RCE REPORT

Northern States Power Company, a Minnesota corporation (NSPM), d/b/a Xcel Energy

Prairie Island Nuclear Generating Plant

Refueling Cavity Leakage
Event Date: 1988-2008

RCE *01160372-01 Revision 01(CAP 01201071)*

CAP AR 01160372

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I. <u>Executive Summary</u>

Problem:

Refueling cavity leakage has been experienced in various areas in containment of both units dating back to approximately 1988. The most prominent and consistent leakage has been through the grout in Sump B. Other leakage locations have included the ceiling and wall in the Regenerative Heat Exchanger Room (Regen HX Room), the nuclear instrument electrical penetrations, the floor near the Reactor Coolant Drain Tank, and the corners of containment near the transfer tube penetration. The most recent event was the fall of 2008 (2R25) when leakage into sump B was reported at about 1gallon per hour (gph).

Revision 1 – Following repairs to the internals stands supports and RCCA change fixture supports during 1R26 in the Fall of 2009, leakage was identified coming from the ceiling of the Regenerative Heat Exchanger Room. Leakage was reported as 7-8 drops per minute, which is equivalent to approximately 0.05 gph. No indications of leakage were identified in other locations or in Sump B.

Event Synopsis:

Leakage events typically begin about two to four days after refueling cavity flood and end about three days after the pool is drained. Leakage has sometimes been successfully mitigated by coating the refueling cavity floor with a spray on strippable liner, and also by caulking the baseplates and anchor studs of the internals stands and the RCC Change Fixture.

Conclusions:

The leakage points are believed to be where the internals stands and Rod Control Cluster (RCC) Change Fixture anchor studs penetrate the associated embedment plates. The studs for these fixtures are set in through-holes of the embedment plates and seal welded on the underside for the internals storage stands, and on top (then ground flush) for the RCC Change Fixture. Failure of these welds would result in a leak path along the threads of the studs allowing water under the cavity liner. The path for leakage that emerges in the ceiling of the Regen HX Room is believed to flow from under the liner, into cracks in the concrete and down, emerging in the ceiling and walls of the Regen HX Room. The water is also believed to enter the construction joint between the floor of the transfer pit and wall behind the fuel transfer tube leaking to the inner wall of the containment vessel. Once at the containment vessel, the water travels down and horizontally potentially filling any voids between the containment vessel and concrete all the way down to the low point of the bottom head of the containment vessel. As the water rises it starts to leak through various construction joints, cracks, and the grout in Sump B.

Revision 1 – Continuing minor leakage observed following the repair of the internals stands support and RCC Change Fixture supports is believed to be coming from the RCC Change Fixture Guide Tube supports located on the cavity wall. These supports are of the same design as the internals *storage stand supports with studs that penetrate the associated embedment plates.*

Nuclear Safety Significance:
This condition could have nuclear safety significance as continued leakage could potentially degrade the carbon steel containment vessel, reactor building structural concrete, and reinforcing steel (rebar) in the reactor building structural concrete.

The preliminary conclusion of the team is that borated water leakage from the refueling pool is not likely to have had, to date, an adverse impact on the ability of the steel containment vessel and reinforced concrete structures in the reactor building to meet nuclear safety related design requirements. Tests at ambient temperature indicate that the rates of corrosion of steel in aerated concentrated boric acid solutions range between 0.002 to 0.007 inches per year. These rates are probably conservative for this application since the pH of the solution in contact with the containment vessel will be buffered by the alkalinity of the concrete. However, the 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 of corrosion thinning: 36 years x 0.007 in./year = 0.25 in. Ultrasonic thickness measurements of the containment vessel in Sump B and suspect areas accessible from the annulus show no degradation. All readings are above the nominal plate thickness of 1.5 inch for the vessel wall and bottom head, and above the 3.5 inch thickness of the insert plate at Sump B. A long term test 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 measured a corrosion rate of 0.005 inches/year. Assuming that this rate applied for the full life of the plant would result in a maximum amount of thinning of 36 x 0.005 = 0.18 inches. Reinforcing bar in containment has not been directly inspected; however, the lack of any observable concrete splitting or spalling provides strong evidence that any corrosion is minimal and has not reduced the strength of the concrete.

Exposure of concrete to acidic borated water can dissolve the cement and carbonate containing aggregates (Prairie Island aggregates contain about 5% of such carbonate material). Dissolution of these constituents leaves behind aggregate with no strength. This type of dissolution occurs slowly, and is estimated to have attacked no more than about 0.31 inches of the concrete under the refueling pool liner. This amount of thinning is judged to be insignificant in most areas, but could be significant in areas where the concrete in contact with the liner is thin at the wall near the transfer tubes. The issue is considered to require more detailed evaluation.

A further conclusion of the team is that allowing continued leakage to occur would be unwise since the potential for structural effects of the leakage increases with time. This is because carbonation of the concrete penetrates deeper into the concrete with time. Carbonation changes the calcium hydroxide in the concrete to carbonates and drops the pH in the concrete from a protective value over about 12.5 to non-protective values of about 8.3. This makes the rebar increasingly more susceptible to corrosion when wetted as the plant ages.

Root Cause:
The evaluation determined a single root cause with no contributing causes.

Root cause: Leakage through failed welds that secure the anchor studs of the internals stands and RCC Change Fixture (revision 1) and RCC Change Fixture Guide Tube supports.

Two additional factors were noted:

1. Failure to remove the nuts when caulking the internals stands and RCC Change Fixture anchors.
2. Failure to adequately cover the baseplates and anchors when applying the InstaCote spray-on strippable liner.

These factors are not considered contributing causes as inadequate liner application and caulking did not contribute to or cause leakage, but rather resulted in a failure to successfully mitigate the symptoms of leakage.

Corrective Action Synopsis:
The corrective actions to prevent reoccurrence are to repair the leaks with repair starting in 1R26. The recommended repair plan includes the following steps:

1. Unbolt and set aside all mechanically fastened fixtures (RCC Change Fixture, internals stands, and guide tube supports).
2. Vacuum Box penetrations and embedment plates to locate existing leaks. Weld repair and vacuum box completed welds
3. Preemptively seal weld and vacuum box all penetrations.
4. Vacuum Box, and/or PT weld seams and repair as needed to ensure no leakage due to stress corrosion cracking.
5. Pressure test or PT transfer tube bellows attachment welds and weld repair as needed.

The team recognizes that some flexibility should be allowed in the repair methodology as improvements will likely be identified as the repair is designed and planned.

Reports to External Agencies:
This event has been reported to the NRC as part of past Inservice Inspection summary reports. It was reported to the industry by a survey of sites with potentially similar leakage. It was recently the subject of a NRC RAI associated with license renewal.

II. Event Narrative

The first documentation of potential refueling cavity leakage was for Unit 1 in 1987 when laborers noted leakage in the regen heat exchanger room and other locations. (See table at the end of this section and Appendix D "Event and Causal Factor Chart" for a chronological list of events). In 1988 a work request M7239-RV-Q (WO8807239) was initiated to "Find leaking cavity liner welds and repair". The completion notes show that three indications were found by visual inspection and weld repaired. In 1989 work request N2434-RV (WO8902434) was initiated to "Fabricate Vacuum Boxes for test reactor cavity welds for leakage … - need for Unit 1 outage" indicating continuing leakage.

From 1987 to 1998 laborers had routinely pumped both sump B (the RHR LOCA recirculation sump) and sump C (the sump under the reactor vessel) during refueling outages. It is not known how much of the sump C leakage was from refueling cavity leakage and how much can be attributed to the reactor vessel cavity seal or sandbox covers as any leakage of the reactor vessel to refueling cavity seal or sandbox covers would leak into sump C. Likewise, leakage into sump B can be from the RHR system through the suction lines. As a result, only leakage that is documented as coming through cracks in the concrete, concrete construction joints, or the grout in sump B can be directly attributed to refueling cavity leakage.

During the 1998 Unit 2 refueling outage (2R19) water was found entering sump B from the area outside the RHR suction penetration sleeve. Leakage was measured at 0.5 gph. The water was sampled and determined to be at refueling water boron concentration, approximately 2700 ppm. The water also contained short lived nuclides. The pH of the water was 7.8, slightly alkaline. The grout around the penetration was partially removed to determine the condition of the containment vessel wall. The vessel showed no signs of degradation. Leakage stopped after the refueling cavity was drained. Efforts to find the leakage included vacuum box testing of accessible seams and fasteners, and dye penetrant testing of suspect areas that could not be vacuum boxed. During vacuum box testing it was found that about 50% of the cap screws on the sandplug covers leaked. Three small discontinuities in the liner plate seams were weld repaired. Automated Engineering Services (AES) performed an evaluation of the effects of borated water on concrete, reinforcing bar, and the containment vessel. The evaluation concluded that the effects of the leakage on the containment structure would be minimal and would not have any safety significance.

Similar leakage was found during the 1999 Unit 1 refueling outage (1R20) and similar actions were taken. Vacuum box testing of Unit 1 did not show any indications other than sandplug cover screws, and no weld repair was done. The AES evaluation was used to disposition the leakage as it was essentially the same as Unit 2.

In the 2000 Unit 2 outage (2R20) a strippable liner (InstaCote™) was applied based on the site's recognition that continued leakage could potentially result in degradation and the recommendations of the AES evaluation. The liner was applied to the upper deck of the refueling cavity around the reactor vessel to six feet up the walls and the floor of the transfer pit. It was not applied to the lower cavity. No refueling cavity leakage was reported.

No actions were taken to mitigate leakage during the 2001 Unit 1 outage (1R21). Based on a memo written to InstaCote in August of 2000, it was decided not to install the liner due to a lack of resources (resignation of one of the RV engineers) and the recognition that installation would require a safety evaluation. There was no leakage reported that could be directly attributed to refueling cavity leakage.

InstaCote was again applied in the 2002 Unit 2 outage (2R21) to the lower cavity and transfer pit and is believed to have been successful in mitigating leakage. One CAP was written on "Boric Acid coming out of concrete walls in sump C". However, there is no indication this was due to current active leakage.

InstaCote was applied in the 2002 Unit 1 outage (1R22) but failed to stop leakage as documented in AR00284714. Leakage was noted through the concrete in the regen room and other locations. Leakage was attributed to failure to spray the feet of the internals stands. It was also noted that the liner had failed to adhere to the cavity in localized areas.

The final application of InstaCote was in the 2003 Unit 2 outage (2R22). The spray on liner had again failed to mitigate leakage due to failure to adequately spray the feet of the internals stands. After the above two consecutive failures, use of InstaCote to mitigate leakage was abandoned. Application proved problematic even with thorough pre-job briefing with the vendor stressing the importance of spraying the internals stands and RCC Change Fixture baseplates and feet.

For the 2004 Unit 1 outage (1R23) it was decided to caulk potential leak paths which were believed to be the baseplates and fasteners of the internals stands and RCC Change Fixture. Nuts and washers were successfully removed for both the upper and lower internals stands allowing caulking of the gap between the studs and the baseplates. The nuts of the upper internals stand were torqued to 260 ft-lb (which was a "pen and ink" change to the work order which indicated 455 ft-lb). The nuts of the lower internals stands were torqued to 525 ft-lb (which was a "pen and ink" change to the work order which indicated 920 ft-lb). The baseplates of the RCC Change Fixture were not caulked due to water from the transfer tube leaking into the transfer pit. The system engineer reported that leakage from the refueling pool was "significantly reduced".

Caulking was repeated in the 2005 Unit 2 outage (2R23). The work order shows that nuts and washers of both internals stands and the RCC Change Fixture were removed allowing caulking of the gap between the studs and the baseplates. Nuts of the upper internals stand and RCC Change Fixture were torqued to 260 ft-lb. The nuts for the lower internals stand were torqued to 525 ft-lb. Engineering notes indicate that no leakage from the refueling pool was observed.

Caulking was repeated in the 2006 Unit 1 outage (1R24). The work order shows that nuts and washers of both internals stands and the RCC Change Fixture were removed allowing caulking of the gap between the studs and the baseplates. The nuts of the upper internals stand and RCC Change Fixture were torqued to 260 ft-lb. The nuts of the lower internals stand were torqued to 525 ft-lb. There was no recorded leakage from the refueling pool.

Caulking was repeated in the 2006 Unit 2 outage (2R24). However, the work order indicates the steps to remove the nuts of the internals stands and the RCC Change Fixture were N/A'd. It was believed that the caulk applied under the nuts in the previous Unit 2 outage would still be intact and provide an effective seal against leakage. An inspection of typical leakage locations showed leakage only through the grout in sump B.

Caulking was repeated in the 2008 Unit 1 outage (1R25) under a new maintenance procedure D99. The work order shows nuts and washers of the both internals stands and the RCC Change Fixture were removed allowing caulking the gap between the studs and the baseplates. Nuts of the upper internals stand and RCC Change Fixture were torqued to 260 ft-lb. The nuts for the lower internals stand were torqued to 525 ft-lb. There is no record of leakage with the exception of a significant sandplug cover leak into sump C.

The most recent refueling outage was the Unit 2 outage in 2008 (2R25). Caulking was repeated under procedure D99. However, the nuts for the internals stands and RCC Change Fixture were not removed due to risk of galling. Leakage was reported in the ceiling of the regen heat exchanger room, the 22 vault, and sump B. The grout was removed from sump B to allow visual and UT inspection of the containment vessel. There was no indication of degradation. The leakage in sump B was reported to well up from the bottom of the removed grout at a rate of approximately 1gph.

Revision 1 – Welded repairs were performed to the RCC Change Fixture and Internals Stand support during 1R26 in the Fall of 2009. Repairs included replacement of the existing nuts with blind nuts and seal welding the nuts to the baseplates and the baseplates to the embedment plates. Leakage of 7-8 drops per minute was identified coming from the Regenerative Heat Exchanger Room ceiling approximately 18 days after the cavity was flooded. Sump B as well as other areas were monitored and inspected for indications of leakage. With the exception of the Regenerative Heat Exchanger Room ceiling, no other indications of leakage were identified. Grout was removed from Sump B to allow for visual and UT inspection of the containment vessel. There was no indication of degradation of the vessel or of the rebar exposed during the excavation.

The table below represents a search of refueling cavity leakage action requests and work orders which provided the basis for this narrative and the Event and Casual Factor Chart in Appendix D.

Chronological Table of Notes, Action Requests and Work Orders Associated with Refueling Cavity Leakage					
Date	**Outage**	**Source**	**Unit**	**Comment**	**Leak in significant location**
Jan-87		Laborer Notes	2	Pumped Sump B and near RCDT	Sump B
Apr-87		Laborer Notes	1	715 wall leak from cavity, Sump C, Regen Room, RCDT	Regen Room
Sept-88		WO8807239	1	Find leaking cavity liner welds and repair.	
Jun-89		WO8902434	1	Fabricate Vacuum Box for refueling cavity	
Sep-90		Laborer Notes	2	Pumped Sump B multiple times	Sump B
Sep-92		Laborer Notes	2	Monitored sump C	
Dec-92		Laborer Notes	2	Pump sump C	
Nov-93		Laborer Notes	2	Pumped sump C and pump sump B then deconned sump B	Sump B
Apr-94		Laborer Notes	1	Pumped sump C	
Apr-95		Laborer Notes	2	Pumped sump C	
Jan-96		Laborer Notes	1	Pumped sump B	Sump B
Oct-97		Laborer Notes	1	Pumped sump C and B	Sump B
Nov-98	2R19	(NCR 19983240) TT006622 00051045	2	BA water found in sump B	Sump B
Nov-98	2R19	WO 9812582	2	Vacuum Box testing of cavity liner	
Nov-98	2R19	Laborer Notes	2	Pumped sump B and C	Sump B
Nov-98	2R19	WO 9812741	2	Weld repair of cavity liner	
Dec-98	2R19	AES report	2	AES evaluation - Evaluation of the Effects of Borated Water Leaks on Concrete, Reinforcing Bars, and Carbon Steel Plate of the Containment Vessel - UNIT 2	
Dec-98	2R19	98T060	2	Tmod removed grout in sump B	
Apr-99	1R20	WO 9900156	1	Vacuum Box testing of cavity liner	
Apr-99	1R20	WO 9901619	1	IWE inspections	
Apr-99	1R20	CAP 13409, NCR 19991420, NCR 19992930	1	IWE inspections find indications, including water in sump B. AES report used for disposition of water in sump B	
May-99	1R20	NCR 19991586 TT012606, 00057041	1	Cavity leakage regen room ceiling 1.25 gph, NIS @715', sump B 0.25 gph. Leakage stopped when pool drained.	
May-99	1R20	Laborer Notes	1	Pumped sump B and C. Monitored regen room, 11 & 12 Vaults and 715 wall near	Sump B

				12 accum	
Apr-00	2R20	WO 9911323	2	Replace grout in sump B	
Apr-00	2R20	WO 0000228	2	InstaCote upper and lower cavity	
Jan-01	1R21	Laborer Notes	1	Pump sump C. Pumped sump B after stroking of MV-32075. 3.5" of water in sump B when pumped.	
Feb-02	2R21	CAP 28102 00405027	2	BA coming out of walls in sump C	Sump C
Feb-02	2R21	Laborer Notes	2	Pumped sump C	
Feb-02	2R21	WO00052395	2	InstaCote lower cavity	
Nov-02	1R22	CAP 26062, CE 1332, EWR 3072, CAP 284349	1	Results of IWE inspections. NCR 19991420 re-evaluated.	
Nov-02	1R22	CAP 284480, CAP 26612	1	BA water found in sump B	Sump B
Nov-02	1R22	00055645	1	InstaCote lower cavity	
Nov-02	1R22	CAP 26667 00284714	1	InstaCote liner failed (delamination)	
Nov-02	1R22	CAP 26917, CAP 26918	1	IWE inspections of RHR penetrations in sump B found discolored	
Nov-02	1R22	WO 0211420	1	Removed and replaced grout in sump B for inspection	
Nov-02	1R22	Laborer Notes	1	InstaCote, 12 Vault leakage, RCDT stairway area, Regen room	Regen Room
Jun-03		CAP 30691, CAP 449041, ACE 8718		SOER 02-04 assessment. Identified cavity leakage as number 1 issue.	
Jul-03		OTHA 6284		Enhancements to refueling cavity InstaCote work plan. Stressed the importance of spraying base plates and bolting on the internals stand	
Sep-03	2R22	WO 0300436	2	InstaCote lower cavity	
Sep-03	2R22	CAP 32884, CAP 531162, CAP 538738, CAP 33233, CAP 33236	2	Leaks found from 2N52, Regen Room Sump B and Sump C. Rolled O-rings found on cover plate to 2N52, 2N41 cover plate bolting found only finger tight.	Sump B
Sep-03	2R22	Responsible Engineer Notes	2	Master Lee full spray. Leakage blamed on light coat on one of the internals stand feet	
Sep-04	1R23	CAP 38417	1	BA found on hot legs in the penetrations to the 11 SG vaults.	
Sep-04	1R23	CAP 38474	1	BA found on 2N52. Evidence was from leakage during previous outages	
Sep-04	1R23	WO 0309439	1	Caulked potential leakage	

				paths in the refueling cavity	
Sep-04	1R23	Laborer Notes	1	Only a small amount of water found in sump C	
Sep-04	1R23	Responsible Engineer Notes	1	Caulking on RCC fixture base plates and bolting was not done due to water in the area. Leakage was reduced	
Jun-05	2R23	CAP 853471	2	Removal of caulking in refueling cavity results in high dose	
May-05	2R23	Laborer Notes	2	Pumped sump B and C	Sump B
May-05	2R23	WO00088274		Caulk potential leak paths in refuel cavity.	
May-05	2R23	Responsible Engineer Notes	2	Caulked all base plates and bolts - ALL LEAKAGE STOPPED - only segmented seal leakage	
Oct-05		CAP 1002262		Cleaning of BA in high rad areas does not address the cause of leakage, contributes to the higher dose and does not address the cause of the leakage	
Apr-06	1R24	WO00099061	1	Caulked potential leakage paths in the refueling cavity	
May-06	1R24	Responsible Engineer Notes	1	Most base plates, studs and nuts caulked. Only caulked accessible base plates in transfer pit.	
May-06	1R24	CAP 1027421, CAP 1027440	1	BA leakage from the Regen room ceiling has come in contact with other components. Evaluation of affects of BA on these components was needed. These CAPs did not identify leaks at that time.	
Nov-06	2R24	WO00158193	2	Caulked potential leakage paths in the refueling cavity	
Nov-06	2R24	CAP 1063531	2	Leakage in sump B. Note CA's as a result of this cap were poorly communicated/written resulting in no action.	
Nov-06	2R24	CAP 1064513	2	Walkdown of all potential leakage areas was performed. Multiple evaluations and actions resulted from this cap including an attempt at a permanent fix.	
Dec-06		CAP 1069509		Need to complete open structural issues. It was noted in this cap that the cracks in the regen room have not been addressed by structural	

				engineering	
Dec-07		CAP 1064513		Actions out of this CAP include ECR/EAR for permanent repair of coverplate leakage and base plates. Issued new procedure to provide guidance for caulking.	
Feb-08	1R25	WO 306965	1	Caulking per D99 performed	
Feb-08	1R25	CAP 1128144	1	Leakage into sump C	
Sep-08	2R25	WO 327768	2	Remove grout in sump B	
Sep-08	2R25	CAP 1152104	2	Did not perform caulking under bolting per D99 and identifies that leakage was possible.	
Oct-08	2R25	CAP 1155029	2	Leakage in regen room, 22 vault, sump B and C	Regen room and sump B
Oct-08	2R25	CAP 1156182	2	Alternate needed to caulking due to the high radiation dose and other safety issues that are present during this job.	
Oct-08	2R25	CAP 1151772	2	Studs for RX internals stand have been over torqued	
Oct-08	2R25	WO 327768	2	Remove and replace grout in sump B. UT of containment vessel in sump B and annulus.	
Oct-08	2R25	Laborer Notes	2	Pumped sump C steadily but low volume. Pumped sump B continuously	
Sep-09	*1R26*	*CAP 1201071*	*1*	*7-8 drops per minute identified coming from Regenerative Heat Exchanger Room ceiling after 18 days of cavity flood.*	*Regen Room*
Sep-09	*1R26*	*WO 372531*	*1*	*Remove and replace grout in sump B. UT of containment vessel in sump B and annulus.*	
Sep-09	*1R26*	*WO 378798*	*1*	*Replaced nuts on internals stands supports and RCC change fixture supports. Seal welded nuts to baseplates and baseplates to embedment plates. Visual and dye penetrant inspections performed of final welds*	
Sep-09	*1R26*	*WO 391275*	*1*	*Dye penetrant inspected embedment plate to liner welds and transfer tube welds*	
Sep-09	*1R26*	*WO 378798*	*1*	*Vacuum box tested lower cavity floor seam welds and on walls to approximately 6 feet above the floor*	
Sep-09	*1R26*	*WO 390645*	*1*	*Inspected lower cavity floor for soft spots and depressions*	

III. Extent of Condition Assessment

Extent of Condition –

Equipment – The extent of condition includes both units with each having essentially the same leak locations (sump B, sump C, regen HX room, walls, vaults,) and leakage contact areas (containment vessel, reactor building concrete). The Leakage could also occur in the spent fuel pool. However, as discussed in OE00422434 the spent fuel pool is a different construction that includes a leak detection system, and there is no risk of degradation of a steel pressure vessel.

Processes – Similar activities to mitigate leakage (InstaCote and caulking) have been applied to both units with similar results. Work orders for mitigation activities have not always been completed as planned. CAP Action Requests have been closed without resolving the issue.

Organizational – Failure to resolve the issue spans the organization vertically and to a lesser extent horizontally. The issue has been well known and documented providing several opportunities for greater management involvement and direction. Although engineering has been the primary owner of the issue, maintenance has also had a stake in mitigation activities. The duration of the condition indicates larger organizational issues.

Human Performance – Procedure Adherence, oversight, and vendor control has been an issue in that for two InstaCote applications and three caulk applications the work procedure was not (or could not) be completed as written.

The process, organizational, and human performance issues noted above have been thoroughly addressed in two recent root cause evaluations and a third RCE in progress. RCE01141755 was initiated in July 2008 and addressed crosscutting issues associated with Technical Support Center functionality, SI-9-5 valve failure and 11 Turbine Driven Aux Feedwater Pump bearing temperature. RCE01165133 was initiated in January 2009 and addressed crosscutting issues associated with valve mispositions, procedure adherence, non-qualified personnel, and troubleshooting. RCE01166830 was initiated in February 2009 and addresses inadequate CAP resolution of significant issues. As such, the charter of this RCE was primarily equipment related with the exception of determining if there had been prior opportunities to identify the issue.

Extent of Cause –

Direct Causes/Root Causes – The cause of leakage (leakage at the internals stands, RCC Change Fixture *and RCC Change Fixture Guide Tube anchors (revision 1)* is believed to be the same for both units and not applicable to other site equipment.

Similar Equipment – See the Extent of Condition section for a discussion of similar equipment.

System Interrelations – Refueling cavity leakage interacts with the containment vessel and internal containment support structures to the extent that borated water could potentially corrode and weaken the vessel, concrete and/or reinforcing steel. There is also a potential for water to adversely effect electrical or instrument components, or leak onto pressure retaining components such as pipe and valves.

IV. **Previous Similar Events**:

As noted in the narrative, documentation of leakage for both units goes back to 1987. Leakage may have occurred prior to this time, but no documentation was found in conducting the RCE that would confirm prior leakage. The scope of this RCE was intended to include all refueling cavity leakage events.

V. **Operating Experience:**

Review of Plant Operating Experience (OPEX) Related to Pool Leakage, Corrosion of Steel Containment Shells and Liners, and Deterioration of Concrete due to Corrosion of Rebar

A. Objective
The objective of this section is to summarize the results of a review of operating experience (OPEX) related to leakage from refuel and spent fuel pools, corrosion of steel containment vessels and liners, and deterioration of concrete due to corrosion of rebar.

B. Background
Xcel Energy has initiated a root cause investigation into the causes and consequences of reactor cavity leakage that has periodically been observed at Prairie Island Units 1 and 2. The main concern regarding such leakage is possible degradation of safety related structures that are wetted by leakage from the refueling pool, especially the steel containment vessel (SCV), but also reinforced concrete structures inside the SCV.

C. Methodology
Searches were made of INPO and NRC databases for relevant documents. In addition, information obtained by a survey conducted by Xcel Energy in 2003 was also used.

Searches of the INPO databases were performed for documents using the following key words:

– “Fuel Pool Leak”
– “Refuel Pool Leak”
– “Borated Water” AND Concrete
– Corrosion AND Rebar
– Corrosion AND Containment
– Tritium AND Leak
– Refuel Pool

– Boric Acid AND Concrete

In some cases, searches for supplementary information on specific events were made using the NRC's ADAMS database system.

D. Detailed Results of Review of OPEX
Relevant documents identified by the search of OPEX databases were categorized into four general categories: (a) reactor cavity and refuel cavity leaks, (b) spent fuel pool leaks, (c) corrosion of steel containment vessels and liners, and (d) concrete degradation. For each category, the events covered in the documents are summarized in chronological order. The next section provides a summary of the main findings for each category.

1. Reactor Cavity and Refuel Cavity Leaks
The main events related to reactor cavity and refuel cavity leaks found by the search of OPEX are covered below.

- A 1985 report by ANO 2 [1] indicates that leakage into the reactor cavity could have occurred due to leakage past the reactor cavity seal plate or as the result of incorrect operation of a sump pump. No damage due to the leakage was reported.

- Indian Point 2 experienced a significant amount of tearing of the stainless steel liner plates at welds in 1993 and 1995 [2, 3]. These flaws were detectable by visual inspection. Based on metallurgical examination, it was determined that the cracking was the result of chloride induced transgranular stress corrosion cracking (TGSCC) that initiated from the outside surface except for one case where the cracking appeared to initiate from the ID. It was speculated that the chlorides came from the concrete, possibly as the result of wetting from an initial flaw that allowed cavity water to get to the outside of the liner plate. Based on the fact that most of the flaws were visibly detectable, it is concluded that significant settling type stresses and strains were present and caused the tearing. Initial repairs in 1993 were made by a combination of welding on stainless steel cover plates and use of an epoxy coating. Based on better performance of the epoxy coating, in 1995 it was selected as the permanent repair method. However, based on the record of a telephone call on 3-21-03 between C. Koehler, NMC, and Rebecca Hurt of Indian Point, the epoxy may not be resilient enough to tolerate the flexing that occurs and they have not had good longevity [4].

- A 2003 Xcel Energy survey [4] identified that, in addition to the above events, reactor cavity leakage had also been experienced at San Onofre 2 and 3, Watts Bar, Ginna, Byron, Braidwood, McGuire 1 or 2, and Point Beach 1. None of the surveyed utilities identified the leakage as causing a structural or safety problem.

- A 2004 report by Robinson indicates that damage due to corrosion occurred of thimble tube straps due to flooding of the cavity with borated water, and that the straps were replaced with corrosion resistant parts [5].

2. Spent Fuel Pool Leaks
   The main events related to spent fuel pool (SFP) leaks found by the search of OPEX are covered below.

- In 1986 at Rancho Seco, when the spent fuel pool (SFP) leak chase drain line was isolated for maintenance of a valve, leakage occurred through the concrete walls of the fuel storage building resulting in an unplanned release of activity [6]. It was concluded that the leak occurred through a small flaw in the SFP liner and that the leakage normally was carried by the leak chase drain system to radwaste but that, when this path was isolated, the leakage penetrated through the concrete walls, which were characterized as porous.

- In June 1992 at Indian Point 2 workers identified an area of radioactive material contamination on the exterior 6' 3" thick concrete wall of the Unit 2 spent fuel pool building [7]. The contamination appeared as boron crystals on the wall in roughly a 20 square foot streaked pattern. An isotopic analysis of the crystals determined that they have the same isotopic breakdown as the spent fuel pool borated water. The leak in the stainless liner was found to be at a location where a tool rack had been removed in January 1990 using an electric cutting torch. The leak was attributed to mispositioning of the torch that had caused a perforation in the liner. The outer surface of the wall completely dried up within three days of the permanent repair. The outer surface had experienced some structural damage which was attributed to corrosion of rebar and that resulted in fracturing of the surrounding concrete. However, it was concluded that the wall still met design requirements.

- In 2002, Salem 1 identified leakage through an interior wall of the auxiliary building mechanical penetration room [8]. The leak, about 10 feet up a wall surface, was identified while following up low-level shoe contamination of personnel who had traversed the room. Other locations were found where radioactive water was leaking through interior walls or penetrations into both the Unit 1 auxiliary building and the Unit 1 fuel handling building (FHB). In 2003 tritium was found in ground water and attributed to leakage from the SFP. The leakage is attributed to blockage of the leakage collection system for the SFP liner, which has experienced leakage since early in life. The blockage was attributed to deposits of boric acid crystals and minerals, and to inadvertent introduction of sealant. Extensive work was done to evaluate the effects of borated water on reinforced concrete [9]. It was concluded that the structure still met design requirements.

- A 2003 Xcel Energy survey [4] identified that SFP leakage had also been experienced at Angra 1, Wolf Creek, Millstone 3, and Harris. None of the surveyed utilities identified the leakage as causing a structural or safety problem.

- In 2005, at Palo Verde Unit 1, weepage was observed from a wall that borders the spent fuel pool [10]. Daily checks of the leak chase tell-tale drains had been suspended due to overflow of the leak chase drain basin. The basin drain line was found to be obstructed with a Thaxton plug, believed to be present since initial construction. When the tell-tale drains were re-opened, a large amount of borated water was released from each drain. Samples of this water indicated boron concentration of about 3800 ppm. An evaluation was performed of the effects of the borated water on the reinforced concrete structure and it was concluded that it still met design requirements.

- In 2007 at Ginna, borated water was observed flowing from the leakage collection system [11]. The only possible source of leakage of borated water through this system is via a leak in the spent fuel pool. The welds in the SFP liner had been thoroughly inspected and repaired in 1973 (all spent fuel had been unloaded). Efforts were indicated as being underway in 2007 to locate and repair the leaks. No safety significance was attributed to the leakage.

3. <u>Corrosion of Steel Containment Vessels (SCVs) and Liners</u>
   The main events related to corrosion of SCVs and liners found by the search of OPEX are covered below.

- In 1986 corrosion from the OD was detected in the Oyster Creek containment in the region where the containment rests on a sand bed [12, 13, 14]. The corrosion was attributed to inadvertent wetting of the sand, coupled with lack of protective paint in the region with the corrosion. A variety of mitigating and remedial measures were taken to keep the area dry and to monitor for future corrosion.

- In 1989 corrosion from the OD of the steel containment vessel (SCV) at Catawba 1 was reported to have occurred as a result of boric acid containing standing water on the floor of the annulus [15]. The area was to be repaired and repainted. Similar corrosion was also reported as having occurred at McGuire Unit 2 in 1989 [15].

- In 1990 corrosion from the ID of the SCV at McGuire 1 was reported to have occurred as a result of moisture being retained in the area where a cork material serves as an expansion joint between the interior structural concrete and the SCV [16]. The coating on the SCV had failed in numerous locations allowing SCV base metal corrosion. The loss of metal was estimated to be as much as 0.045 inches at isolated areas. It was indicated that a comprehensive action plan would be developed that includes but is not limited to the following: a) prioritize areas to receive corrective action, b) develop an acceptance criteria for expansion joint material and coatings, and c) remove and replace failed coatings and expansion joint material as deemed necessary.

- In 1990 Obrigheim reported that corrosion had occurred on the ID of the SCV at the transition range of the SCV/concrete inside containment [17]. This transition range was provided with a thermal isolation inside the containment. The intent was that, in the case of a LOCA, this isolation would minimize thermal stresses. During an inspection the above-mentioned isolation was removed completely and corrosion attack under it, i.e. at the SCV, was detected. The corrosion was attributed to an insufficient sealing of the isolation. In this regard, complete sealing against humidity, especially during leak tests of the SCV, is not practical. Therefore humidity got through the isolation to the inside of the SCV and thus degraded it. The average depth of the corrosion was less than 1 mm (0.04 in.), and locally up to 6 mm (1/4 in.). The corrosion attack was located in the reinforced section of the shell, so it did not cause a significant weakening of the SCV. Additionally it was determined that impairment of the isolation effectiveness was not serious either.

- In 1997, the NRC alerted the industry to occurrences of corrosion at seven units of the liner plates of reinforced and pre-stressed concrete containments and to the detrimental effects that such corrosion could have on containment reliability and availability under design-basis and beyond-design-basis events [18]. It was noted that the inside surfaces of concrete containments are lined with thin metallic plates, generally between 1/4 and 3/8 inch thick. The most significant corrosion was at Brunswick Units 1 and 2 in 1993. The sealing material along the circumference at the junction of the drywell wall and the bottom floor had significantly degraded from water accumulation at the junction. The liner plate was found to have pitted significantly (as much as 50 percent of the original thickness) at various locations. Before the restart of the two Brunswick units, the joint was cleaned, repaired, and resealed.

- In 1998 at Cook 1 an inspection of the steel containment liner identified pitting resulting in the thickness of the steel containment liner being less than 0.250 inches [19]. The location of the pitting is at the bottom of the containment near where the vertical section of the liner joins the horizontal section and is in close proximity to the seal located between the concrete floor slab and the steel liner. The seal was removed and the area was cleaned and recoated. Analysis indicated that the containment continued to meet safety requirements.

- In 1999 at North Anna 2 a through wall hole was discovered in the containment liner [20]. The hole was at a location where corrosion had occurred from the OD. At this location a piece of wood had inadvertently been left in the concrete in contact with the liner. It was hypothesized that the presence of the wood prevented alkalinity from the concrete from protecting the shell in the local area where the corrosion occurred.

- In 1999 through wall corrosion was noted at several locations in the dry well liner at Brunswick 2 [21]. In two cases the corrosion was characterized as pitting that occurred from the inside at defects in the coating, and occurred despite the presence of a 99% nitrogen atmosphere during plant operation. In one case, a large thinned area had developed from the OD at a location where what appeared to be a work glove had been left in the concrete to which the liner was attached. The corroded areas were repaired and recoated.

- In 1999, Palisades found that the moisture seal at the juncture of the containment liner and basement floor slab had not been installed even though the original design called for such a seal [22]. Instead, there was fiber board material at the juncture which was wet with borated water. Based on industry experience and the detected level of corrosion, Palisades concluded that there was no safety significance to the situation. However, they indicated that a new moisture seal was being investigated.

- In 2004, NRC Information Notice 2004-09 noted the occurrence of several instances of corrosion of SCVs and containment liners in addition to those described above, as follows:

Year	Plant	Description
1996	Robinson	The vertical portion of the containment liner at Robinson is protected by insulation and a metal sheathing material. A portion of the insulation sheathing material was found to be loose and some of the caulking between the sheathing panels was deteriorated. Later it was determined that the protective coating on the containment liner was degraded. While some corrosion of the containment liner had occurred, the liner met design requirements. The coating and insulation panels were restored.
1998	Cook 1 and 2	Pitting of the containment liner was detected at the moisture barrier seal areas of both units. At Unit 1, there were more than 60 areas in which the thickness of the 3/8 inch steel liner plate had been reduced below the minimum design thickness value of 0.25 inch. The licensee subsequently installed a new liner-to-floor moisture barrier seal.
2001	Cook 2	A through-wall hole in the containment liner plate was discovered. Examination indicated corrosion of the liner from the embedded side of the liner. The cause of this corrosion was found to be a wire brush handle lodged in the concrete at the interface with the liner. An area about 12 inches square in the liner plate was replaced.
2001	Dresden 2	There was an area of missing coating and prime encircling the drywell shell adjacent to the basement floor. The area was 2-4 inches wide. In this area, the base metal was found to be corroded.
2002	Davis Besse	Corrosion occurred at the location where the SCV meets the floor. Subsequently a moisture barrier was installed.

2002	Sequoyah 2	Degraded coating and rusting at the floor of the annulus had occurred where water ponding was present as a result of a clogged drain.
2003	Surry 2	Degraded coatings and rust were detected on the containment liner at the junction of the metal liner and interior concrete floor. The moisture barrier at the junction between the metal liner plate and interior concrete floor was degraded.

- In 2006 at Beaver Valley1 inspection from the concrete side of the containment liner revealed the presence of pitting to about one half of the 3/8 in. thickness [23]. Access for the inspection occurred as a result of cutting of a window through the containment for SG and RVH replacement. It was concluded that the pitting had probably occurred during original construction. The heavily pitted areas were repaired.

- In 2006 at Turkey Point 4 a through wall hole developed in the containment building liner plate at the floor of the reactor cavity sump [24]. The hole developed when a sump pump support plate was moved, and a jet of water shot up through the hole about 30 in. high. The source of water was believed to be residue from high pressure water used for cutting a hole in the containment building as part of the RVH replacement during the previous refueling outage. The sump floor had not been inspected or coated since original construction. The hole was attributed to pitting corrosion from the outside. The liner was repaired and coated.

4. <u>Concrete Degradation</u>
   The main events related to concrete degradation found by the search of OPEX are covered below.

- In 1984 at San Onofre 1 cracking and spalling of concrete in the intake structure was detected [25]. The cracking and spalling were found to be due to chloride induced corrosion of rebar in the structure, even though the structure had been built to the ACI Code. The damaged areas were to be repaired, and the repairs were to be protected by the addition of cathodic protection.

- In 1992, degradation of the concrete in the SFP wall was detected at Indian Point and attributed to leakage through the liner [7]. The degradation was described as cracking and spalling of concrete caused by corrosion of rebar. The degradation was not significant enough to prevent the wall from continuing to meet its design requirements.

- In 2004 it was reported that Calvert Cliffs Units 1 and 2 were experiencing significant spalling of concrete floors and walls inside the intake structure building [26]. The spalling was attributed to chloride induced rebar corrosion. Repairs were made and use of cathodic protection was being considered.

- In 2008 at Brunswick it was reported that delamination and subsequent spalling has been caused by chloride-induced corrosion of rebar in areas where structures are exposed to salt through the air, bodies of water, or leaking equipment with sea water as the process fluid [27]. The chloride intrusion has occurred mainly due to historical equipment leaks in areas where the surrounding concrete surfaces were not coated. Areas affected include areas of the service water building, reactor buildings, turbine building, and intake structure. Galvanic or cathodic protection was reported as being added.

E. Summary of Results

1. Reactor and Refuel Cavity Leaks
   At least ten PWRs have reported experiencing reactor cavity leaks via flaws or penetrations in stainless steel liner plates. Most of the leaks are attributed to cracks at welds. None of the plants have concluded that the leakage is causing a structural or safety problem. Inspection methods to determine the source of the leaks have included monitoring leakage as the water level is varied, visual inspections, vacuum box, underwater vacuum box inspections, bubble checks using air pressure applied behind the liner plates, acoustic monitoring, and dye penetrant inspections. Repair methods have mainly involved use of weld patches, epoxy coatings, and InstaCote.

2. Spent Fuel Pool Leaks
   At least nine PWRs have reported experiencing SFP leaks in the stainless steel liner plates. Most of the leaks are attributed to cracks at welds. Most of the plants have concluded that the leakage has not caused a structural or safety problem. However, in one case, involving leakage of the Indian Point 2 SFP, the SFP concrete wall exhibited degradation that was attributed to corrosion of rebar caused by the leak [7]. The inspection and repair methods that have been used are essentially the same as discussed above for the reactor cavity leaks.

3. Corrosion of Steel Containment Vessels and Liners
   A significant number of cases of serious corrosion of SCVs and containment liners have occurred as plants have aged. Some of the more important causes appear to be the following:

- Corrosion that has occurred at and below the juncture of the steel wall or liner and the concrete floor. This has been aggravated in some cases by the absence of a moisture barrier, and/or the presence of a filler such as cork or fiber board that retains moisture at the juncture.

- Corrosion that has occurred from the concrete side at locations where foreign objects such as pieces of wood or cloth have prevented contact between the concrete and steel, thus interfering with maintenance of high alkalinity at the steel surface by the concrete. These foreign materials may also have served to keep the steel surface wetted.

- Corrosion that has occurred in areas where unexpected long term exposure to water has developed, such as due to clogging of drains, side effects of repair or modification activities, or degradation of seals.

4. Degradation of Concrete
   Reported cases of actual degradation of concrete have mostly been associated with exposure to marine environments; in these cases, the degradation has been attributed to chloride induced corrosion of rebar. However, in one case, degradation of the wall of a spent fuel pool was attributed to rebar corrosion caused by leakage of borated water. On the other hand, no cases of concrete degradation have been attributed to occasional wetting with borated water due to reactor cavity leaks.

VI. Nuclear Safety Significance

Evaluation of Technical Aspects

The preliminary conclusion of the Root Cause Evaluation (RCE) team is that borated water leakage from the refueling pool and transfer pit is not likely to have an adverse impact on the ability of the steel containment vessel and reinforced concrete structures in the reactor building to meet nuclear safety related design requirements, for reasons discussed below. The RCE team notes that a more detailed evaluation of this issue is being conducted by Dominion Engineering, Inc. (DEI), with completion expected by March 1, 2009.

Based on review of the USAR, especially Chapters 5 and 12, there are three aspects of nuclear safety that might be affected by leakage of borated water from the refuel pool and transfer pit, as follows:

- Pressure retaining capability of the steel containment vessel.
- Leakage prevention capability of the steel containment vessel.
- Seismic resistance of the Class I reinforced concrete structures in the lower regions inside the reactor building, i.e., below the top of the refuel pool.

The impacts of borated water leakage on the above three aspects of nuclear safety are discussed below.

Pressure Retaining Capability of the Steel Containment Vessel and Leakage Prevention Capability of the Steel Containment Vessel
These two safety aspects 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 or transfer pit. Considerations regarding the amount of corrosion that could have occurred are as follows.

- Corrosion will only be significant in areas that are wetted by the borated water since rates of corrosion of steel in atmospheric environments are very low, 0.6 mm (0.024 in.) in 36 years in an aggressive industrial atmosphere (Figure 2 on page 520 of [28]). Thus, attention will be paid only to wetted regions. In this regard, 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' and 755'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' 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 boric acid solutions range between 0.002 to 0.007 inches (Section 4.4.1 of the Boric Acid Corrosion Guidebook, Rev. 1 [29]). 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. However, the 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 x 0.007 in./year = 0.25 in.

- 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 [30]. Another test in 1998 of water collected on the floor of the RCDT room indicated a pH of 7.0 [30]. 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 at ambient temperatures are about 0.2 mm/year (0.008 in./year) (Figure 3 on Page 536 of [28]). However, the upper limit corrosion rate of 0.007 in./year cited above for borated water is considered more applicable; as noted above, using this upper limit indicates that the maximum depth of corrosion is expected to be less than 36 x 0.007 in. = 0.25 inches.

- 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 [31]. This test measured a corrosion rate after 8 years of test of 0.005 inches/year. Assuming that this rate applied for the full life of the plant would result in a maximum amount of thinning of 36 x 0.005 = 0.18 inches.

- The above estimates are considered to be highly conservative since 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 very much 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 small portion 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 [32 and 33] and again at Unit 2 in 2008 [34]. These inspections covered substantial areas, 5.5' x 5' and 6' x 6' respectively. No areas with wall thickness below the nominal value of 1.5 inches were detected. The area around the RHR pump suction lines was also inspected in 2008, and indicated that the wall thickness was always above the nominal 3.5 inch thickness of the sump B thickened insert plate. 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.

In summary with regard to the amount of corrosion that could have occurred, 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 steel containment vessel in the event of an accident. In addition, since the steel containment vessel is fully encased in grouted concrete on the outside as well as on the inside below elevation 711, loads imposed on the steel containment vessel in the thinned areas will be very low, such that thinning by 0.25 inches is not expected to impact the ability of the containment vessel to retain accident pressure. For example, using a remaining thickness of 1.25 inches, the tensile stress at the thinned area is given by PR/2t where R is the radius (630"), P is the accident pressure of 46 psi, and t is the remaining thickness, taken as 1.25 in. (page 298 in [35]). This indicates a tensile stress of 10,800 psi, which is far below the yield stress, let alone the tensile strength. While this calculation indicates that there is considerable margin, any detected thinning below the nominal wall thinning would need to be evaluated per Section XI of the ASME Code.

<u>Seismic Resistance of Class I Reinforced Concrete Structures</u>
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 [36]. As indicated in that document, the concrete used in the Class I structures at PINGP 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 [37] 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 [38] 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 [39, 40, 41, 42].

<u>Degradation of Concrete Due to Chemical Attack</u>
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 [38], 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 [43]). 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 suffer 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.

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 [40, 41, 42]. 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 that: (1) the attack starts at the concrete surface and proceeds inwards at a deceasing rate, as predicted for diffusion controlled processes; (2) the effect of the attack is to reduce the effective section of the concrete that carries load (the degraded material at the wetted surface carries no load); and (3) the results indicate a predicted depth of degradation of 1.3 inches for continuous exposure over a lifetime of 70 years.

The aggregate at Salem is all of igneous origin and contains no material that is susceptible to dissolution in boric acid (only the cement products in the concrete are soluble). However, the aggregate in the Prairie Island concrete has a small amount, about 5%, of carbonate type rocks (e.g., dolomite) which are susceptible to dissolution in acids. While this probably has no effect on the rate of attack by boric acid, it is considered prudent to increase the rate measured for the Salem concrete by a factor of two to account for the possible effects of the carbonate type aggregate. Using a rate of attack twice that measured for the Salem concrete, 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 inches.

The effects of the degradation of 0.31 inches 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 [44], and since grout is not relied upon for strength. For the walls of the refueling pool, the concrete cover was specified to be 5 inches [45]. 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 inches 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 transfer tube as shown on drawing NF-38488-1 [46]). It was not possible within the scope of this project to evaluate the effect of degradation of 0.31 inches of this concrete on its performance.

The above discussion covered attack from the concrete surface. 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.

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 tubes. Effects on the rebar and the composite behavior of the reinforced material are discussed below.

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 [38]), 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. These factors are discussed below.

- The chloride concentrations in the borated water observed in Sump B at Prairie Island is about 7 ppm or less [30], 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 continuously refreshed [42, 48]. 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 [49]). In this 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 [38] indicates that, for a medium strength steel 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 [38] 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. 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 corrosions of carbon steel in near neutral water is at most about 0.008 inches per year, as discussed earlier. 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 x 0.008 = 0.016 inches, which is not significant.

- 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 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 [50].

  – 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 [38] (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 0.5 inches. 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.

  – If this area has dried out between refueling outages, carbonation may have reached the rebar, but the time during which it was exposed to near neutral pH would have been of reduced duration, and the amount of corrosion would correspondingly be limited.

Summary of Effects of Borated Water on Reinforced Concrete

The above review indicates that, with one possible exception, neither degradation of the concrete nor corrosion of the rebar have 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 inches 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.

Structural Assessment of Internals Stands and RCC Change Fixture Anchor Studs

Evidence indicates the refueling cavity leakage in both units is the result of leakage through the welds that attach the internals stands and RCC change fixture anchor studs to their associated baseplates.

As shown on drawing NF-38488-2 the RCC change fixture is anchored by three baseplates. Each baseplate has eight 1 inch diameter x 2'-2" long "J" bolts set into the concrete below the transfer pit. The studs penetrate the baseplates and anchor the fixture directly to the concrete. As a result, the sealwelds between the anchors and the baseplates have no structural significance.

As shown on drawing NF-38488-2 the upper internals stand is anchored by four baseplates. Each baseplate has four 1-1/4 inch diameter studs set in a thru-hole in the baseplate attached and sealed with a 1/4" fillet weld on the underside of the baseplate. The lower internals stand is a similar construction using 1" diameter studs. The Unit 1 internals stands studs were last torqued in 1R25 under work order 00306965 to 260 ft-lb for the upper internals stand and 525 ft-lb for the lower internals stand. The Unit 2 internals stands were last torqued to the same values in 2R23 under work order 00088274 (film 4427-1827). These torque values indicate the fillet welds are largely intact.

Assuming a 1 inch diameter stud with a 1/4" fillet weld, the pull-out strength can be estimated as follows: The cross sectional area of the weld is the throat x the circumference or 0.75" (1/4" throat x 3" circumference = 0.75 sq-in.). The stud is stainless steel with a tensile strength of 75ksi (18-8 stainless steel from drawing XH-1001-1021 with tensile strength from ASME section VIII). Assuming the strength of the fillet weld is 1/2 the tensile strength of the weld material x the area of the weld, each stud would have an estimated pull-out strength of 28,000 lbs. (75ksi x 0.5 x 0.75 sq-in. = 28,125 lb).

By engineering judgment, the combined pull-out strength of the sixteen studs exceeds the weight of the internals stands by approximately a factor of 10. As a result, only a small fraction of the sixteen welds would be required to secure the stand in a seismic event with a significant downward vertical acceleration exceeding 1g. A downward acceleration of a design basis earthquake of 0.12g would not result in additional tensile stress on the anchors. Resistance to lateral acceleration is less dependent on the welds as the studs are set in thru-holes with the welds on the underside. Most of the lateral strength is provided by contact between the stud and the hole in the baseplate.

Lateral and vertical acceleration of internals set on the stands would not contribute to tensile stress on the studs as the internals are set on the stands and not fastened down. The internals are free to tip or to disengage from the stand in the event of a significant downward or lateral acceleration. As a result, the only significant force the internals can impose on the stands is compressive and lateral. In addition, by engineering judgment the 0.12g design basis earthquake acceleration is small compared to the acceleration that would be required to tip or disengage the internals from the stands. Last, it should be noted that neither the refueling cavity nor internals stands are listed in USAR table 12.2-1 as seismic qualified, indicating there is no nuclear safety significance associated with the internals stands or anchors

Based on the above, there is a high level of confidence the weld failures associated with the leakage of approximately 1 to 3 gallon per hour would not a have a significant adverse effect on the anchor studs ability to secure the internals stands in a seismic or other design basis accident event.

Revision 1 – Engineering Evaluation EC 14139 evaluated the effects of borated water leakage on the containment vessel, concrete and concrete reinforcing bar. This evaluation concluded that any degradation that had occurred was minor. Based upon the leakage identified during 1R26, Engineering Evaluation EC 15044 was completed to evaluate the impact of continued leakage on the EC 14139 conclusions. Engineering Evaluation EC 15044 determined that the conclusions of EC 14139 remained valid.

Evaluation of Safety Culture Impacts

Refueling cavity leakage was evaluated against the safety culture related cross cutting issues identified in NRC Inspection Manual Chapter 0305 "Operating Reactor Assessment Program" as listed in QF-0436 with the following issues identified.

- **HU – (H.1) Decision Making** – Although refueling cavity leakage had been occurring since the 1980's, and the site apparently understood the significance (as indicated by the AES evaluation, inspections, and grout removal), there is no clear evidence of a systematic decision process or management involvement in what steps should be taken to mitigate leakage. It appears mitigation was largely championed at the individual contributor level and was a function of what the individual thought might work based on past experience.
- **HU – (H.2) Resources** – No actions were taken to mitigate leakage in 1R21. Based on a memo written to InstaCote in August of 2000, a decision was made not to install the liner in 1R21 due to a lack of resources (resignation of one of the RV engineers) and the decision that installation would require a safety evaluation as opposed to a screening.
- **HU – (H.3) Work Control** – There is a direct correlation between refueling cavity leakage and failure to remove the anchor nuts for caulking for three outages since 1R23. In two previous outages leakage was attributed to the InstaCote vendor failure to adequately spray internals stands and RCC Change Fixture supports. In each case, the work procedure was not (or could not) be followed.
- **HU – (H.4) Work Practices** – The failures noted in work control may also have elements of worker practices, worker oversight, and vendor control.
- **PI&R – (P.1) Corrective Action Program** – The issue has a long history with numerous CAPs. A review of the CAP associated with the Davis-Besse SOER in 2003 shows refueling cavity leakage was recognized as the highest ranking site issue. The associated ACE was closed with no actions to mitigate leakage. (AR01175917 was initiated to review SOER 02-04 issues and final resolution.) A second CAP written in 2006 resulted in an ACE and eleven corrective actions. All actions were closed with no permanent mitigation indicating the corrective action process has not been effective in addressing the issue.
- **SCWE – (S.1) Environment For Raising Concerns** – A positive is noted in that the numerous CAPs indicate an unimpeded recognition of the issue at all levels of the organization. The CAPs and associated evaluations appear to provide an objective assessment of the issue including the potential for and consequences of degradation.
- **SCWE – (S.2) Preventing, Detecting, and Mitigating Perceptions of Retaliation** – A positive is noted in that individual contributors who have been involved with the issue have generally been encouraged to report the issue and take corrective action.

- **OTH – (O.13) Accountability** – The fact that leakage has been an issue for over twenty years suggests a past lack of organizational accountability to take the actions needed to permanently resolve the issue.

The remaining Safety Culture Components (Operating Experience, Self and Independent Assessments, Continuous learning environment, Organizational change management, Safety policies) were reviewed and determined to have not directly contributed to the deficiency.

VII. Reports to External Agencies & the NSPM Sites

The issue has periodically been reported to the NRC by inclusion in the Inservice Inspection summary reports. The Code of Federal Regulations 10CFR50.55a requires in paragraph (b)(2)(ix)(A) that "the licensee shall evaluate the acceptability of inaccessible areas when conditions exist in accessible areas that could indicate the presence of or result in degradation to such inaccessible areas. For each inaccessible area identified, the licensee shall provide the following in the ISI Summary Report as required by IWA-6000: A description of the type and estimated extent of degradation, and the conditions that led to the degradation; An evaluation of each area, and the result of the evaluation, and; A description of necessary corrective actions".

In June of 2008 it was recognized that the site had failed to include a discussion of the 2R24 refueling cavity leakage in the associated ISI summary report (AR01140617). A review of past summary reports of outages when leakage may have contacted the containment vessel indicated a failure to discuss leakage in the 2R22 and 2R24 summary reports, although leakage had been documented in previous reports as shown in the table below.

Leakage Documented in ISI Summary Reports				
Outage	**Approx. Date**	**Leakage**	**Cap #**	**Included in 90 Day Report?**
2R18	Apr-97	Unknown		
1R19	Oct-97	Unknown		
2R19	Oct-98	Leakage in Sump B and other locations. Initial AES evaluation.	00051045	Yes. Reported by amendment AR00122811
1R20	Apr-99	Leakage in Sump B and other locations.	00057041	Yes. Reported by amendment AR00122811
2R20	Apr-00	No Leakage. Installed strippable liner.		N/R
1R21	Jan-01	Unknown		
2R21	Feb-02	No Leakage. Installed strippable liner.		N/R
1R22	Nov-02	Leakage in Sump B. Strippable liner failed to stop leakage.	00284714	Yes. Included in original summary report.
2R22	Sep-03	Leakage in various locations.	00531162	Failed to include in report.
1R23	Sep-04	Leakage noted in regen room	00751496	N/R

2R23	May-05	No Leakage. Caulked penetrations		N/R
1R24	May-06	No Leakage. Caulked penetrations		N/R
2R24	Nov-06	Leakage in Sump B. Revised AES evaluation.	01064513	Failed to include in report.
1R25	Jan-08	No Leakage. Caulked penetrations		N/R
2R25	Sep-08	Leakage in Sump B	01155029	Yes. Included in original summary report.
1R26	*Oct-09*	*No indications of leakage reaching containment vessel – Only in Regen Room (revision 1)*	*01201071*	*N/R*

2R22 was in a previous closed ISI inspection interval. As a result, it was decided there was no value in amending the 2R22 report. The 2R24 summary report was amended to include a discussion of refuel cavity leakage. An evaluation was also included in the most recent 2R25 summary report.

In 2003 Prairie Island initiated a Nuclear Network survey to assess industry experience with refueling cavity leakage which included the following questions:

1. Does your plant have a current or historical problem with leakage through the refueling cavity steel liner?
2. