

CONTAINMENT LINER CORROSION

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Abstract

Of the 104 currently operating nuclear power plants in the U.S, there are 66 plants that have containment buildings constructed with an inner steel liner plate in contact with a thick concrete shell. The steel liner is nominally 6 to 10 mm [0.25 to 0.375 in] thick and is designed in conjunction with the concrete containment building to function as an essentially leak tight barrier against the release of radiation under accident conditions. Corrosion of the containment liner has been observed and corrosion penetration of the liner associated with foreign materials embedded in the concrete from original construction has occurred in a few U.S. plants. This paper reviews plant operating experience, evaluates factors that can affect containment liner corrosion susceptibility, and discusses the mechanisms for through-wall corrosion initiated at the concrete/liner interface.

Introduction

In the U.S., commercial nuclear power plants employ 3 barriers to radiation release. These barriers are the fuel cladding, the reactor coolant system boundary including the reactor vessel, and the containment building. Three barriers provides defense in depth against release of radioactive materials in the event of an accident. The construction of the reactor containment buildings varies considerably depending on plant type, containment design, and plant vintage.¹⁻³ Containment designs used by all BWR and PWR plants are summarized in Table 1. Of the 104 currently operating plants, 11 BWRs and 55 PWR's are of interest in this paper. Those plants employ a steel containment liner in contact with concrete.^{1,4}

In 1996 the NRC amended its regulations (10 CFR 50.55a) to incorporate by reference the 1992 Edition and Addenda of Subsections IWE and IWL of Section XI of the ASME code to assure that critical areas of the containments are routinely inspected to detect and to take corrective action for defects that could compromise the integrity of the containment structure. Specifically, NRC Information Notice 97-29 stated that the amended rule became effective on September 9, 1996.⁵ Licensees were required to incorporate the new requirements into their inservice inspection (ISI) plans and to complete the first containment inspection within five years.

Containment liner inspections are intended to identify damage to protective coating and liner corrosion initiated on the interior surface. However, the exterior liner surface in contact with the concrete cannot be visually inspected under normal circumstances. Because these steel containment liners are typically 6 to 10 mm [0.25 to 0.375 in] thick, the frequency of inspections

required by Subsection IWE is designed to detect corrosion prior to significant damage to the liner. Corrosion of the exterior of the steel liner would be expected to proceed at a very slow rate due to the stabilization of a passive oxide film on the steel in the alkaline concrete environment. Nevertheless, since the revision of 10 CFR 50.55a there have been 5 domestic incidents of external corrosion of containment liners. This includes 3 cases where the through-wall corrosion of the containment liner was discovered and caused by corrosion that initiated at the concrete/liner interface.

The objective of this paper is to analyze the available data on corrosion related degradation of steel containment liners used with reinforced or prestressed post tensioned concrete containment structures. Because low corrosion rates would normally be expected for steel in contact with concrete, it is of interest to evaluate the corrosion of the steel containment liner that has initiated from the exterior surface that is in contact with the concrete containment structure.

Operating Experience Summary

Information on the degradation of the containment structure including the steel containment liner and concrete structure have been compiled from a variety of sources including NRC inspection reports, licensee inservice inspection reports, operational experience, and NRC Information Notices.⁵⁻¹⁰

Through-wall corrosion of the containment liner initiating at the concrete interface

Between 1999 and 2009 there have been several reported incidents of external corrosion and through-wall penetration of containment liners in U.S. plants. Most of these cases were associated with defects including wood pieces that were used in original construction to position reinforcement prior to concrete placement and other construction debris that were inadvertently embedded in the concrete. Incidents of through-wall corrosion that initiated at the liner/concrete interface were discovered by visual examination of interior surface of the liner. After discovery, repairs typically included removing the foreign materials, filling voids left in the concrete with grout and if necessary, replacing corroded sections of the liner plate.

In May of 1999 at Brunswick Unit 2, three areas were identified where corrosion had penetrated the drywell liner. Two areas were initiated in areas with coating failures. The third location was associated with a work glove that was embedded in the concrete and in contact with the containment liner.^{9, 11}

In September of 1999, North Anna Unit 2 discovered a through-wall hole in the containment liner. Removal of the liner plate in the area of the through-wall corrosion revealed a piece of wood that was approximately 10 cm x 10 cm x 1.8 m [4 in x 4 in x 6 ft].

