Xcel Energy

External Design Document Suitability Review Checklist

External Design Document Being Reviewed:

Title: **Evaluation of Effect of Borated Water Leaks on Concrete, Reinforcing Bars, and Carbon Steel Plate of the Containment Vessels at Prairie Island Units 1 and 2**

Number: R-4448-00-01 Rev: 0 Date: 3/2009

This design document was received from:

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REVIEW

		Reviewed	N/A
1.	Design inputs correspond to those that were transmitted to the External Design Organization.	☒	☐
2.	Assumptions are described and reasonable.	☒	☐
3.	Applicable codes, standards and regulations are identified and met.	☐	☒
4.	Applicable construction and operating experience is considered.	☒	☐
5.	Applicable structure(s), system(s), and component(s) are listed.	☒	☐
6.	Formulae and equations are documented. Unusual symbols are defined.	☒	☐
7.	Acceptance criteria are identified, adequate and satisfied.	☒	☐
8.	Results are reasonable compared to inputs.	☒	☐
9.	Source documents are referenced.	☒	☐
10.	The document is appropriate for its intended use.	☒	☐
11.	The document complies with the terms of the Purchase Order and/or DIA.	☒	☐
12.	Inputs, assumptions, outputs, etc. which could affect plant operation are enforced by adequate procedural controls. List any affected procedures.	☐	☒
13.	Plant impact has been identified and either implemented or controlled. (e.g., For piping analyses, the piping and support database is updated or a tracking item has been initiated.)	☐	☒
14.	Design and Operational Margin have been considered and documented.	☒	☐

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13. Note that section 2.2 of this report contains recommendations to validate the assumptions within the report. AR 01160372 contains actions resulting from these recommendations.

Completed by: [signature] Date: 4/28/09

Evaluation of Effect of Borated Water Leaks on Concrete, Reinforcing Bars, and Carbon Steel Plate of the Containment Vessels at Prairie Island Units 1 and 2

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The last revision number to reflect any changes for each section of the report is shown in the Table of Contents. The last revision numbers to reflect any changes for tables and figures are shown in the List of Tables and the List of Figures. Changes made in the latest revision, except for Rev. 0 and revisions which change the report in its entirety, are indicated by a double line in the right hand margin as shown here.

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1 INTRODUCTION

The work described in this report was performed in response to a request from Xcel Energy to evaluate the effects of borated water leaks from the Prairie Island Unit 1 and 2 refueling pool inside containment on the safety functions of the concrete and reinforcing bars (rebar) inside the reactor building, and on the safety functions of the carbon steel plate of the containment vessel [1, 2, 3, 4].

1.1 Background

There have been occasional leaks of borated water from the refueling pool inside the containment at Prairie Island Units 1 and 2. The refueling pool includes an area above the reactor vessel (the upper cavity), a deeper area for storage of the upper and lower reactor internals (the lower cavity), and a still lower area for fuel transfer (known as the transfer pit). The history of leaks from the refueling pool and their likely sources and leak paths are documented in a draft Root Cause Evaluation (RCE) [5] that is being performed in parallel with preparation of this report (it is an assumption of this report that the history of leaks in the draft RCE report is correct). Over the years, many efforts have been made to eliminate the leaks, with varying success depending on the methods used and the care and completeness of their application.

There has been no identification of any structural damage caused by the refueling pool leaks. However, as part of the license renewal project, it has been decided to evaluate the possible effects on safety related items that conceivably could be affected by the leakage. These items are the steel containment vessel and the Class I reinforced concrete structures that support the refueling pool and other safety related equipment inside containment. The reinforced concrete consists of the concrete itself, which is made of cement plus aggregate, and reinforcing steel bars (rebar). Assessments to date by the license renewal project for Prairie Island have not identified any significant aging concerns regarding attack of the steel containment vessel or reinforced concrete inside the containment [6, 7]. However, while the assessments of [6 and 7] indicate that the effects of leakage will be managed over the life of the units, they do not address in detail the possible effects to date of the borated water leakage from the refueling pool; these aspects are evaluated in this report.

1.2 Organization of this Report

This report is organized as follows:

- Section 1 provides background information for the report.
- Section 2 provides a summary of the main conclusions and recommendations developed during preparation of the report.
- Section 3 summarizes what is known about the borated water leakage that has occurred over the years at Prairie Island.
- Section 4 contains an evaluation of the effects of borated water leakage on the steel containment vessel.
- Section 5 contains an evaluation of the effects of borated water leakage on reinforced concrete, including effects on the concrete itself, on the rebar, and on the behavior of reinforced concrete considering both the concrete and rebar.
- Section 6 contains the references cited in the report.
- Appendix A contains figures illustrating possible leak sources and leak paths.

2 SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

2.1 Conclusions

The main conclusions developed by this evaluation are as follows.

- Steel Containment Vessel
  - There is no evidence that any significant corrosion has occurred to date of the steel containment vessel. In this regard, ultrasonic wall thickness measurements in 2003, 2004 and 2008 of the steel plate thicknesses in the transfer tube area and at Sump B around the RHR suction pipes indicate that the wall thicknesses are above the nominal specified thicknesses in these areas (1.5 inches and 3.5 inches, respectively).
  - Some inaccessible areas of the containment vessel steel plate in the lower parts of the containment are likely to have been wetted for long periods. Evaluation of the environmental conditions that may have been present in these inaccessible areas indicates that they have probably been benign. This is based on the fact that there are large amounts of concrete in contact with the limited volume of water in the containment vessel to concrete gap. In addition, this water has been in contact with the concrete for long periods of time, e.g., years. These two factors have likely caused the pH in the water to have increased to a protective level by dissolution of the calcium hydroxide in the concrete, similar to the situation for pore water in concrete, which is known to reach protective pH levels. However, because of the differing surface to volume ratios for crevice water vs. pore water, it would be desirable to confirm that that there is high assurance that the increase in pH to fully protective levels has occurred in the steel containment vessel to inner concrete crevice.
  - While the above assessment is that environmental conditions have probably been benign, it is difficult to be certain that active corrosion at low rates has not occurred. This is because there appear to be no test data that demonstrate that the water in the steel plate to concrete gap in the lower parts of the containment must have been raised in pH to a fully protective level, e.g., to a pH greater than 12.5. Assuming that such a protective pH has not developed, a conservative upper estimate of the corrosion that could have occurred is 0.25 inch, resulting in a minimum remaining wall thickness of 1.25 inches.
  - Evaluation of the maximum plausible thinning that could have occurred (0.25 inch) indicates that it raises no concerns about the ability of the steel containment vessel to meet its safety related function of being leak tight under accident conditions. Preliminary calculations indicate that this amount of thinning would not jeopardize the ability of the vessel to meet its safety function of resisting accident pressure. However, any actual measured thinning below the nominal wall thickness would need to be formally evaluated in accordance with ASME Code Section XI rules.

- Concrete
  - There is no direct evidence that any significant degradation of the concrete subject to the borated water leakage has occurred. However, the concrete most likely to have been affected, i.e., located adjacent to the refueling pool liner plate at leak locations, is not readily accessible for inspection, since it would require removal and replacement of the liner plate. Thus, assessment of the effects of the leakage on the concrete is performed in this report based on analyses considering results of applicable tests and experience. The most useful data in this regard are those recently developed for Salem, as discussed below.
  - Based on tests performed for Salem (see Section 5 for details and references), the main effect of exposure of concrete to long term borated water leaks is degradation of the concrete that starts at the wetted surface and proceeds inwards. This degradation involves dissolution of the cement binder by the acid and leaves unbonded aggregate with no strength. The rate of degradation occurs in a predictable fashion and decreases with time. The authors of the Salem reports emphasize that the Salem results are applicable only to concretes of the same type as those at Salem, which were igneous in origin and included no aggregates that are soluble in acids, i.e., contained no carbonates. The aggregates that were used at Prairie Island were mostly igneous in origin, but did include about 5% carbonates that are soluble in acids. This requires that adjustments be considered before application of the Salem results to Prairie Island.
  - About 10 to 15% of concrete is normally cement. All of this cement is soluble in acids, and this cement is what is considered to have dissolved in the Salem tests. The addition of about 5% soluble aggregate increases the percent of soluble material in concrete from the 10 to 15% at Salem due to cement to 15 to 20% at Prairie Island considering both cement and carbonate-form aggregates. While it is not certain that this increase in soluble fraction will increase the rate of degradation (and may in fact decrease the rate of degradation as discussed in Section 5.2.3), it is considered that any increase can be conservatively bounded by applying a factor of two increase.
  - Applying the degradation rate measured at Salem adjusted upwards by a factor of two as described above to the Prairie Island refuel pool leakage case leads to an estimated maximum credible depth of degradation of 0.31 inch. A thinning of 0.31 inch would have no effect on the safety related structural behavior of the refuel pool floor since the grout on the floor is 4 inches thick and is not counted upon for structural strength. Similarly, for most of the refueling pool wall, which has a wall thickness of four or five feet with a concrete cover of five inches, a loss of strength in 0.31 inch of the thickness would affect the section thickness by less than 1%, and is thus insignificant. However, in one location, near the transfer tube, the pool wall thickness appears to be less than a foot, and the loss of 0.31 inch could be over 3% of section thickness and thus might be significant, and needs to be evaluated.
- Rebar and Reinforced Concrete
  - Rebar in concrete is normally protected against corrosion by the alkalinity (high pH) developed in the pore water by the presence of calcium hydroxide in the concrete. This high pH is expected to have protected most of the rebar in the reinforced concrete in the reactor building for much of plant life, despite occasional wetting by boric acid. This includes locations with stress cracks in the concrete.

- The protection provided by the alkalinity of the concrete can be reduced over time by a process called carbonation. Carbonation involves the conversion of the calcium hydroxide in the concrete to calcium carbonates and is caused by diffusion of carbon dioxide into the concrete from the atmosphere. Carbonation starts at the surface and proceeds inwards into the concrete as time progresses. The estimated depth of carbonation after 36 years of concrete exposed to indoor environments is about 1.2 inches. Once carbonation reaches the rebar, corrosion of the rebar can occur.
- Many of the concrete surfaces in the reactor building have rebar cover depths of more than 1.2 inches, and thus rebar in these areas has always been protected against corrosion. However, there may be areas that have covers as low as the minimum allowed by the ACI 318 code, i.e., ¾ inch. The rebar in these areas could have experienced some corrosion. Quantitative estimates indicate that this corrosion is less than 0.016 inch in depth, which is not considered significant.
- There have been no visibly detectable signs of rebar corrosion induced concrete cracking or spalling in the reactor building lower levels, nor have there been indications of significant rust stains at leakage locations. These are the typical results of corrosion of rebar and their absence indicates that rebar corrosion has not been significant.
- The area in the lower regions of the containment, below an elevation of about 695 feet (just below the RHR suction pipes) or 697 feet (lowest floor elevation in containment), could have been wetted with borated water for much of plant life. Moist concrete experiences carbonation at a lower rate than dry concrete. Taking this into account together with the 1.5 inch depth of concrete cover of the rebar near the containment shell indicates that carbonation is not likely to have reached this rebar, such that no corrosion of the rebar is expected to have occurred in the possibly wetted area at the bottom of the containment.

2.2 Recommendations

- Steel Containment Vessel
  - It is suggested that tests be performed to determine if there is high assurance that the pH that is present in the water between the containment steel plates and the concrete is at a fully protective level, i.e., over 12.5. If the pH is at such a high level, then it can be confidently concluded that no significant corrosion of the steel containment vessel has or will occur in the lower regions of the containment. This would also demonstrate that the rebar in the reinforced concrete in this area has not been subject to significant corrosion.
  - If tests to determine if the pH in the steel to concrete gap do not conclusively rule out the possibility of significant corrosion (i.e., do not demonstrate that the pH has been >12.5 for most of the time when wetted), it is recommended that attempts be made to monitor the thickness of the plates in the lower regions of the steel containment vessels. The specific region of interest is from about the elevation of Sump B (~695 foot elevation) and below. The suggested wall thickness monitoring method is to explore use of a guided wave ultrasonic technique being developed by EPRI [8], supplemented by removal of concrete from inside the containment at selected locations to allow use of direct ultrasonic thickness measurements. The suggested

locations include (1) in Sump C and (2) through the walls at the ~695′ elevation, and close to the transfer tube since the transfer tube is located close to the source of the leakage, i.e., the refuel pool. If concrete is removed for such inspections, the pH of the water at the metal surface should be measured, with care being taken to ensure that exposure to air does not alter the pH of the crevice water.

- Concrete
  - It is recommended that a detailed evaluation be performed of the effects of possible thinning of the concrete by as much as 0.31 inch in the thin area of the reinforced concrete inside the containment shell near the transfer tube. It is expected that this evaluation will show there to be no significant effect on the safety performance of the structure. However, if the evaluation unexpectedly shows that there could be an adverse effect, then corrective measures should be taken.
- Rebar and Reinforced Concrete
  - The detailed evaluation discussed above of the thin area of reinforced concrete near the transfer tube should consider the loads in that area, the quantity of rebar present, and the margins available.
- General Recommendation. It is recommended that strenuous efforts be made to prevent further leakage from the refueling pool, especially leakage in areas that lead to wetting under the refueling pool liner and between the steel containment vessel and the reinforced concrete in the bottom regions of the reactor building. This recommendation is based on:
  - Carbonation is a continuing process that it is likely to make both the rebar and the steel containment vessel more susceptible to corrosion as time progresses. This is because carbonation ties up more and more of the calcium hydroxide in the concrete as time progresses, reducing the extent to which it inhibits corrosion of the steel vessel and the rebar.
  - Boric acid attack of the concrete will continue in any areas that are wetted by fresh boric acid. As discussed above, the estimated maximum depth of the attack to date is about 0.31 inch. As time progresses, this value would increase if leakage were allowed to continue. Depending on the allowable amount of degradation in the thinnest areas of concrete that are affected (the pool wall near the transfer tube), continued degradation could result in unacceptably small structural margins or eventually structural problems.

3 SUMMARY DESCRIPTION OF BORATED WATER LEAKAGE FROM REFUELING POOLS IN PRAIRIE ISLAND UNITS 1 AND 2

3.1 Introduction

The purpose of this section is to summarize what is known about the leakage of borated water from the refueling pools at Units 1 and 2 to serve as an input to the evaluations of later sections of the report that deal with the effects of the leakage on the steel containment vessel, concrete and rebar.

The information in this section is based on information assembled by the root cause team that is working on the borated water leakage issue [5].

Probable locations of leak sources and possible paths for the leaks to have taken to locations where they have been detected are shown on the figures in Appendix A. Since definitive information on the exact sources of the leaks and on the leak paths is not available, the figures in Appendix A should be considered as suggestive rather than definitive.

3.2 Sources of Leakage

There are several sources of leakage that have been active over the years as discussed in the following sections.

