?
5. What is source of moisture?
6. Do cracks in containment increase likelihood for localized carbonation?
7. Is location of the plant conducive to corrosion (e.g., in a marine environment)?
8. Are there regions of the liner that are more susceptible, e.g., because of temperature gradients, penetrations, welds, other discontinuities?

Table 4. Corrosion of steel containment liners – Phenomenon/Process Table

<table>
<tr><th>question number(s)</th><th>phenomenon/process (sections discussed)</th><th>importance ranking (H/M/L)</th><th>knowledge gap (H/M/L)</th></tr>
<tr><td>1</td><td>Foreign object embedded in concrete and in contact with liner induces corrosion (4.1.1, 4.1.2)</td><td>H</td><td>H</td></tr>
<tr><td colspan="4">comment: Observed in most through-wall corrosion incidents. Promotes macrocell-accelerated localized corrosion. Proposed mechanism is likely but no direct confirmation exists at present.</td></tr>
<tr><td>2</td><td>Temperature of the liner and concrete, change in temperature during outages (4.1.4)</td><td>H</td><td>H</td></tr>
<tr><td colspan="4">comment: The elevated temperature of the liner can cause a non-passive alkaline environment and increase chloride solubility.</td></tr>
<tr><td>3</td><td>General corrosion without foreign material (4.1.3)</td><td>L</td><td>H</td></tr>
<tr><td colspan="4">comment: General corrosion cannot be ruled out, but less likely. May depend on liner buckling (void) for water to accumulate between liner and concrete. Includes other construction defects such as voids and poorly consolidated concrete. The Beaver Valley incident showed corrosion that could not be positively traced to a foreign body so knowledge gap remains.</td></tr>
<tr><td>4</td><td>Oxygen needed for corrosion (4.1.1, 4.1.2)</td><td>H</td><td>L</td></tr>
<tr><td colspan="4">comment: Oxygen needed but expected to be present in sufficient amounts.</td></tr>
<tr><td>5</td><td>Moisture source at liner/concrete interface (4.1.2)</td><td>H</td><td>L</td></tr>
<tr><td colspan="4">comment: The high water to cement ratio of the concrete when constructed will cause there to be a high relative humidity in the concrete.</td></tr>
<tr><td>6</td><td>Cracking in concrete leading to carbonation (4.1.7)</td><td>L</td><td>L</td></tr>
<tr><td colspan="4">comment: Cracking not considered to be sufficient for carbonation to reach the liner interface.</td></tr>
<tr><td>7</td><td>Plant location increasing corrosion susceptibility (4.1.8)</td><td>M</td><td>M</td></tr>
<tr><td colspan="4">comment: Initial construction in a marine environment could have introduced corrosion contributors, but high ground water, especially in a marine environment thought to be of higher concern. However, effects of this are expected to appear at other plant location before the liner/concrete interface.</td></tr>
<tr><td>8</td><td>Regions of the containment more susceptible to corrosion (4.1.9)</td><td>M</td><td>M</td></tr>
<tr><td colspan="4">comment: Embedded foreign material is more significant however, the probability of embedded foreign material may be more likely in higher rebar density regions.</td></tr>
</table>

Concrete aging and degradation

Questions/Issues:

1. What is the significance of carbonation?
2. What is the significance of chloride ingress?
3. What is the significance of concrete cracks and spalls on containment liner corrosion?
4. Does the likelihood of containment liner corrosion increase as a function of time?
5. Is increase in likelihood of corrosion with age (if any) general or plant-specific?
6. How does plant location affect aging and degradation mechanisms that may, in turn, affect containment liner corrosion susceptibility?
7. Do the original construction materials affect liner corrosion?

Table 5. Concrete aging and degradation - Phenomenon/Process Table

question number(s)	**phenomenon/process (sections discussed)**	**importance ranking (H/M/L)**	**knowledge gap (H/M/L)**
1,2,3	Carbonation, external chlorides, and cracking effects on liner corrosion (5.1.2)	L	L
comment: Concluded that pathways cannot reach from the exterior containment to the liner.			
4	Time effects on corrosion (5.1.3)	M	H
comment: Time could allow for ettringite formation and change oxygen levels.			
5	Long-term effects general or plant-specific (5.1.4)	M	M
comment: Conditions at individual plants could vary enough to increase long-term corrosion susceptibility.			
6	Degradation mechanisms affecting plant corrosion as a function of plant location (5.1.4)	L	L
comment: Degradation will most likely be detected and repaired prior to affecting the liner. Location, therefore, not critical to liner corrosion.			
7	Original construction materials (5.1.5)	L	M
comment: Fly ash may increase susceptibility to corrosion, but effects of fly ash would be manifested at the containment exterior prior to liner/concrete interface.			