In June 2009 Beaver Valley Unit 1 was conducting an ASME XI IWE general visual examination when an area of blistered paint approximately 75 mm [3 in] in diameter was identified on the interior of the steel liner. After paint removal and cleaning, a rectangular shaped corrosion penetration measuring approximately 2.5 x 1 cm [1 x 3/8 in] was observed. A

section of the liner plate was removed and a piece of wood, which was approximately 5 x 10 x 15 cm [2 x 4 x 6 in], was discovered to be embedded in the concrete.

Through-wall corrosion of the embedded steel liner was discovered at Barsebeck Unit 2 (Sweden) in 1993 following a failed integrated leak rate test. The Barsebeck design differs from U.S. plants since the containment construction consisted of a 6 mm [0.24 in] thick liner plate in contact with a 900 mm [35 in] thick layer of concrete on the outside and a 200 mm [8 in] thick layer of concrete on the inside. Corrosion was believed to be initiated at an area of poorly consolidated concrete around a penetration into containment where water had accumulated. No foreign material in the concrete was identified.

Through-wall corrosion at Koeberg Unit 1 (South Africa) was discovered in 2010. Similar to incidents reported in the U.S., a section of the liner measuring 44 x 36 cm [17 x 13 in] was removed, and a wedge shaped piece of wood was found to be in contact with the liner.

Containment liner damage from corrosion initiated at the liner/concrete interface

In addition to through-wall corrosion of the containment liner, operating plants have also discovered localized reduction in the containment liner thickness as a result of corrosion initiated at the containment liner interface.

In March of 2001, D.C. Cook Unit 2 discovered a through-wall hole in the containment liner plate that was approximately 0.47 cm [$\frac{3}{16}$ in] in diameter on the exterior surface and 1.9 cm [$\frac{3}{4}$ in] on the interior surface. The licensee reported that the hole appeared to be related to an inadequate construction repair. After the damaged liner plate section was cut out, a wire brush with a wooden handle was found embedded in the concrete. Corrosion on the concrete side of the liner was measured to be 1.8 - 4.8 mm [72 - 188 mils] deep in the area of the embedded wire brush.

In March 2006 Beaver Valley Unit 1, during the hydroblasting of concrete to create a temporary construction opening in the containment structure for the replacement of the steam generators and reactor vessel head, three areas of corrosion in the containment liner plate were identified. Local metal loss (corrosion depth) was measured between 1.1 and 5.8 mm [45 to 227 mils]. The sections of the liner removed for analysis were replaced with new plate material. The root cause of the corrosion was indeterminate. Several pieces of wood were found during a subsequent inspection of the concrete debris pile; however, there was no clear evidence that the corrosion damage to the liner was a result of contact with this embedded foreign material. Similarly, other foreign material that may have been in contact with the liner could have been destroyed by the hydroblasting operation.

Embedded foreign material in concrete without liner corrosion

At Arkansas Nuclear One Unit 1, the licensee reported that a triangular wooden wedge 1.3 x 5 x 6.3 cm [5 x 2 x 2 $\frac{1}{2}$ in] was found in the containment structure that was not removed when the original construction opening was closed. Although the licensee determined that the wood did

not compromise the structural or shielding performance requirements of the containment building, the wood was removed and the concrete was repaired with grout.

At Point Beach Unit 1, a piece of wood was found near a spare electrical penetration. The licensee reported that the wood was dry with no evidence of degradation and indicated that there was no concern for structural effects on the concrete. Based on previous industry experience with embedded wood, the licensee conducted a visual examination under the IWE inspection program and indicated that volumetric examination would be conducted on the spare electrical penetration in the area of the embedded wood.

At North Anna Unit 1 in 2001 six pieces of wood were discovered embedded in the concrete dome. Three of the pieces were very small and easily removed with no concrete repairs necessary. The remaining three pieces were removed and repaired with grout. No rebar was exposed. The largest of these pieces was 3.8 x 3.8 cm [1 ½ x 1 ½ in] and extended through the concrete dome to the steel liner. The wood was removed and the liner was cleaned. Examination by UT and showed no indication of metal loss.

In 2002, Indiana Michigan Power Company indicated that three pieces of wood and one piece of plastic were found embedded in the concrete of the D.C Cook unit 1 containment building.¹¹ The licensee reported that all items were shallowly embedded in the concrete and that the areas around these items did not indicate any significant leaching or any other distress conditions.