3.2.1 Sources Above Sump C

There are several potential sources of leakage that are located around the reactor vessel flange and result in leaks that feed into Sump C directly below the reactor vessel. These sources include leaks at the reactor vessel annulus seal plate, at sandbox edges, and at nuclear detector well cover plates. These leaks go directly to Sump C. The leakage that collects in Sump C is periodically pumped out of containment. While some surface rust associated with this leakage has been noted, no significant corrosion has been observed, i.e., the leakage has not resulted in wetting of structural components for long enough durations to result in damage. Accordingly, this type of leakage into Sump C is not a safety concern and is not addressed further in this report.

3.2.2 Leaks Through the Refueling Pool Liner

As discussed in detail in the Root Cause Evaluation [5], there have been occasional indications of leakage coming through the refueling pool liner since about 1987. These indications include the following, including indications observed in both Units 1 and 2 (see the figures in Appendix A for probable locations of leak sources and possible leak paths):

- Leakage at the RHR suction line sleeves in Sump B. After the grout was removed, this leakage was observed welling up from the concrete to steel containment vessel junction at the bottom of the area that had been cleared of grout.
- Leakage in the Regen HX room at a stress crack in the ceiling.
- Leakage in the RCDT space (the RCDT is mounted on the floor at elevation 697′).
- Visible signs of deposit buildup that appear to be the result of leakage into Sump C that enters at a construction joint, possibly at elevation 691′-6″.
- Vaults 11, 12 and 22.
- Wall near accumulator 12.
- RCDT stairway area.

As also discussed in the root cause evaluation, several possible locations for the leakage sources have been evaluated. The seam welds between the plates of the liner are not considered likely to be a significant source based on results of inspections of these welds and based on the fact that there have been outages with no evidence of leakage even though no leak preventive steps were taken at the seam welds. The most likely sources are considered to be at equipment support locations that have studs that penetrate the embedment plates. There are numerous locations in the refueling pool lower cavity and transfer pit areas that have equipment supports. Some of these involve bolt holes that penetrate the embedded support plates and that are designed to have seal welds. However, based on the success during several outages at preventing leakage by means of caulking applied to the penetrations, it is believed that the leaks are most likely at these penetrations.

3.3 Leak Paths and Possibly Wetted Areas

The range of possible paths for the leakage are illustrated in the figures in Appendix A. The main structures and components that are possibly wetted by this leakage are as follows:

- Reinforced concrete floors, walls, beams, and slabs located at elevations at and below the refueling pool lower cavity floor elevation of 719′ and the transfer pit floor elevation of 713′ 6″.

- Containment vessel steel shell at elevations below 711′ 6″ for most of circumference, and below 719′ for region around transfer tube where the upper cavity and transfer pit abut the containment.

Review of the drawings and discussions with plant staff did not identify any other safety related equipment that was susceptible to damage by wetting by leakage from the refueling pools.

4 EFFECTS OF BORATED WATER LEAKAGE ON STEEL CONTAINMENT VESSEL

This section evaluates the possible effects of borated water leakage on the pressure retaining capability of the steel containment vessel and also on its leakage prevention capability. These two safety aspects of the steel containment vessel are discussed together since they are both a function of corrosion of the steel containment vessel as a result of wetting by borated water leaking from the refueling pool. Considerations regarding the amount of corrosion that could have occurred are discussed below. Atmospheric corrosion is briefly reviewed since it could occur in the same general areas where corrosion due to borated water leakage could occur.

4.1 Atmospheric Corrosion

The wall thickness of the steel containment vessel is nominally 1.5 inches [9]. The ID surface of the steel containment vessel in the region exposed to concrete was in an uncoated condition when concrete was poured into it [10]. It is assumed that some areas of the uncoated steel containment vessel are continuously exposed to the atmosphere as a result of lack of bonding to the concrete.

Rates of corrosion of steel in atmospheric environments are low, 0.6 mm (0.024 in.) in 36 years in an industrial atmosphere (Figure 2 on page 520 of [11]) which is considered to be more aggressive than the environment in the containment. This is a small fraction, about 1.6%, of the wall thickness of 1.5 inches. The original vessel design included only a minimal margin on thickness; in this regard, the calculated required wall thickness in the lower ellipsoidal head was indicated as 1.5 inches, although the detailed numbers calculate to 1.4908 inches (sheet A2 in [12]). Since the nominal material thickness is 1.5 inches, the effective corrosion allowance was only about 0.0092 inch. Additional margin in an area experiencing corrosion may be provided by the actual thickness which, in areas where it has been measured, is about 1.523 inches minimum [13, 14, 15], adding at least another 0.023 inch of corrosion allowance. Detailed acceptance of any actually detected thinning below the nominal thickness of 1.5 inches would need to be performed in accordance with Section XI of the ASME Code, and is not within the scope of this evaluation.

4.2 Corrosion in Wetted Areas

As discussed in Section 3, there are two general areas of the steel containment vessel that could be wetted by the leakage: (1) an area between the concrete and steel containment vessel between elevations 711′ 6″ and 719′ in the region where the transfer pit and lower part of the refuel pool abut the steel containment vessel, and (2) the area between the concrete and the steel containment vessel from elevation 711′ 6″ and below, for the full circumference of the steel containment vessel.

Tests at ambient temperature indicate that the rates of corrosion of steel in aerated, concentrated (and in one case saturated) boric acid solutions range between 0.002 to 0.007 inch per year (Section 4.4.1 and page 4-35 of the Boric Acid Corrosion Guidebook, Rev. 1 [16]). These rates are probably conservative for the current application since the pH of solution in contact with the steel containment vessel will be buffered by alkalinity from the cement in the concrete, which is expected to raise the pH to > 12.5 and reduce actual corrosion rates to close to zero (e.g., such that actual total corrosion to date is probably 10 mils (0.010 inch) or less). However, the Guidebook test results provide an upper limit that can be used to help bound the situation. Assuming that an area has remained continuously wetted since plant startup leads to the following conservative upper limit corrosion thinning: 36 years × 0.007 in./year = 0.25 in. For areas that are deaerated, i.e., for most of the wetted area in the lower head, the corrosion rate is about 0.0002 inch/year (pages 4-25 and 4-27 of [16]).

A test in 1998 of leaking water at the RHR penetration in Sump B where grout had been removed indicated that the pH was 7.8 [17]. Another test in 1998 of water collected on the floor of the RCDT space indicated a pH of 7.0 [17]. The water had high concentrations of boron which, if it had not been buffered, would have resulted in pH values of 5 or less. This indicates that the boric acid had been buffered by alkalinity from the cement in the concrete. Corrosion rates in near neutral water of various compositions at ambient temperatures are about 0.2 mm/year (0.008 in./year) (Figure 3 on Page 536 of [11]); however, the rate discussed earlier (maximum of 0.007 in./year) for borated water is considered to be more applicable. Note that this estimate of 0.007 in./year is expected to be conservative since stagnant water in contact with the steel and concrete is expected to increase in pH to values around 12.5 or more as a result of alkalinity (calcium hydroxide) in the concrete, which is expected to cause complete passivation of the steel, i.e., to essentially stop corrosion (Section 4.3.2.1 of [18]). It is recommended that further work be done to verify this expectation, as covered in the recommendations section of this report.

A long term test was performed by Florida Power and Light to determine the corrosion rate of carbon steel rebar in contact with concentrated boron solution (2370 ppm) at pH 7.4 at ambient temperature [19]. This test measured a corrosion rate after 8 years of testing of 0.005 inch/year. Assuming that this rate applied for the full life of the plant would result in a maximum amount of thinning of $36 \times 0.005 = 0.18$ inch.

The above estimates are considered to be conservative since, as discussed earlier, it is expected that the pH of water in contact with the steel vessel will normally be at a high protective pH. In addition, it is expected that only the region near the water surface will have sufficient oxygen to maintain a corrosion rate near the values used in the estimates, and this limited region will change with time such that any one area will have a total time in an aggressive environment less than that used for the estimate. This is because the water enters the crevice between the concrete and the steel containment vessel only once per refueling cycle. It is expected that the water level will continuously drop during the power operation period of the refueling cycle as a result of evaporation, thus resulting in any one area being exposed to the more aggressive condition for only a fraction of the cycle.

Inspections of the wall thickness of the steel containment vessel in an area around the transfer tube were taken in Units 1 and 2 in Sep. 2004 and 2003 respectively [13,14] and again at Unit 2 in 2008 [15]. These inspections covered substantial areas, over 25 square feet. No areas with wall thickness below the nominal value of 1.5 inches were detected. While these inspections did not necessarily cover the area exposed to the most severe corrosion conditions (which could be at a lower elevation), the absence of any significant thinning indicates that serious corrosion is not likely to have been occurring. An area around the RHR pump suction lines was also inspected for wall thickness during the 2R25 outage in 2008. All measured wall thickness values were over the nominal value of 3.5 inches [15].

In summary with regard to the amount of corrosion that could have occurred in wetted areas, it is considered that 0.25 in. is a conservative upper limit. This amount of corrosion clearly does not raise a risk of causing leakage through the 1.5 in. thick steel containment vessel in the event of an accident.

With regard to the acceptability of the upper limit projected wall thinning, the following evaluation indicates that it is not likely to have affected the ability of the containment to perform its safety function of resisting accident pressure. However, any actual measured wall thickness below the design value of 1.5 inches would need to be evaluated in accordance with Section XI of the ASME Code. With this caveat, the following evaluation is provided to indicate the margin available. Since the steel containment vessel is fully encased in grouted reinforced concrete on the outside to elevation 706′ 6″ as well as on the inside below elevation 711′ 6″, bending loads imposed on the steel containment vessel in the thinned areas will be very low, such that thinning by 0.25 in. is not expected to impact the ability of the steel containment vessel to retain accident pressure. For example, using a remaining thickness of 1.25 inches, the axial tensile stress at the thinned area is given by PR/2t (page 298 in [20]) where R is the radius (105′/2 = 52.5′ = 630″), P is the accident design pressure of 46 psig, and t is the remaining thickness, taken as 1.25 in. This indicates an axial tensile stress of ~11,600 psi, which is far below the yield stress of 34.0 ksi (Table 1-8 in Chapter (I)1-12 of [21]) at the accident design temperature of 268°F (Sheet I2 in [12]), let alone the tensile strength of about 70 ksi. As mentioned above, the reinforced concrete inside and outside the steel containment vessel is expected to prevent bending stresses from significantly adding to the accident applied axial tensile stress. In addition, the outside reinforced concrete is expected to prevent significant accident caused hoop stresses since it will prevent diametral expansion. However, even if the concrete failed to provide this support, the hoop stress would only be 23.2 ksi, still well below the yield stress at 268°F of 34.0 ksi.

4.3 Summary Regarding Corrosion of Steel Containment Vessel

In summary with regard to possible corrosion of the steel containment vessel caused by leakage of borated water from the refueling pool, it is concluded that:

- Because of the buffering effect of alkalinity from the concrete, the pH of the water in continuously wetted areas between the concrete and lower dome of the steel containment vessel is expected to have been in a range that inhibited corrosion of the steel, e.g., over about pH 12.5. As a result, it is expected that, as a best estimate, the maximum amount of corrosion that has actually been experienced in the wetted areas between the concrete and the inside surface of the steel containment vessel is insignificant, no more than a few mils (e.g., < 10 mils).
- While it seems unlikely, the possibility cannot be completely ruled out that the pH of the water in contact with the steel containment vessel could have been at the near neutral values that have been measured in Sump B. Analysis of this case, assuming continuous wetting of an aerated neutral pH region for the full 36 years of operation, leads to an upper limit estimate of about 0.25 inch of corrosion. It needs to be understood that this estimate is conservative since it is unlikely the pH has been at such a low level, and since it is unlikely that the aerated region at the water line has remained in the same area, such that the accumulated time duration of exposure at any one elevation is much less than 36 years.
- Thinning of the upper limit amount of 0.25 inch poses no risk of leakage under normal or accident conditions since the wall thickness is 1.5 inches.
- Preliminary evaluation of the effects of thinning at the upper limit amount of 0.25 inch is that it will not result in excessive stresses or strains under accident conditions. This is a result of the bending stresses and hoop stresses in the possibly thinned area at the lower knuckle region of the steel containment vessel being essentially eliminated by the support

provided by the reinforced concrete on both the ID and OD of the steel containment vessel in the knuckle region. Support for this conclusion is provided by limit load analyses of steel containment vessels that have shown that, even for steel containment vessels with 65% of wall loss for significant parts of their circumference (about 13 feet), the failure pressure is still over four times the accident design pressure (Table 2 in [22]). However, it needs to be understood that any actually detected thinned areas would need to be formally reviewed and accepted per Section XI of the ASME Code, and not per the above preliminary evaluation.

5 EFFECTS OF BORATED WATER LEAKAGE ON REINFORCED CONCRETE

This section of the report reviews the possible effects of leakage of borated water on the properties of the reinforced concrete in the lower parts of the containment, and assesses whether the ability of the reinforced concrete to meet Class I structural requirements has been affected. This includes evaluation of the effects of the leakage on the concrete itself, on the rebar, and on the behavior of reinforced concrete considering both the concrete and rebar.

5.1 Issues that Need to be Addressed

The main issues that are raised by exposure of reinforced concrete to aggressive solutions are reviewed in an on-going aging effects evaluation for PINGS [6]. As indicated in that document, the concrete used in the Class I structures at PINGS is high quality and is resistant to degradation by exposure to aggressive water. However, that document does not specifically address exposure to borated water. Similarly, EPRI documents also do not address this environment, e.g., Section 5.2.3 of [23] indicates that exposure to borated water is "event driven" and thus outside the scope of the document. Accordingly, the issues that need to be addressed must be identified based on engineering principles and industry experience, as discussed below.

A recent ORNL report for NRC [18] comprehensively reviews the degradation mechanisms that can affect reinforced concrete used in nuclear power plants. For the refueling pool leakage situation, it is considered that the degradation mechanisms noted below are possibly applicable to this situation and need to be considered. This list takes cognizance of the fact that the reinforced concrete that can be exposed to leaking borated water from the refueling pool is not subject to exposure to freeze-thaw cycles, high radiation, high temperature, salts, nor aggressive chemicals other than borated water. The remaining items that need to be considered are:

- Chemical attack of the concrete by the leaking water, which could possibly result in disintegration, loss of material, leaching, and/or spalling of the concrete.
- Corrosion of rebar which could possibly result in spalling, cracking and/or loss of section of the rebar and loss of strength of the concrete.

Identification of the above two issues as those that need to be addressed is confirmed by experience with evaluations of the effects of leakage on the integrity of the fuel handling building at Salem Unit 1 due to leakage from the spent fuel pool, as documented in references [24, 25, 26, 27].

5.2 Degradation of Concrete Due to Chemical Attack

5.2.1 Introduction

Boric acid can react with components in the concrete resulting in the dissolution of some of these components, thereby reducing the strength of the concrete. As indicated in Figure 4-9 of [18], exposure to acids can result in the attack of cement constituents and cause their transformation into soluble calcium compounds such as calcium sulfate, calcium acetate, or calcium bicarbonate. Dissolution of these materials removes the cement bonding material upon which the strength of concrete depends. In addition to the constituents of the cement, carbonate type aggregates such as limestone and dolomites are also susceptible to dissolution by acids (pages 272-273 in [28]). The areas of concrete that would most likely be damaged by this type of attack are those that are exposed to fresh boric acid since it has the greatest acidity. For the refueling cavity leakage case, these areas are those that are located next to the liner. Areas close to the leak sources would see the freshest boric acid and thus experience the greatest rate of attack, but any areas adjacent to the liner and below the water level in the pool could be wetted and experience some level of degradation.

5.2.2 Available Industry Data

The type and rate of the type of attack caused by continuous exposure to boric acid for long times has recently been quantified for two plants, Salem 1 and Conn Yankee, as discussed in references [25, 26, 27]. The cited references emphasize that the results are only directly applicable to cases with the same type of concrete, i.e., with similar aggregates, strengths, water to cement ratios, and air entrainment values. Nevertheless, the results for these two plants provide a useful indication of what type of attack can be expected due to exposure to boric acid. Some main results were as follows:

- The attack by boric acid starts at the concrete surface and proceeds inwards. The only exception is that, where there are cracks in the concrete, the degradation proceeds into the material from the wetted surfaces in the cracks as well as from the original surfaces.
- The effect of the attack is to reduce the effective section of the concrete that carries load. In other words, the degraded material at the wetted surface carries no load.
- In the case of Salem 1, long term tests of samples showed that the rate of attack followed a parabolic law consistent with a diffusion controlled process. For a test temperature of 100°F, the depth of attack of the concrete was given by [27]:

$$d = 0.00812\sqrt{t} \qquad [5\text{-}1]$$

where d = depth of degradation in inches for exposure at 100°F

t = time, in days

The above equation gives a predicted depth of degradation of 1.3 inches for continuous exposure over a lifetime of 70 years. For an exposure of 15 days for each of 25 outages at Prairie Island, this formula predicts a depth of 0.16 inch.

- In the case of Conn Yankee, the maximum depth of attack after 37 years exposure was found to be about 0.91 inch. The depth predicted by Equation [5-1] for 37 years is 0.94 inch. Thus, experience at Conn Yankee supports the applicability of Equation [5-1] to concrete of the Salem type with aggregates that are non-reactive to acids.

5.2.3 Application of Industry Data to Prairie Island

Considerations regarding whether the above results can be reliably applied to the Prairie Island case and, if so, with what adjustments, include the following:

- The aggregate at Prairie Island is mostly of igneous origin which is resistant to acid attack, similar to that of Salem and Conn Yankee. However, it has percents of carbonate based aggregates ranging between about 2.2 to 9.1% [29] (an average of about 5%); these fractions are susceptible to acid attack.
- All cement paste materials are susceptible to acid attack (page 33 of [18]). The cement paste typically is about 10 to 15% of the concrete (footnote on page 10 of [18]). Thus, the use of aggregate with about 5% susceptible material increased the fraction of the concrete that is susceptible to acid attack from 10 to 15% to 15 to 20% or, on average, from 12.5% to 17.5%, an increase by a factor of 1.4.
- The results of the tests performed for Salem indicate that the mode of attack is a diffusion controlled process. This indicates that the rate controlling step is diffusion away from the leading edge of the attack of the dissolved materials, and diffusion in to the leading edge of the attack of fresh boric acid. An increase in the fraction of the material that is soluble to dissolution would be expected to reduce the rate of attack since, for the same depth of attack, more material must diffuse away and more boric acid must diffuse in.

Based on the above factors, it is considered that the Salem and Conn Yankee results could safely be directly applied to the Prairie Island case. However, to be conservative, a factor of two conservatism is applied to this evaluation of the Prairie Island case, i.e., the constant in Equation [5-1] is increased from 0.00812 to 0.0162. Using this constant, and an exposure of 15 days for each outage and assuming that the number of outages is 25 leads to a maximum depth of attack after 36 years of 0.31 inch.

The exposure used for this estimate is considered to be conservative for several reasons. First, the 15 day per outage value for exposure to fresh boric acid is consistent with the observed times of leak initiation and cessation at outages where refueling pool leaks were observed. Second, there is no evidence that refueling pool leakage through the liner plates occurred before 1987, and leakage has only been observed at about one half of the outages since 1987, such that the estimate of 25 outages with leaks is conservative. Thus, the product of 15 days per outage times 25 outages with leaks is judged to be a conservatively high estimate for the total exposure to fresh boric acid.

5.2.4 Effect of Attack on Concrete Performance

The effects of the degradation of 0.31 inch of the concrete that is in contact with the refueling pool liner are judged to be negligible. For the refuel pool floor in the lower cavity and transfer pit this is readily demonstrated since there is a four inch layer of grout in these areas [30], and since grout is not relied upon for strength. For the thicker walls of the refueling pool, the concrete cover was specified to be 5 inches [31]. The general wall thickness of the refueling pool walls is four feet at the end near the center of the containment, five feet along each side, and variable at the containment wall. For the four and five foot thick wall, loss of 0.31 inch represents a loss of less than 1% of the wall thickness and thus is clearly insignificant from a structural and functional standpoint. The variable thickness wall at the containment end has areas that appear to be less than one foot in thickness (e.g., at the transfer tube as shown on drawing NF-38488-1 [32]). It was not possible within the scope of this project to evaluate the effect of degradation of 0.31 inch of this concrete on its performance.

5.2.5 Effect of Dissolution of Calcium Hydroxide

The preceding discussion focused on areas that could be exposed to fresh boric acid solution leaking from the pool, i.e., areas in contact with the refueling pool liner. For areas away from the liner, the borated water is raised in pH and is no longer aggressive against concrete. This is demonstrated by the near neutral pH measured for water leakage at Sump B and in the RCDT space [17]. The increase in pH is attributed to dissolution of calcium hydroxide by the fresh boric acid at locations where the leakage first contacts concrete; this raises the pH and makes the borated water no longer acidic and no longer aggressive against concrete as the borated water travels away from the liner. For this reason, it is considered that regions of the concrete structures that are away from the liner and that are wetted by leaking borated water have not been degraded by contact with the leaking borated water. These non-attacked regions include the area between the steel containment vessel and the concrete at bottom of the reactor building, as well as the reinforced concrete materials in the lower parts of the reactor building that are not in direct contact with the pool liner.

5.2.6 Concrete Degradation at Cracks

Attack from the concrete surface was discussed earlier. Degradation of concrete by exposure to borated water can also occur at cracks in the concrete. This could possibly lead to loss of strength of the concrete in a narrow band through the thickness of the material. However, such degradation would have only a minor effect on the mechanical behavior of the concrete since the concrete is not relied upon for tensile strength (tensile strength is provided by rebar), and the degraded material would still resist compression unless it was washed out. No evidence of washout or significant leaching of material has been observed at cracks in the concrete in the containment at Prairie Island. Thus, it is concluded that concrete degradation at cracks has not degraded the strength of the reinforced concrete.

5.2.7 Conclusion

Based on the above discussions, it is concluded that degradation of concrete by borated water leakage from the refueling pools at Prairie Island has most likely had a negligible effect on the concrete itself, but that further evaluation is required in the area with thinnest concrete near the transfer tube. Effects on the rebar and the composite behavior of the reinforced material are discussed below.

5.3 Corrosion of Rebar Caused by Exposure to Borated Water

The rebar in reinforced concrete is normally protected against corrosion by the alkalinity of the concrete, which is typically in the range of pH 12.5 or more (page 42 of [18]), and which promotes a protective passive layer on the steel. The main source of this alkalinity is the presence of calcium hydroxide in the cement paste. As long as the calcium hydroxide is present, no significant corrosion occurs. The main mechanisms by which this protection can be defeated are by overwhelming the protective pH with high chloride concentrations, by removal of the protective calcium hydroxide by acid dissolution, or by conversion of the calcium hydroxide to calcium carbonate by carbonation [18]. These factors are discussed below.

- As noted on page 47 and 48 of [18], corrosion of rebar can be initiated at chloride concentrations of 0.1% (1000 ppm) or more, depending on the level of carbonation and other factors. Since the chloride concentrations in the borated water observed in Sump B at Prairie Island are about 7 ppm or less [17], chlorides are judged not to be a factor that needs to be considered in assessment of borated water leaks from the refueling pool at Prairie Island.
- Dissolution of calcium hydroxide from the concrete around rebar at cracks in the concrete would seem to develop conditions that might lead to increased rates of corrosion of the rebar. However, tests performed for Salem and other tests described in the open literature indicate that corrosion in such situations has been negligible, even when the low pH borated water reaching the cracks was regularly refreshed [27, 33]. It is speculated that conditions at the rebar remain sufficiently alkaline in such situations to passivate the surface, despite the presence of refreshed borated water.
- Carbonation is a process in which carbon dioxide from the atmosphere either directly, or after dissolution in pore water, converts the calcium hydroxide in the concrete to calcium carbonate. This results in the pH decreasing from over 12.5 to about 8.3 (Section 5.2.3 of [34]). In this lower pH range, corrosion of rebar can occur, although generally at a low rate. Carbonation progresses through concrete at a relatively low rate. Table 4.9 in [18] indicates that, for a medium strength concrete in an indoor environment, carbonation will have reached a depth of about 25 mm in 25 years. Fitting an equation to the data in Table 4.9 in [18] and extrapolating to a time of 36 years indicates that the depth of carbonation will be about 30 mm, or 1.2 inches. This depth of carbonation is much less than the concrete and grout cover of 5 inches for the concrete in contact with the refuel pool liner, so corrosion of rebar in that region does not need to be considered since these areas will be maintained at a high protective pH by the non-carbonated concrete.
- Carbonation of a depth of about 1.2 inches is expected to have occurred at all non-wetted concrete surfaces, including at cracks. This value is approximate, and actual depths could be deeper. The thickness of the cover on structural concrete in the reactor building varies from about 5 inches under the liner of the pool to a possible minimum of ¾ inch at other areas based on the minimum allowed by ACI 318 [36]. For this reason, it is judged that there are likely to be some areas where carbonation has reached and passed the rebar, leaving the rebar susceptible to corrosion if it should be wetted. Despite this possibility, corrosion of the rebar is judged to not be a concern based on the following:
  - There have been no visibly detectable signs of rebar corrosion induced concrete cracking or spalling in the reactor building lower levels, nor have there been indications of significant rust stains at leakage locations. These are the typical results of corrosion of rebar and their absence indicates that rebar corrosion has not been significant.
  - The wetting of the rebar in most areas has been of limited duration since the leaks are observed to stop flowing a few days after the refueling pool is drained. The rate of corrosion of carbon steel in borated near neutral water is at most about 0.007 inch per year, as discussed in Section 4. Applying this rate to the expected duration of exposure to wetted conditions, which is conservatively assumed to be 30 days per refueling outage (i.e., twice the duration of the refueling pool being filled) leads to a total time of 25 outages times 30 days per outage = 750 days or 2.05 years. This

leads to an upper limit depth of corrosion of 2.05 × 0.007 = 0.014 inch, which is insignificant.

- Contrary to the rebar in the higher levels of the reinforced concrete structures in the reactor building, which is dry for most of the cycle, the reinforced concrete that is in contact with the bottom of the steel containment vessel has possibly been wetted for a large fraction of plant life. Thus, corrosion of this rebar needs to be evaluated separately. Considerations in this regard are as follows:
  - The concrete cover in the area in contact with the lower shell of the containment is specified as 1-1/2 inches [35]. Since this depth exceeds the 1.2 inches depth of penetration of carbonation calculated above for dry areas, carbonation would not have reached the rebar in this area even if it had been dry for essentially all of the time.
  - If this area has remained moist, carbonation will occur at about 2/5 of the rate that it occurs in an indoor dry environment, as shown in Table 4-9 of [18] (the presence of moisture inhibits penetration of the carbon dioxide into the concrete). Thus the estimated depth of carbonation after 36 years of operation is 2/5 of the 1.2 inches calculated above for the non-wetted indoor environment, or 0.48 inch. This indicates that carbonation will not have reached the rebar in the wetted regions, and that corrosion of the rebar in this region will be negligible because pH has remained at a level that fully passivates the steel.
  - The most likely situation is somewhere in between the two above cases, i.e., the concrete has probably been moist part of the time. Since for both extremes (dry all the time and wet all the time) carbonation is not predicted to reach the rebar, it is clear that it would not have reached the rebar in this intermediate case, and that corrosion of rebar in this area is not a concern.
  - If carbonation unexpectedly has occurred at a higher rate than expected, it is possible that it could have reached the rebar, and that some minor amounts of corrosion could have occurred. However, this would only have occurred in recent years, such that the depth of corrosion would be minimal.

5.4 Summary of Effects of Borated Water on Reinforced Concrete

The review in the above sections indicates that, with one possible exception, neither degradation of the concrete nor corrosion of the rebar has had a significant deleterious effect on the reinforced concrete in the portions of the reactor building where the reinforced concrete could have been wetted by leakage of borated water from the refueling pool. Thus, except for one possible exception requiring further evaluation as discussed below, it is concluded that the reinforced concrete seismic I structures in the lower regions of the reactor buildings remain capable of meeting design requirements.

The possible exception mentioned above that is considered to require further evaluation is the following. If degradation of concrete inside the liner should occur in the area around the transfer tube, it could represent a significant fraction of the wall. Accurately determining the concrete thickness in this area was not possible with the drawings available to DEI but, based on rough scaling, the thickness could reach a minimum of less than one foot, e.g. 10 inches. The estimated maximum degradation thickness of 0.31 inch would be about 3% or more, which might be significant depending on how highly loaded the concrete is in this area. It is recommended that this issue be resolved by further detailed evaluation.

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A FIGURES SHOWING LEAK SOURCES AND LEAK PATHS FOR PRAIRIE ISLAND UNIT 2

The purpose of this appendix is to present figures that illustrate what is known about the locations of leak sources and where borated water has been found in Unit 2, and also to illustrate possible leak paths. In all of the figures displaying leakage, the exact leak sources and precise leak paths are unknown. However, postulated paths of leakage have been drawn to present an idea of how water could arrive at leaking locations via gaps in construction joints and failed welds. Note that this appendix is marked "FOR INFORMATION ONLY" because the CAD model used to generate the figures in this appendix was not rigorously checked versus the Prairie Island drawings per the requirements of DEI's nuclear safety-related QA program.

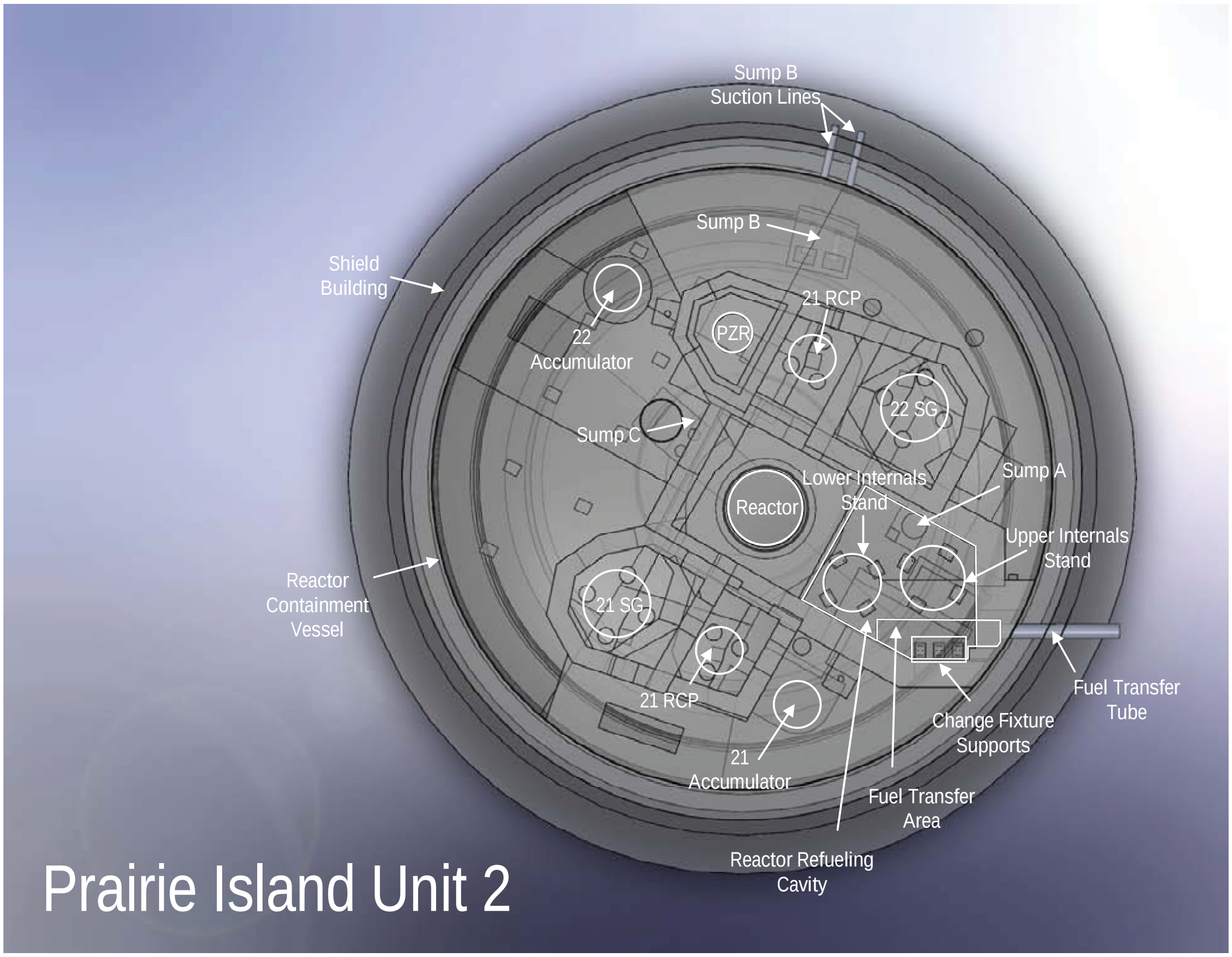

Figure A-1 Prairie Island Unit 2 Plant Layout

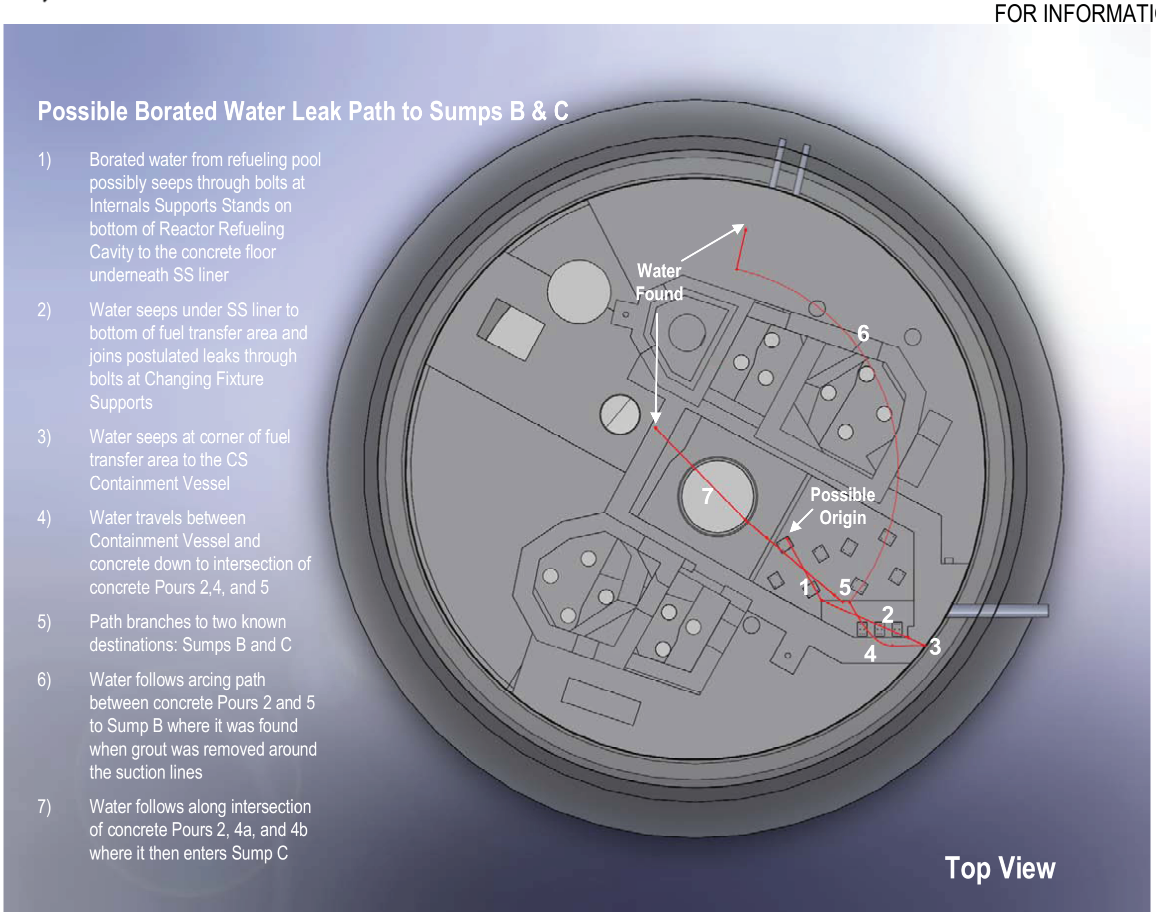

Figure A-2 Possible Borated Water Leak Paths to Sumps B & C in Unit 2 – Top View

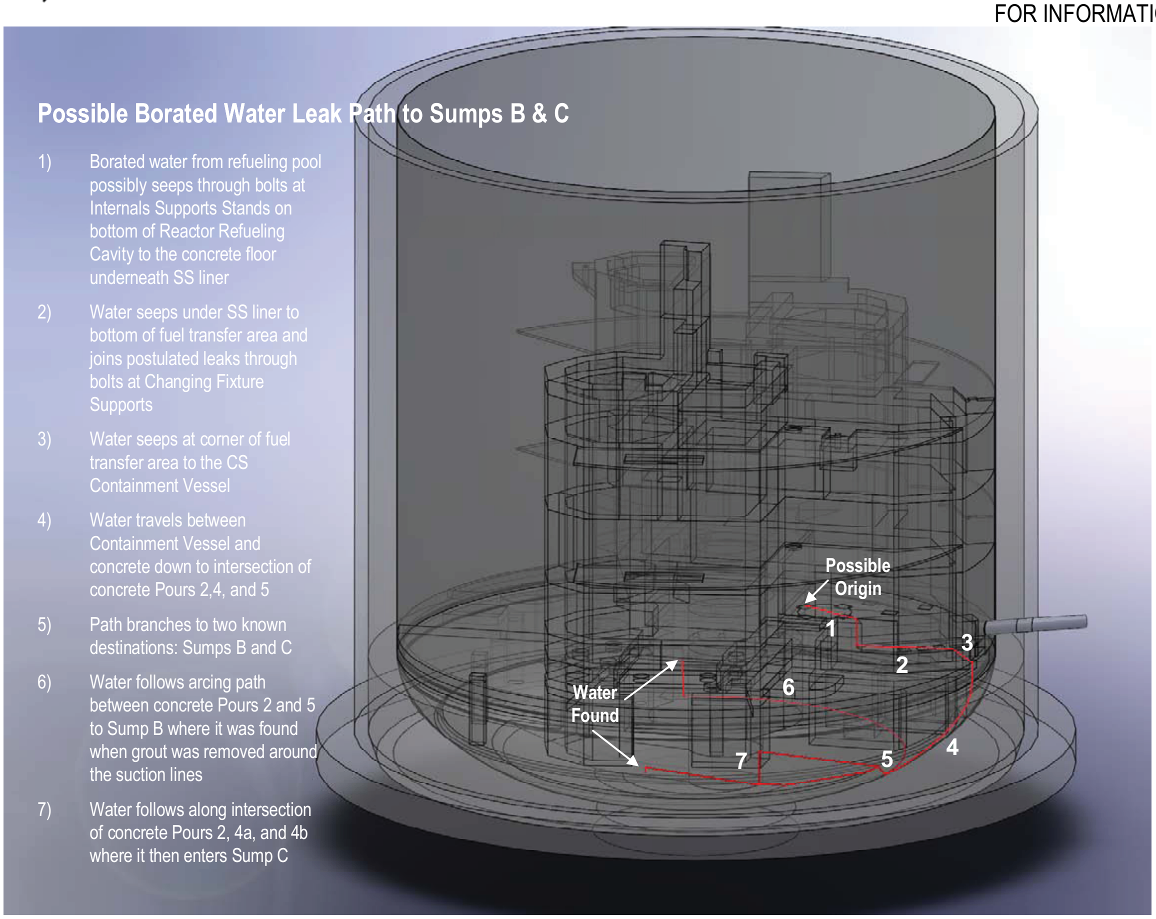

Figure A-3 Possible Borated Water Leak Paths to Sumps B & C in Unit 2 – 3D View

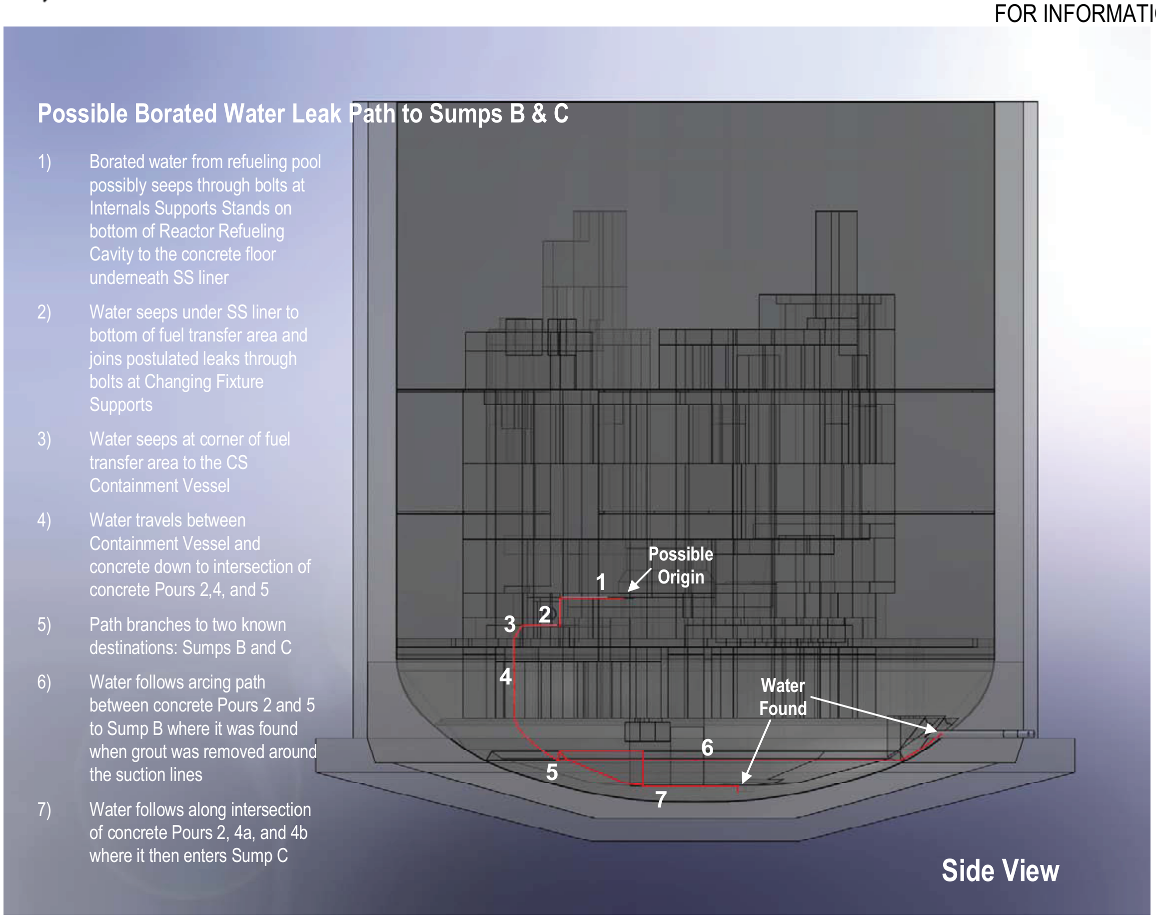

Figure A-4 Possible Borated Water Leak Paths to Sumps B & C in Unit 2 – Transparent Side View

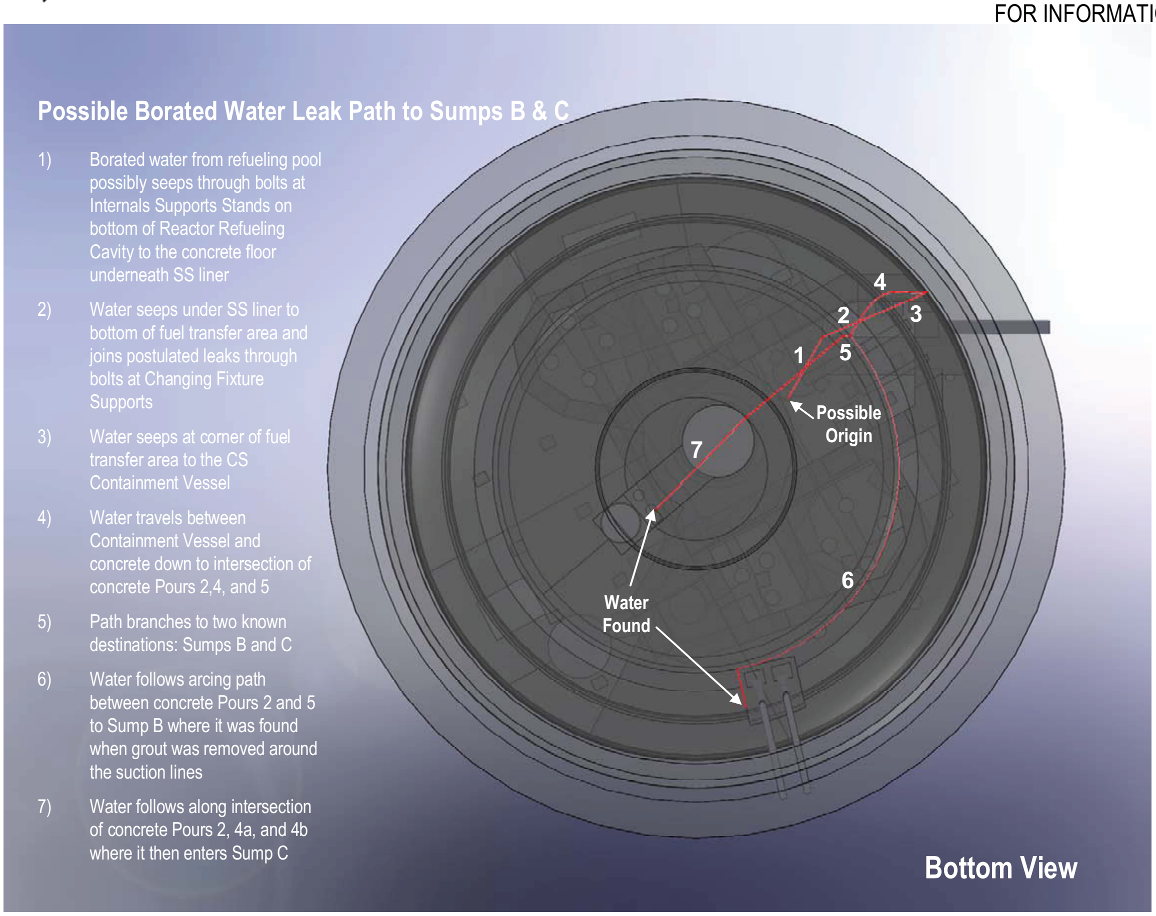

Figure A-5 Possible Borated Water Leak Paths to Sumps B & C in Unit 2 – Transparent Bottom View

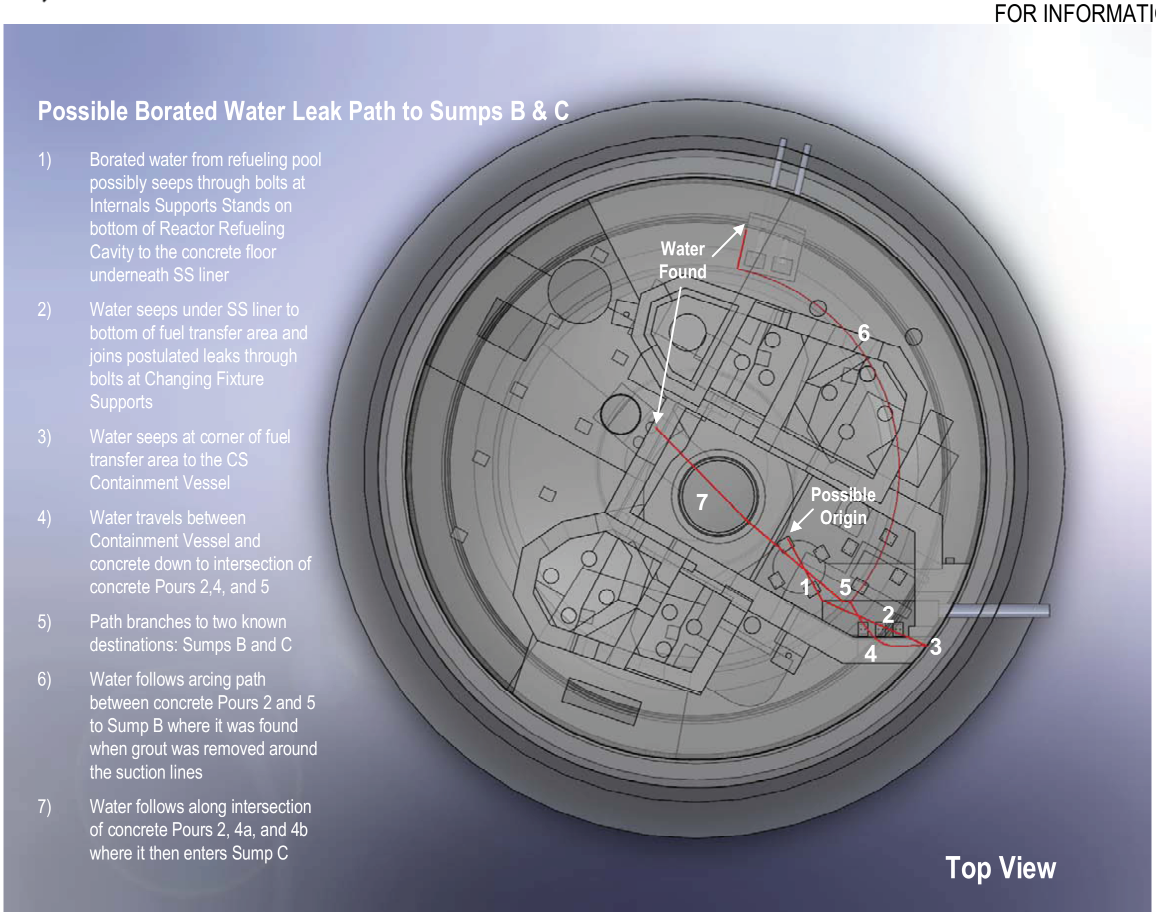

Figure A-6 Possible Borated Water Leak Paths to Sumps B & C in Unit 2 – Transparent Top View

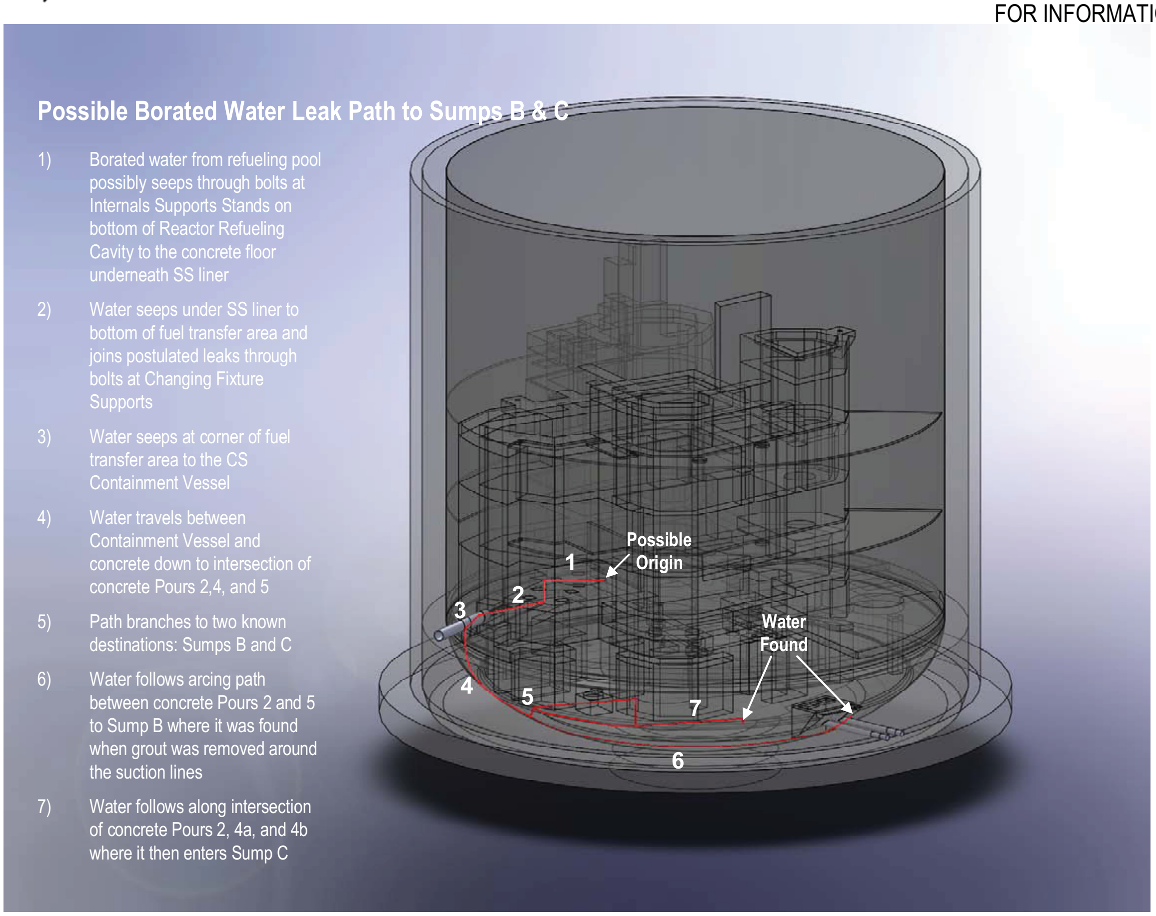

Figure A-7 Possible Borated Water Leak Paths to Sumps B & C in Unit 2 – Alternate Transparent 3D View

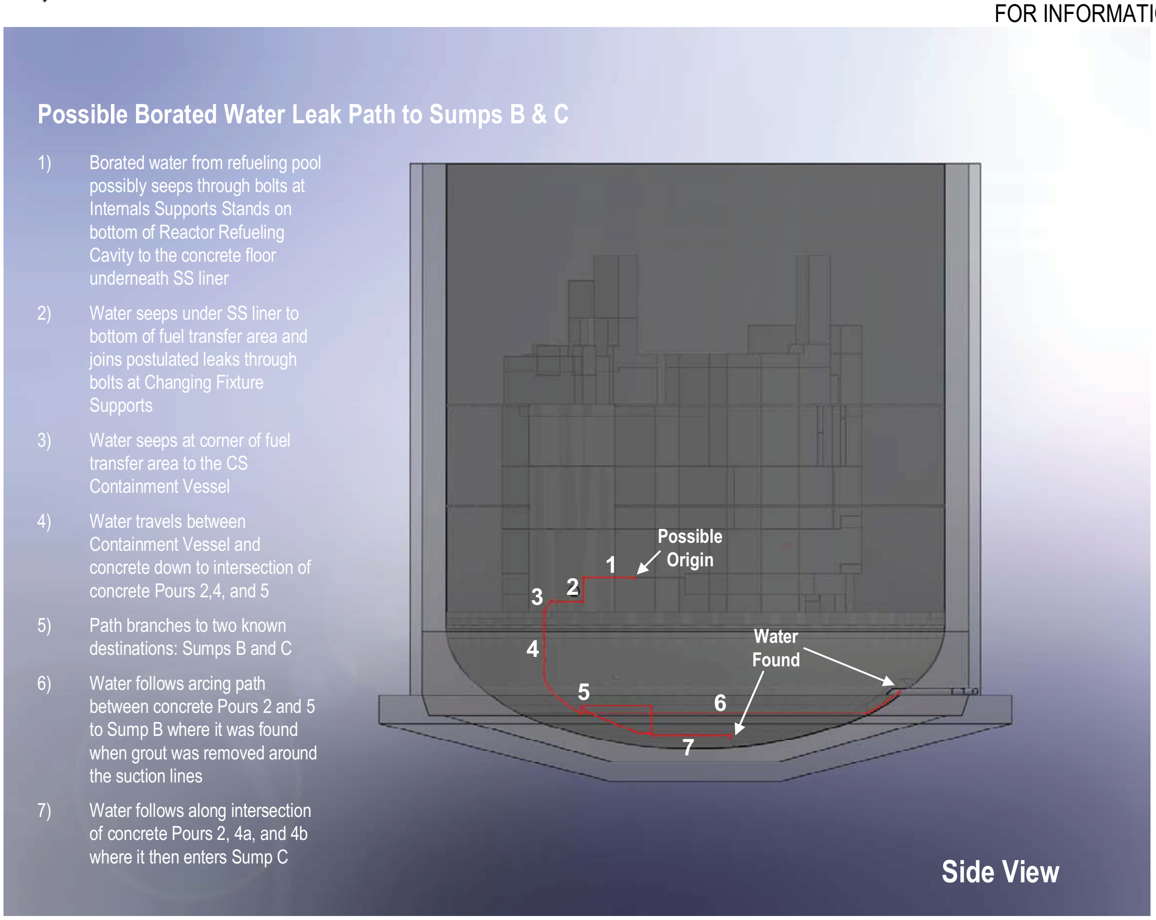

Figure A-8 Possible Borated Water Leak Paths to Sumps B & C in Unit 2 – Side View

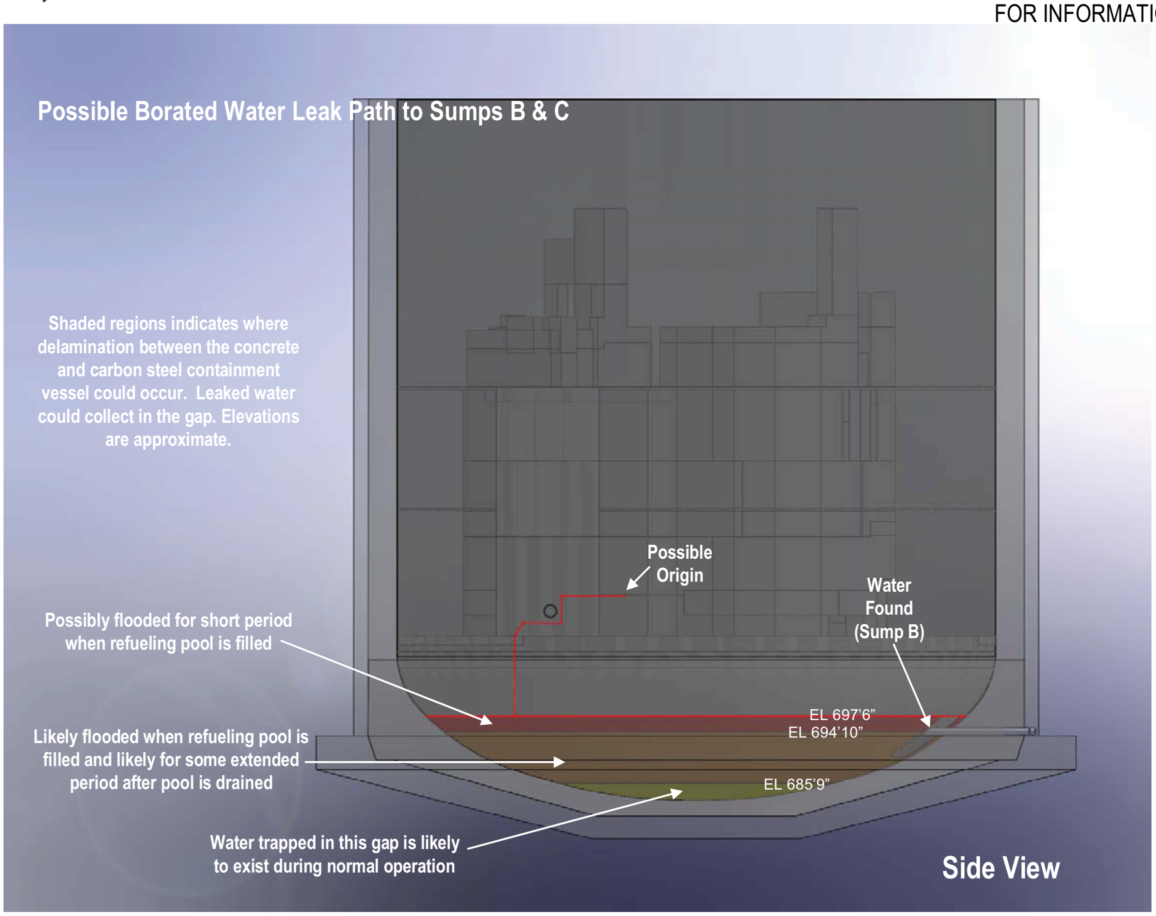

Figure A-9 Lower Regions Wetted by Possible Borated Water Leak Paths to Sumps B & C in Unit 2 – Side View

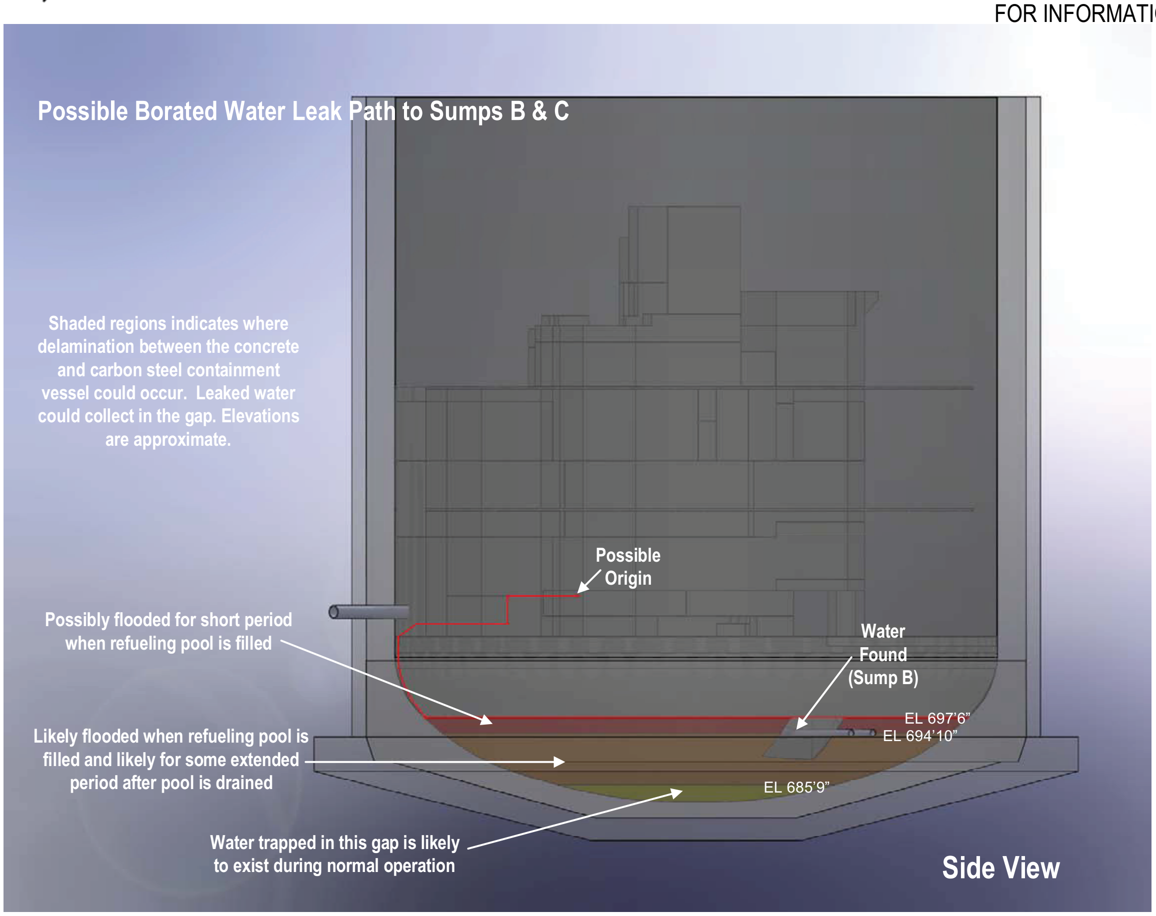

Figure A-10 Lower Regions Wetted by Possible Borated Water Leak Paths to Sumps B & C in Unit 2 – Alternate Side View

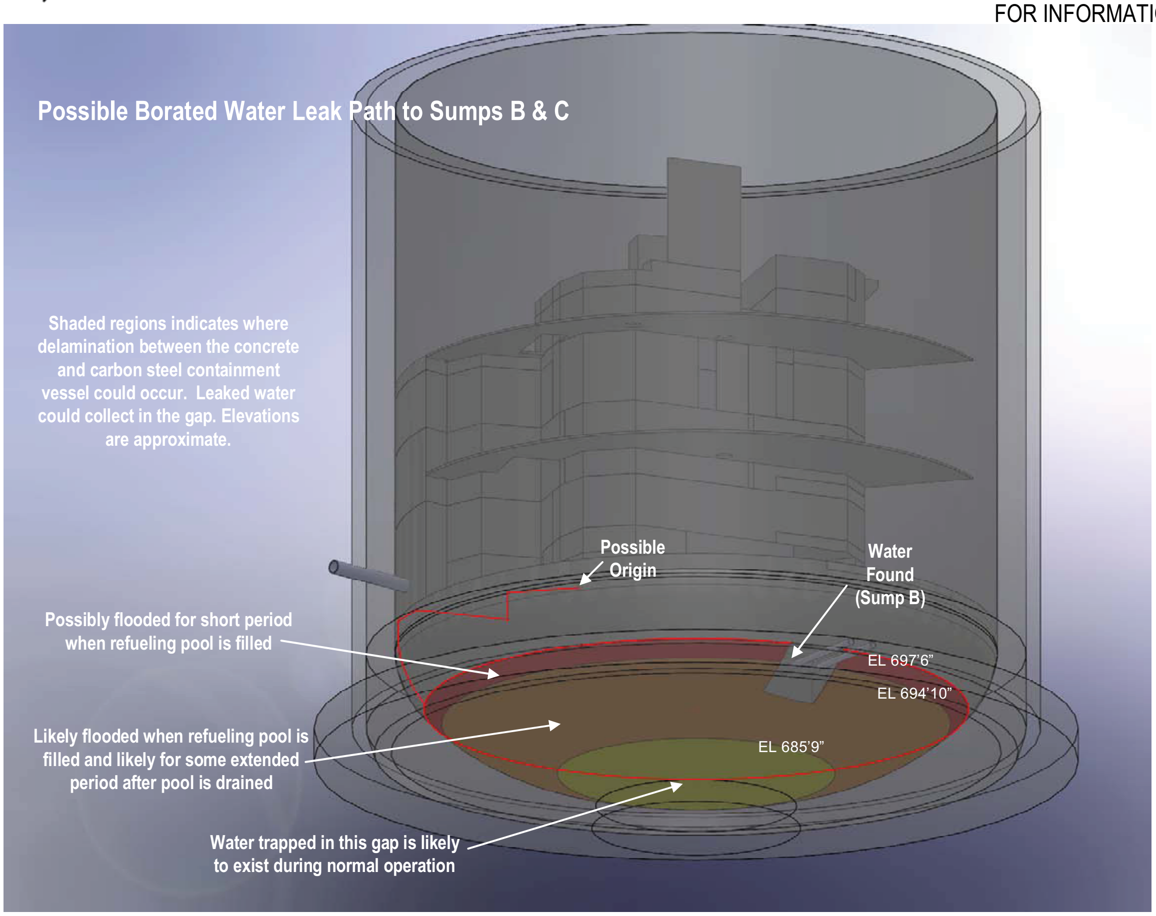

Figure A-11 Lower Regions Wetted by Possible Borated Water Leak Paths to Sumps B & C in Unit 2 – Bottom 3D View

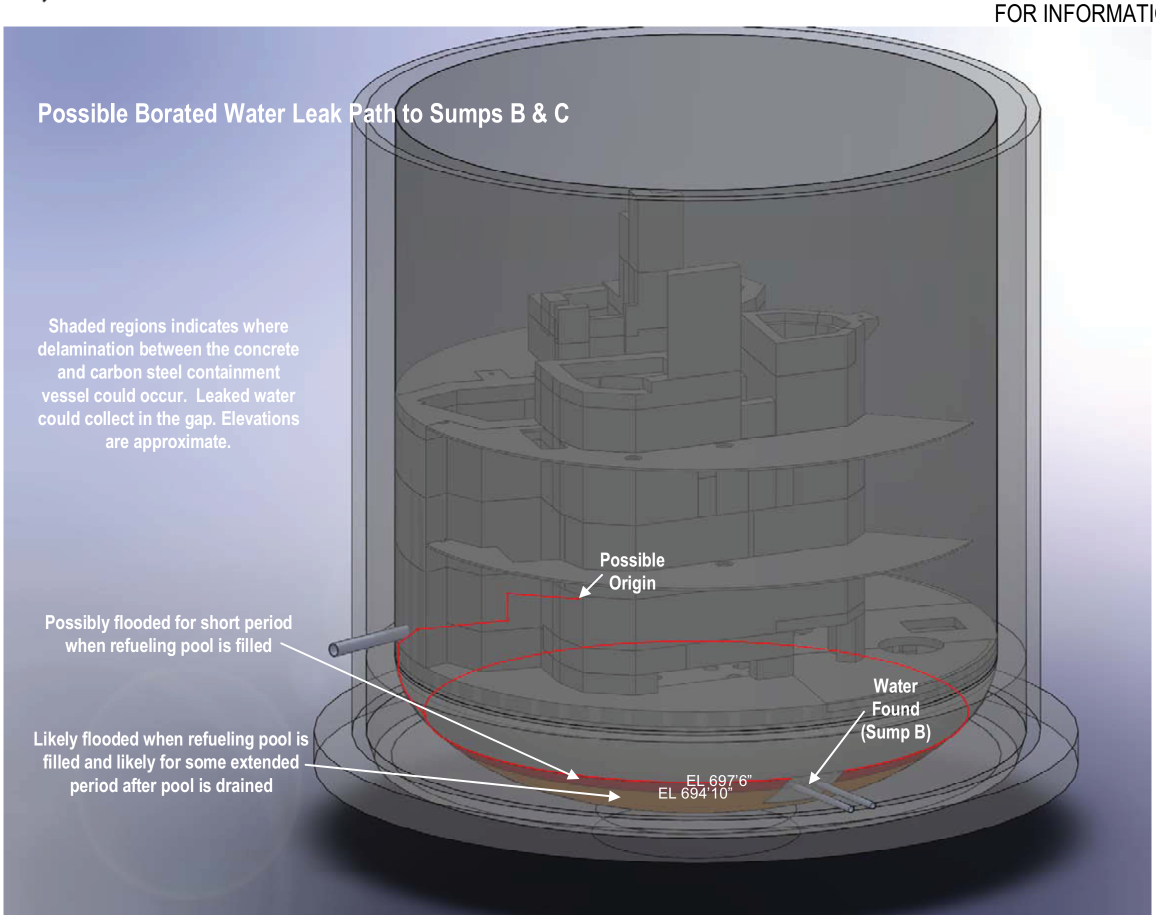

Figure A-12 Lower Regions Wetted by Possible Borated Water Leak Paths to Sumps B & C in Unit 2 – Top 3D View

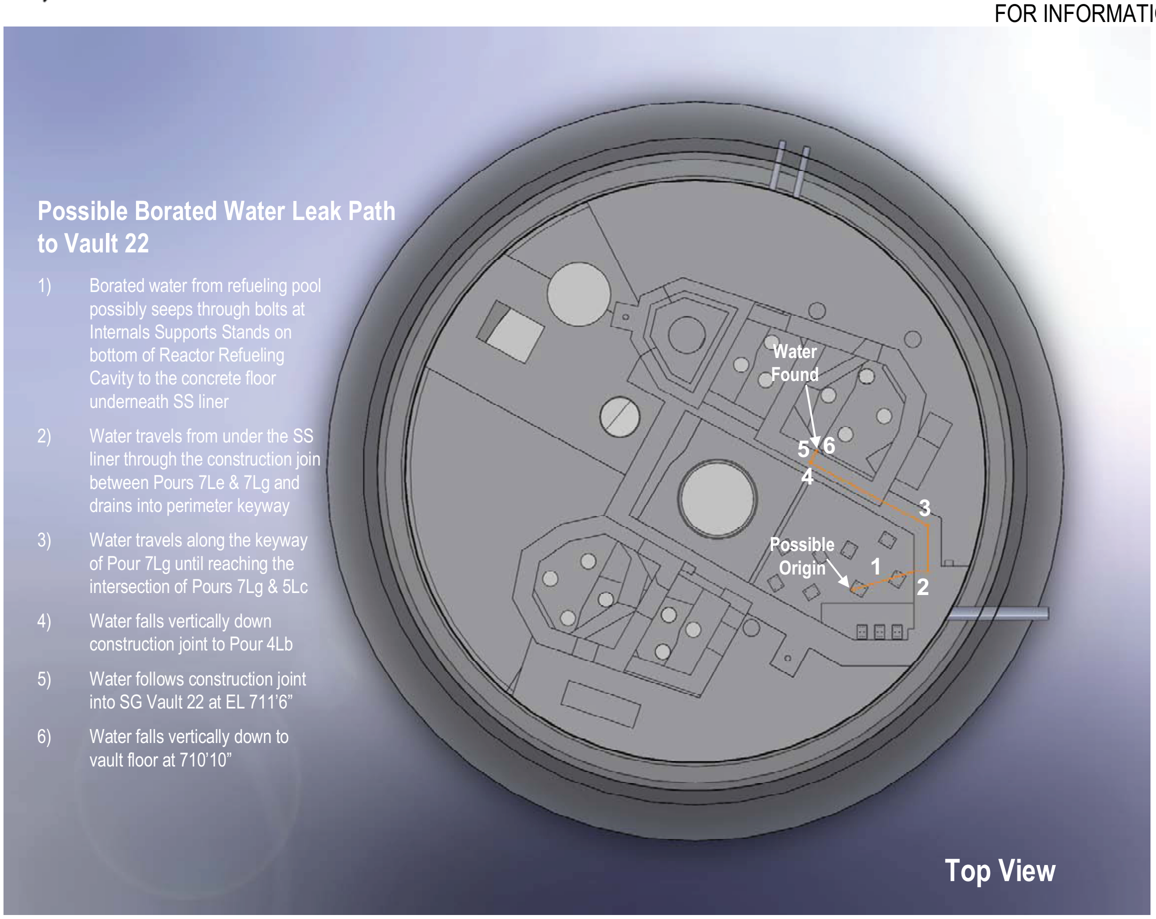

Figure A-13 Possible Borated Water Leak Path to Vault 22 – Top View

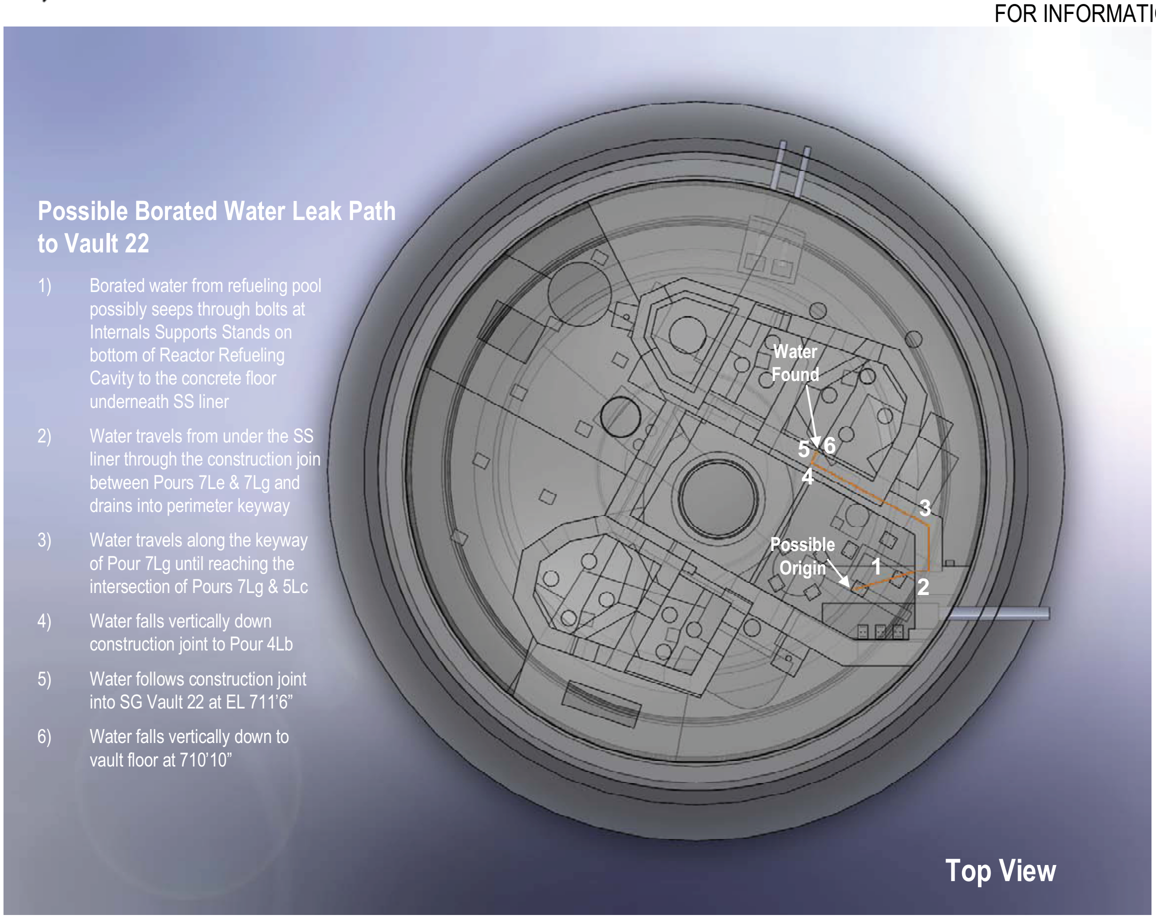

Figure A-14 Possible Borated Water Leak Path to Vault 22 – Transparent Top View

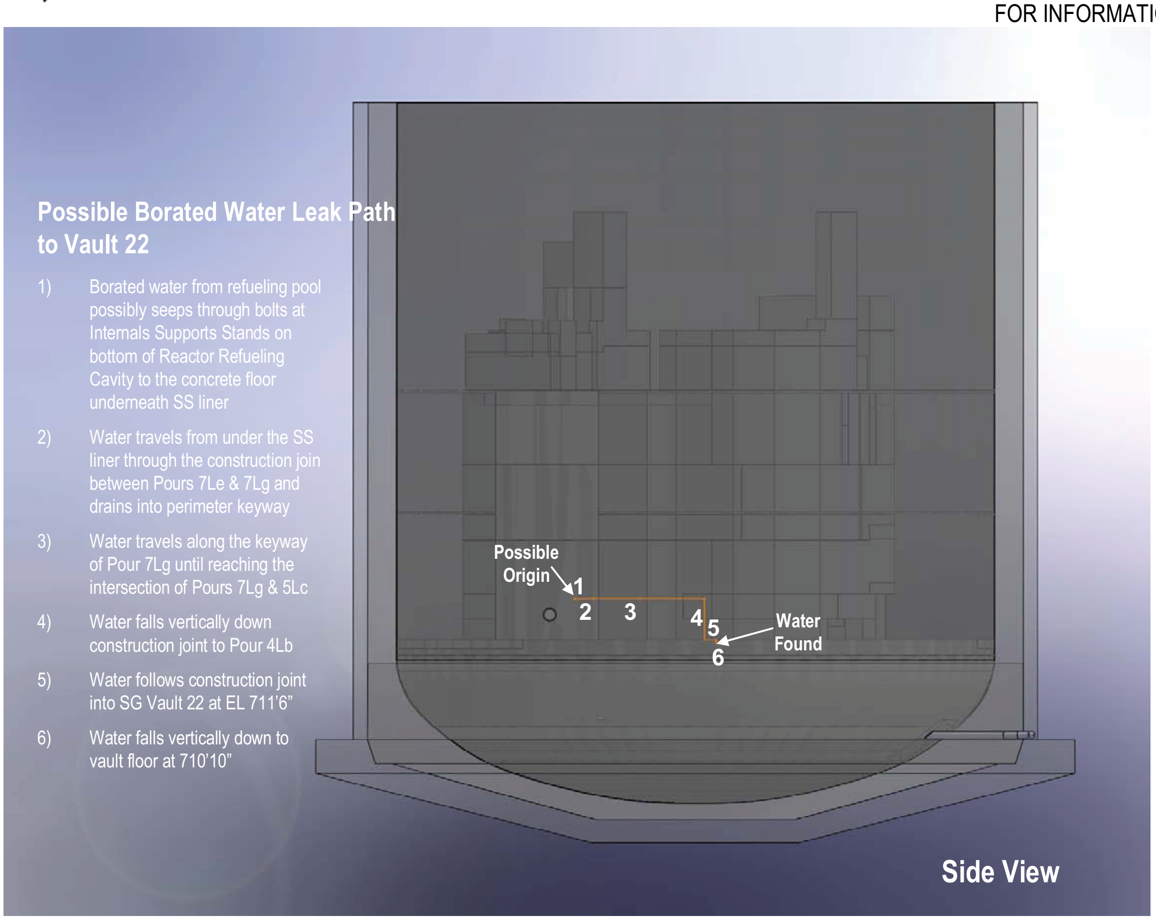

Figure A-15 Possible Borated Water Leak Path to Vault 22 – Side View

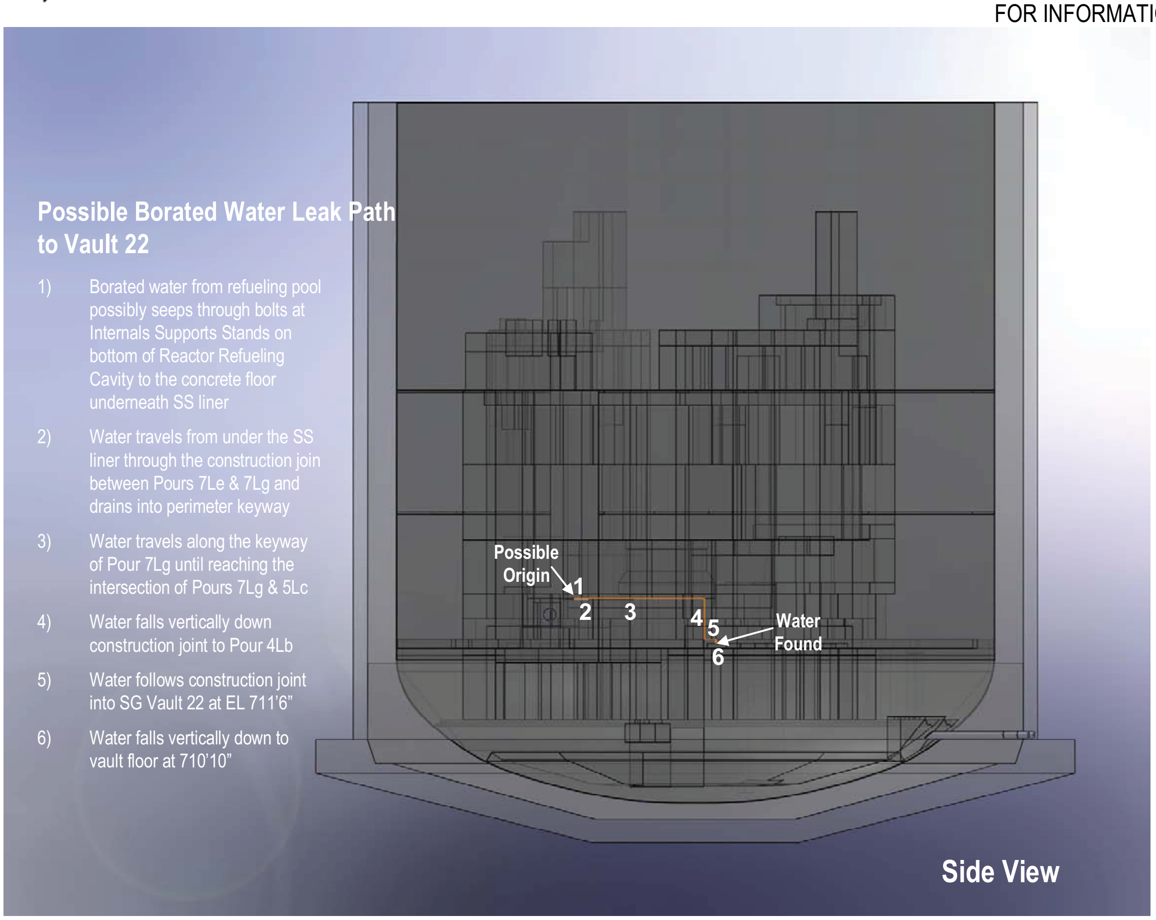

Figure A-16 Possible Borated Water Leak Path to Vault 22 – Transparent Side View

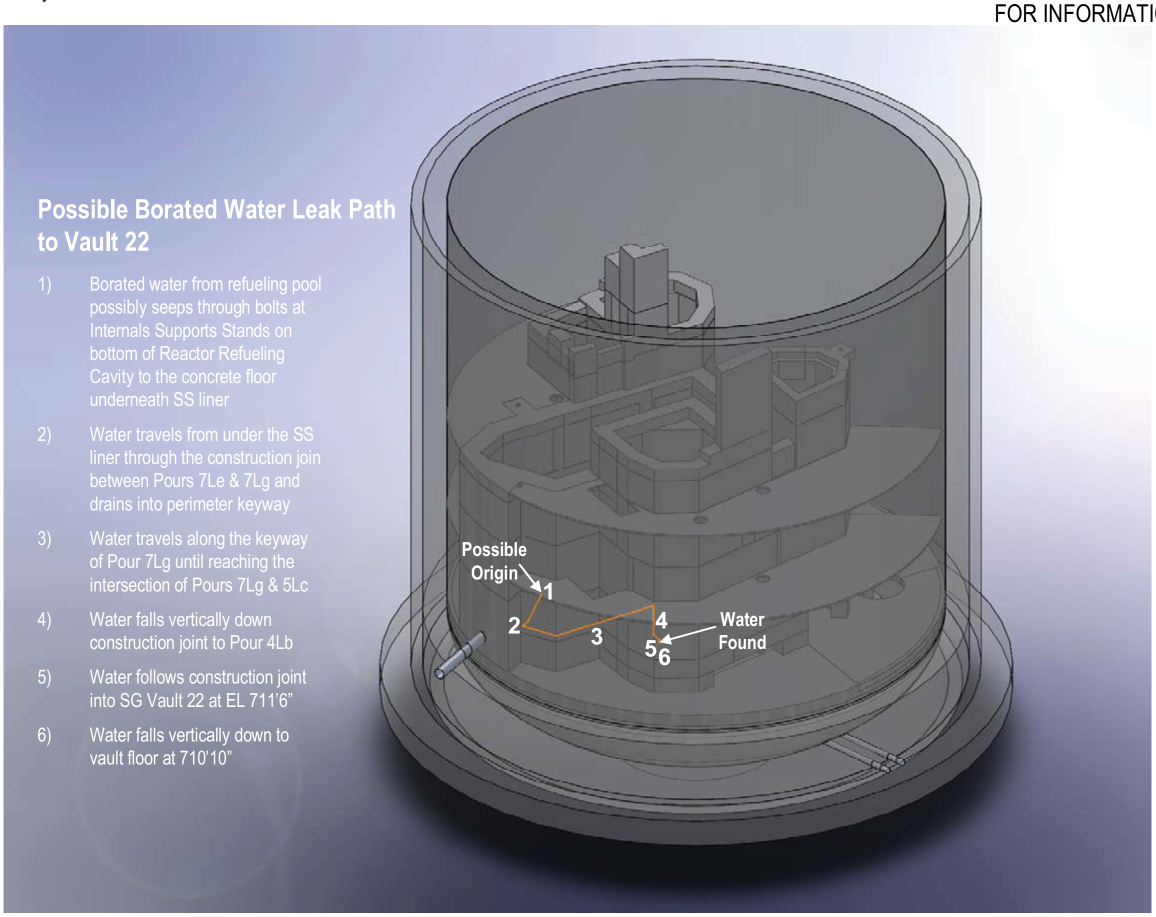

Figure A-17 Possible Borated Water Leak Path to Vault 22 – Top 3D View

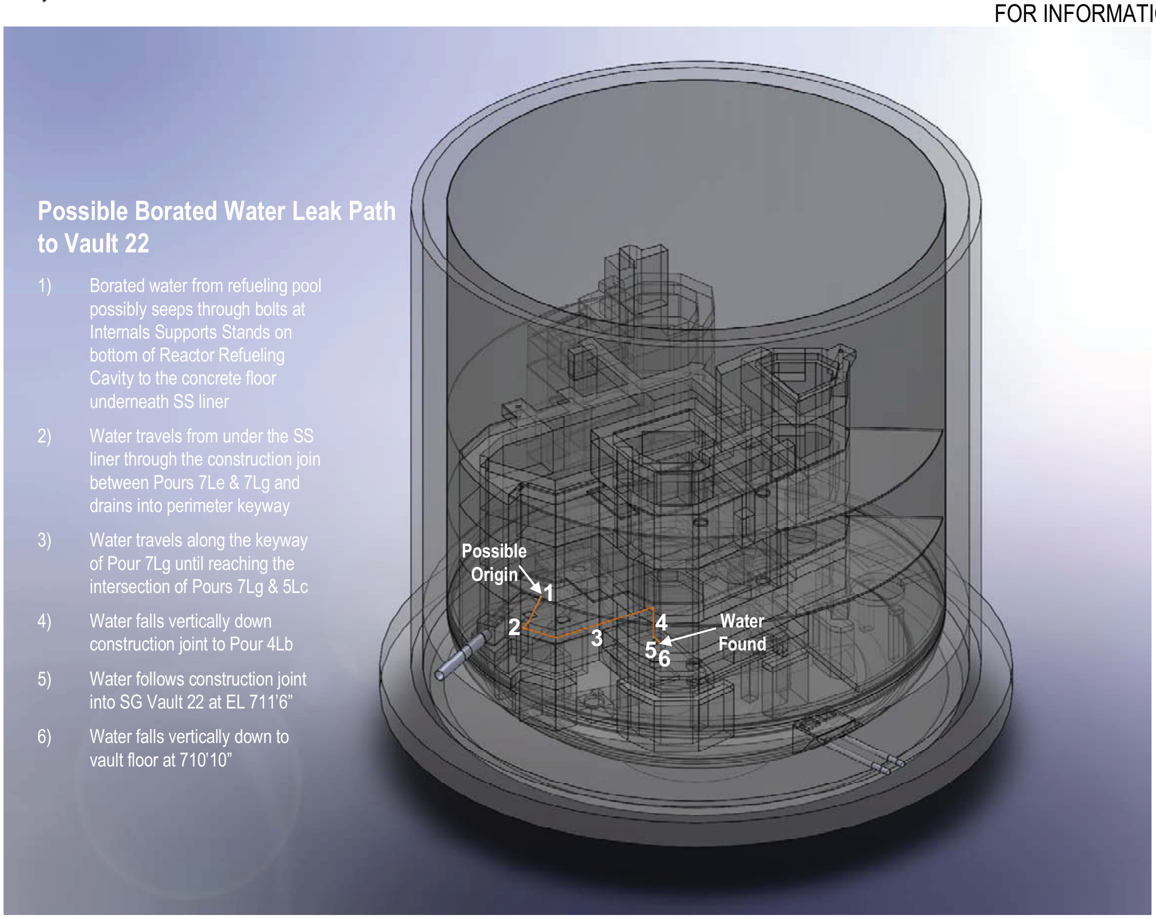

Figure A-18 Possible Borated Water Leak Path to Vault 22 – Transparent Top 3D View

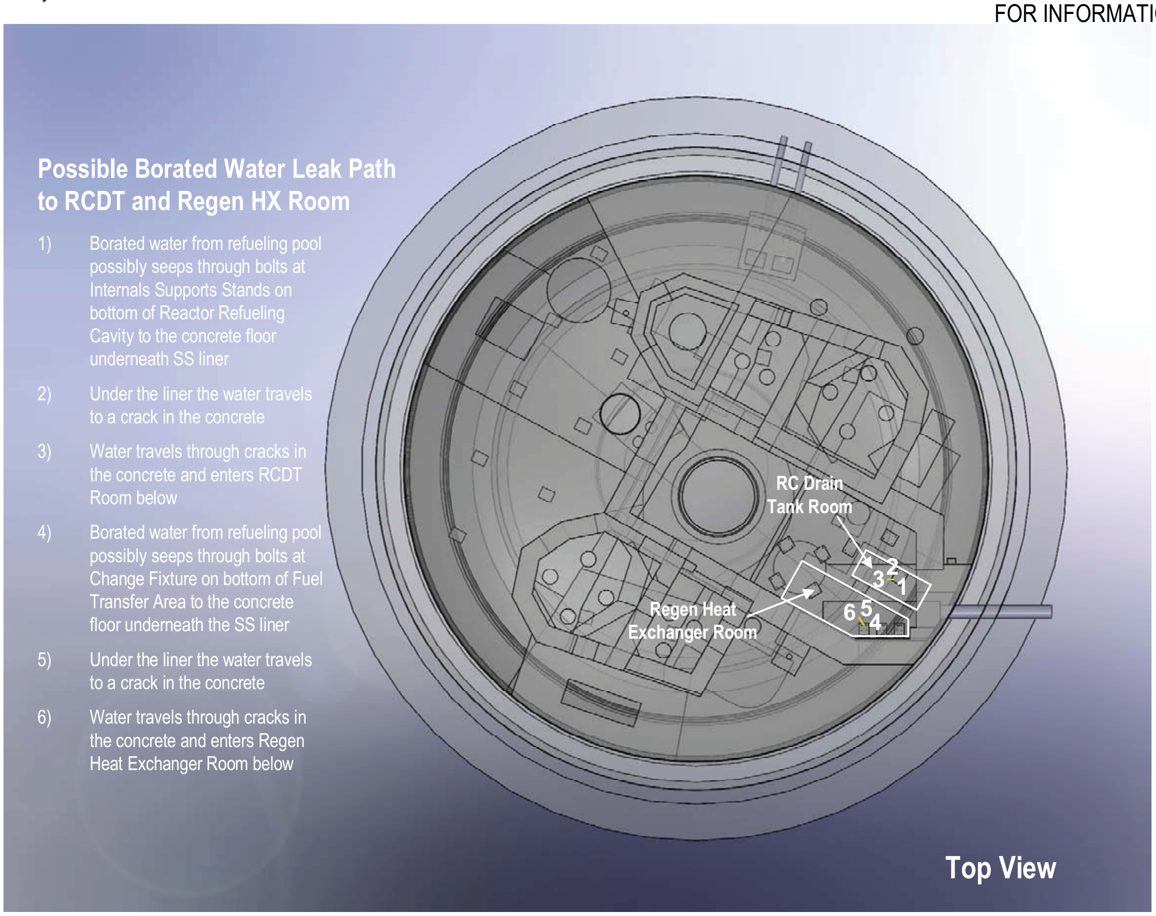

Figure A-19 Possible Borated Water Leak Path to RCDT Space and Regen HX Room in Unit 2 – Top View

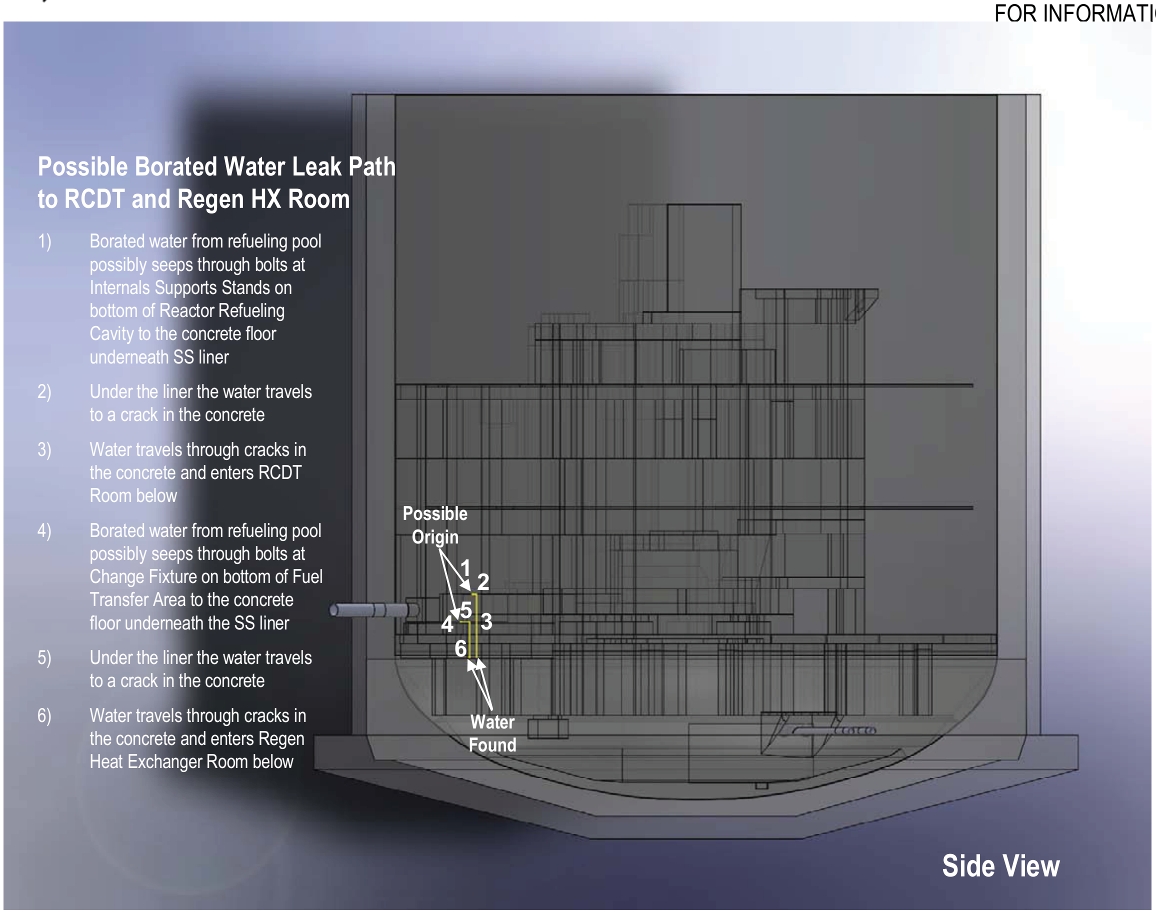

Figure A-20 Possible Borated Water Leak Path to RCDT Space and Regen HX Room in Unit 2 – Side View

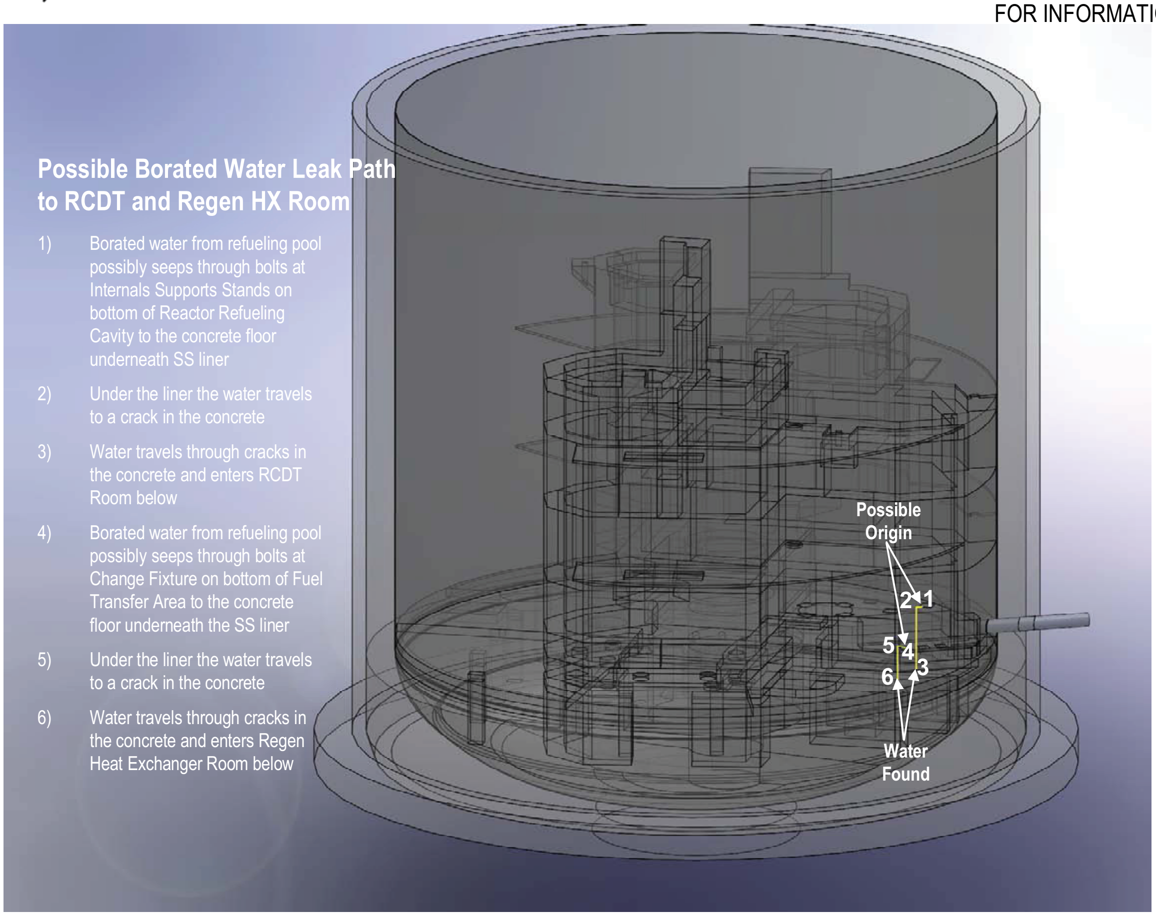

Figure A-21 Possible Borated Water Leak Path to RCDT Space and Regen HX Room in Unit 2 – 3D View