Concrete/steel NDE, characterization testing, and sampling

Questions/Issues:

1. Are the ASME Section XI, IWE examination requirements for containment liners adequate to detect OD-initiated corrosion for all plants?
2. Effectiveness of UT?
3. Effectiveness of VT ?
4. Are there other methods not currently in use which may identify corrosion sooner?
5. Is conducting UT on only parts of a liner sufficient to characterize the entire liner?
6. Are there any techniques to identify corrosion from the outer surface of the liner?

Table 6. Concrete/steel NDE, characterization testing, and sampling – Phenomenon/Process Table

question number(s)	phenomenon/process (sections discussed)	importance ranking (H/M/L)	knowledge gap (H/M/L)
1	Effectiveness of ASME Section XI, IWE examination for detecting liner/concrete interface corrosion (6.1.1)	H	L
comment: ASME inspections procedures will not detect corrosion until a blister forms and through-wall corrosion has occurred.			
2	UT effectiveness (6.1.3)	M	L
comment: UT effective over small regions, but is not practical over entire containment inner surface. Crawlers can damage liner coatings.			
3	VT effectiveness (6.1.4)	M	L
comment: Corrosion only observed after a through-wall hole has been created. Inaccessible areas cannot be observed with VT.			
4	Other techniques for detecting corrosion (6.1.5)	M	H
comment: Electromagnetic acoustic transducers, magnetostrictive sensors, multimode guide waves, and electrochemical techniques have potential, but not currently developed for this application			
5	UT sampling on liner surface effectiveness in characterizing entire liner (6.1.6)	L	L
comment: Liner corrosion appears to be a local issue (e.g., foreign material initiation), so UT on limited sections of the liner could easily miss these areas of corrosion.			
6	Corrosion detection from outer surface (6.1.7)	L	L
comment: No techniques can effectively scan through the concrete and rebar to view the liner.			

Concrete repair and corrosion mitigation

Questions/Issues:

1. Is weld overlay sufficient to increase plate thickness in corrosion damaged areas of the containment liner?
2. Is cathodic protection effective or appropriate?
3. Are coatings effective or appropriate for mitigation aging related degradation of the concrete and/or effective for preventing corrosion of the containment liner?
4. Are localized repairs of the concrete effective in mitigating environmental degradation and/or corrosion of the containment liner?
5. Are the current criteria for concrete repair (i.e., crack width, and size of concrete spalls) sufficient for mitigating environmental degradation and/or corrosion of the containment liner?
6. What are the effects of steam generator replacement activities?

Table 7. Concrete repair and corrosion mitigation – Phenomenon/Process Table

question number(s)	phenomenon/process (sections discussed)	importance ranking	knowledge gap
1	Weld overlay effectiveness in repair (7.1.1)	L	L
comment: Weld overlays are effective in repairing corroded liners, but the liner section is typically cut out and replaced.			
2	Cathodic protection to prevent liner corrosion (7.1.2)	L	L
comment: Not practical due to the large amount of steel in the concrete containment walls (e.g., rebar, tendons)			
3	Moisture barrier coatings effectiveness in preventing corrosion (7.1.2)	L	L
comment: Coatings on liner can prevent interior surface corrosion, but do not prevent liner/concrete interface corrosion. Coatings on exterior wall of the containment will not prevent corrosion associated with embedded foreign material			
4	Repairs to the concrete (7.1.3)	L	L
comment: Repairs would be made to the concrete after finding through-wall corrosion. If a foreign material causes the corrosion, the repair should be effective in preventing further corrosion.			
5	Concrete repair criterion (7.1.3)	L	L
comment: Concrete repair criteria are well established, and cracking/spalling not thought to affect liner corrosion.			
6	Steam generator replacement (7.1.4)	M	H
comment: Cuts in the containment made to replace steam generators (and other components) would create cold joints. There could be issues with these joints that could lead to liner corrosion.			

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