Temporary openings in PWR containments

As of December 2010, 21 PWRs have replaced steam generators and/or reactor pressure vessel heads utilizing a temporary opening in the containment building. Information on the condition of the containment liners during reactor pressure vessel head and steam generator replacement were collected by reviewing NRC on site inspector reports and licensee documents including inservice inspection reports. Corrosion of the external surfaces of the liner was only observed during the replacement of the steam generators at Beaver Valley Unit 1 in 2006 as previously described. Liner plate sections at Braidwood Unit 1 (1998) and Turkey Point Unit 4 (2005) were damaged during the containment removal operation, and required repair prior to containment restoration.

Inservice inspection of containment liners

Available inservice inspection reports of concrete containments with steel liners from 1999 to February 2010 were reviewed to understand the frequency and potential factors that influence liner corrosion. This effort was limited to the 11 BWR and the 55 PWR plants with steel containment liners in contact with a concrete containment structure. Domestic instances of liner corrosion at the concrete/liner interface were not associated with concrete degradation such as cracks, spalls, and exposed rebar. Only one instance of voids in the concrete and 2 instances of liner bulges were identified, none of which was associated with liner corrosion. Liner corrosion on the interior surfaces was associated with coating or moisture barrier degradation. In most instances, the corrosion of the liner is limited to surface rusting; however, cases of pitting corrosion have been observed coincident with moisture barrier degradation and coating failures.

Analysis of Operating Experience

The information obtained from the ISI reports indicates that liner corrosion on interior surfaces is observed more frequently than external corrosion. Factors that are significant for the corrosion of the containment liner on the interior surfaces include the presence of moisture, coating deterioration and plant design have been identified in previous NRC Information Notices.⁵⁻⁹ At the concrete basemat/liner interface, corrosion of the liner is most often initiated by degradation of the moisture barrier.

On the external surface of the liner, the main factor that appears to affect corrosion is construction defects. Cases of through-wall corrosion have been attributed to the presence of foreign material in the concrete as a result of inadequate practices/housekeeping at the time of the original construction. Aging related degradation such as cracking, carbonation, and chloride ingress does not appear to be a factor in any of the known cases of through-wall corrosion initiated at the liner/concrete interface.

Containment Construction with Embedded Foreign Material

The differences in the designs between post-tensioned and reinforced concrete construction may be a significant factor for containment liner corrosion at the liner/concrete interface. During containment construction, the steel liner is fabricated prior to the placement of the concrete. The liner also served as the inner diameter form for concrete placement and was connected to an outer form by steel tiebars. The outer form was removed after concrete placement and curing. In reinforced concrete containments, it is likely that the tiebars may have been in contact with the liner and multiple layers of rebar.

Table 2 lists the typical containment volumes and accident design pressures for BWR and PWR containment designs constructed using either reinforced or post tensioned concrete with a containment liner. To obtain the required strength, an increase in the density of rebar was necessary for larger containment volumes with higher design pressures. During construction, wood pieces were commonly used to position the rebar at a designed distance from the liner. The congestion caused by the multiple layers of rebar increases the likelihood that some of the wood pieces and construction debris such as gloves and wire brushes were inadvertently left in place. Corrosion at the concrete liner interface has been most frequently observed in subatmospheric containments which have a high design pressure and are significantly larger than all BWR and PWR ice condenser containments. Although no embedded foreign material has been reported in the 10 reinforced PWR large dry containments, these are the largest reinforced containments and typically have high design pressures.

Corrosion Rates

Incidents in which corrosion was observed on the external surface of the liner are summarized in Table 3. Based on the age of the plants and the thickness of the liner, the average corrosion rate can be determined to be in the range of 0.29 to 0.50 mm/yr [11 to 19 mpy]. Although the corrosion rate may vary considerably, perhaps by several orders of magnitude, during the period

from construction to discovery, the average corrosion rate for the liner corrosion penetration incidents can be compared to both measured atmospheric corrosion rates and the range of observed localized corrosion rates for steel. Atmospheric corrosion rates for steel are dependent on the type of environment and range from 0.005 to 0.02 mm/yr [0.2 to 0.8 mpy] in rural atmospheres to 0.03 to 0.08 mm/year [1.2 to 3.2 mpy] in marine environments.¹² Localized corrosion rates as a result of differential aeration or differential pH can be in excess of 3 mm/yr [120 mpy].¹³

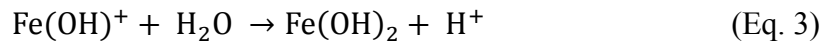
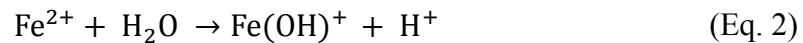
Corrosion Mechanism

Corrosion initiated at the concrete/liner interface associated with construction defects such as embedded foreign materials appears to be consistent with localized corrosion processes such as pitting corrosion or crevice corrosion. A schematic of liner corrosion initiated as a result of wood embedded in the concrete and in contact with the liner is shown in Figure 1. The effects of embedded foreign material are likely dependent on a variety of factors including the composition, size, and location of the foreign material. In the absence of aggressive contaminants such as chlorides, carbon steel is passivated when exposed to the alkaline environment of concrete. Wood, which has been identified as contributing to the steel containment liner exterior corrosion incidents at D.C. Cook Unit 2, Brunswick Unit 2, North Anna Unit 2 and Beaver Valley Unit 1, is naturally acidic¹⁴ and may also trap sufficient moisture for corrosion reactions.

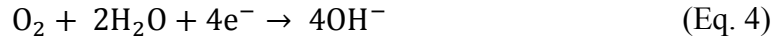
In order to elucidate the likely corrosion mechanism(s) and understand factors that affect these mechanism(s), the NRC sought the input of experts with experience in containment design and construction, concrete degradation, corrosion in concrete and non-destructive examination. Professor Alberto Sagues indicated that macrocell accelerated localized corrosion was the likely corrosion mechanism for through-wall penetration of the containment liners.¹⁵ Embedded wood at the concrete liner interface results in the formation of a crevice. The acidic pH of wood locally disrupts or prevents the formation of a passive film on the steel liner and the active dissolution of the low carbon steel (>99% Fe) occurs according to equation 1.



The Fe^{2+} cations are then hydrolyzed in the aqueous environment to produce $\text{Fe}(\text{OH})_2$ (solid) and H^{+} anions as shown in Equations 2 and 3.¹⁶



Anions with high mobility diffuse into the crevice to maintain electro-neutrality. Chloride ions have high mobility and are often present in many systems either as a natural species or a contaminant. The result is a locally acidic environment with chloride ions that significantly increases the corrosion rate of the steel. Outside of the crevice, the steel in contact with the concrete is passivated by the alkaline concrete environment. The iron oxide is semiconductive and the cathodic reduction of oxygen can readily occur on the passive steel surface according to equation 4



The reduction reaction complete the electrochemical circuit necessary to support the anodic reactions.^{16,17}

While the corrosion reactions are well known, localized penetration of the containment liners in contact with thick sections of reinforced concrete required additional analysis. If the cathodic reaction locus were limited to that of the anodic location, all available oxygen in the vicinity would be depleted and corrosion rate should decrease with time.¹⁸ However, the structure of the reinforced containment, where the containment liner is electrically connected through tiebars to multiple layers of rebar, creates a macrocell which allows the supporting cathodic reaction to occur over a large area.¹⁵ As a result, oxygen depletion occurs over the entire macrocell and is not limited to the immediate vicinity of the anodic corrosion reactions. Therefore, the rate of localized corrosion of the liner is not expected to decrease with time.

Professor Sagues also estimated the corrosion rates assuming that the conductance of the metallic path is many orders of magnitude greater than that for the electrolyte.¹⁵ Because of the high rebar density and the small dimension of the anodic area compared to that of the rest of the liner, much of the passive steel assembly is expected to experience relatively little polarization. For the corrosion rate calculation, a nominal polarization of $\Delta E = 0.25 \text{ V}$ was assumed between the area of active corrosion at the liner/concrete interface and the passive surfaces of the rebar and adjacent surfaces of the liner that are in contact with alkaline concrete pore water. The resistance of the electrolytic path was assumed based on resistivity values representative of very low, medium and high concrete resistivity in field structures corresponding to 1, 10, and 100 k Ω -cm respectively.¹⁹

The geometry of the system was 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. With such geometry, the effective resistance of the ohmic path is finite²⁰ and given by equation 5.

$$R = \frac{\rho}{4r} \quad (\text{Eq. 5})$$

where ρ is the resistivity of the medium and r is the radius of the disk anode. The macrocell current density at the anode was assumed to be 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 at the anode, i_{corr} , is given by equation 6.

$$i_{\text{corr}} = \frac{\Delta E}{RS} = \frac{4\Delta E}{\pi r \rho} \quad (\text{Eq. 6})$$

where $S = \pi r^2$ is the area of the disk anode. The radius of the anodic area was assumed to be either 1, 3, and 10 cm which bounds observed dimensions of corroded areas. The corrosion current density was converted into an equivalent steel corrosion rate by simple Faradaic

conversion assuming formation of Fe^{2+} ions. With a corrosion current density of $1 \mu\text{A}/\text{cm}^2$, this yields $\sim 12 \mu\text{m}/\text{y}$ for steel penetration.²¹

Full wall penetration of a representative 1 cm thick liner over a service time of 30 years was predicted for all anode sizes if the lowest resistivity case ($1 \text{ k}\Omega\text{-cm}$) is considered (Figure 2). Such a condition is reasonable in water saturated concrete scenarios. Even when assuming a value as high as $10 \text{ k}\Omega\text{-cm}$, corrosion penetration within the service life range of interest appears plausible if small anodes were to develop or if the driving potential were larger.

Summary

Available information on corrosion related degradation of steel containment liners used with reinforced or prestressed post tensioned concrete containment structures and originating from the concrete/steel interface was reviewed. The corrosion mechanism was determined and simplified modeling has been conducted and compared to observed corrosion incidents. The following summary is based on the review and analysis of the available information.

- For U.S. plants, there have been 5 instances of containment liner corrosion that initiated from the outside surface at the concrete/steel liner interface. All 5 containment buildings were reinforced concrete construction. In 4 of these cases foreign material was found embedded in the concrete and in contact with the liner. Through-wall corrosion of the containment liner was observed in 3 cases.
- Foreign materials such as wood and worker's gloves or organic materials such as felt have been shown to promote the corrosion the steel liner. Wood is naturally acidic and may disrupt the passivity of carbon steel. In addition these materials may retain moisture, create crevices, and provide decomposition products as a source of contaminants such as chloride.
- Through-wall penetration of the containment liners by corrosion initiated at the liner/concrete interface is a result of macrocell accelerated localized corrosion. Localized corrosion of the liner is driven by reduction reactions occurring on adjacent liner surfaces and on the surfaces of the embedded rebar. The large cathodic surface area drives corrosion at the anodic area even if oxygen availability at the anodic site is limited.

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Table 1. Summary of domestic nuclear power plant containment designs

Containment Design	Number of Domestic Plants ¹		
	Free standing steel with concrete enclosure	Post-tensioned concrete with a steel liner	Reinforced concrete with a steel liner
BWR MK I	21	0	2
BWR MK II	1	2 ²	5
BWR MK III	2	0	2
PWR Ice condenser	7	0	2
PWR Sub-atmospheric	0	0	7
PWR Large Dry	7	36	10
Totals	38	38	28

¹Hessheimer and Dameron, 2006

²Reinforced drywell, post-tensioned wetwell

Table 2. Summary of containment design parameters, incidents of embedded foreign materials and liner corrosion.

Containment Design	Construction R: Reinforced PT: Post-tensioned	Typical values		Number of Plants		
		Volume	Design pressure	Total	Embedded Foreign material	Corrosion at the liner/concrete interface
BWR MK I	R-Drywell R-Wetwell	7600 m ³ [27000 ft ³]	0.40 MPa [58 psi]	2	1	1
BWR MK II	R-Drywell R-Wetwell	11300 m ³ [40000 ft ³]	0.35 MPa [50 psi]	5	0	0
	R-Drywell PT-Wetwell	11300 m ³ [40000 ft ³]	0.35 MPa [50 psi]	2	0	0
BWR MK III	R-Drywell R-Wetwell	37000 m ³ [130000 ft ³]	0.10 MPa [15 psi]	2	0	0
PWR Ice-condenser	R	34000 m ³ [120000 ft ³]	0.14 MPa [20 psi]	2	2	1
PWR Sub-atmospheric	R	48000 m ³ [170000 ft ³]	0.36 MPa [52 psi]	7	3	2
PWR Large Dry	R	62000 m ³ [220000 ft ³]	0.37 MPa [53 psi]	10	0	0
	PT	62000 m ³ [220000 ft ³]	0.37 MPa [53 psi]	36	2	0

Table 3. Average containment liner corrosion rates associated with observations of external corrosion

Plant /Location	Plant Information	Year of incident	Plant age, years	Liner/metal thickness	Maximum corrosion penetration	Average corrosion rate
Barsebeck-2 Sweden	BWR ASEA-Atom	1993	16	7 mm 0.275"	7 mm 0.275"	0.44 mm/yr [17 mpy]
Brunswick-2 North Carolina	BWR GE 4 Mark 1	1999	24	8 mm 0.312"	8 mm 0.312"	0.33 mm/yr [13 mpy]
North Anna-2 Virginia	PWR West-3LP Sub-atmospheric	1999	19	10 mm 0.375"	10 mm 0.375"	0.5 mm/yr [20 mpy]
D.C. Cook-2 Michigan	PWR West-4LP Ice-condenser	2000	22	10 mm 0.375"	4.8 mm 0.188"	0.22 mm/yr [8.5 mpy]
Beaver Valley-1 Pennsylvania	PWR West-3LP Sub-atmospheric	2006	30	10 mm 0.375"	5.8 mm 0.227"	0.19 mm/yr [7.5 mpy]
		2009	33	10 mm 0.375"	10 mm 0.375"	0.29 mm/yr [11 mpy]
Koeberg-1 South Africa	PWR Framatome-3LP	2010	26	6 mm 0.236"	6 mm 0.236"	0.23 mm/yr [9.1 mpy]

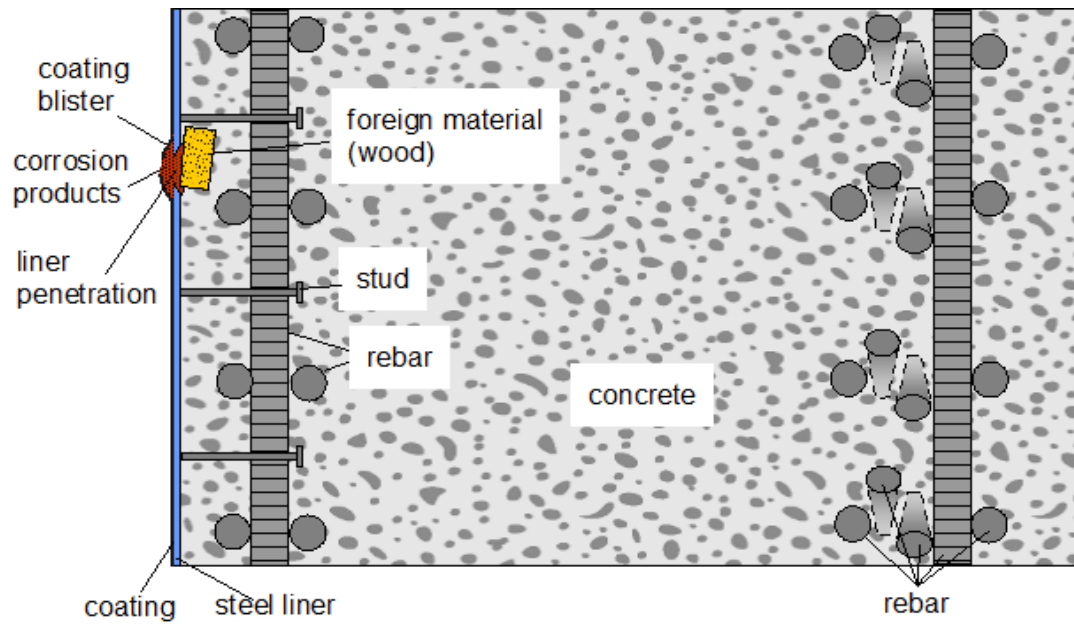


Figure 1. Schematic of a reinforced containment cross-section showing embedded foreign material and containment liner corrosion

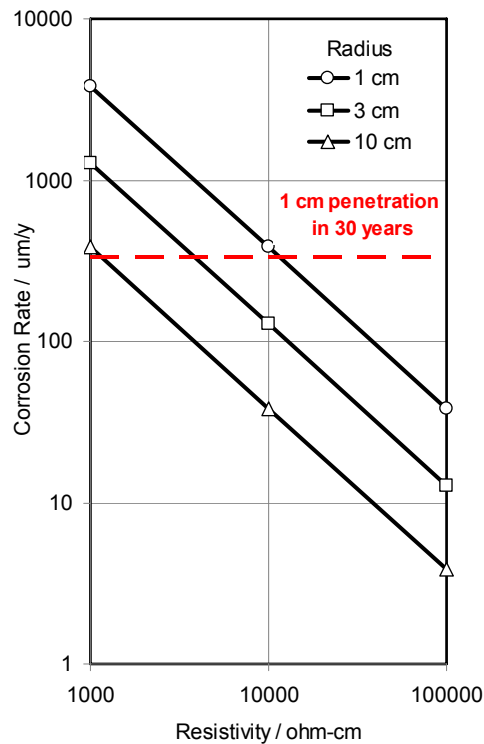


Figure 2. Calculated containment liner macrocell accelerated localized corrosion rate as a function of concrete resistivity and radius of the anodic area.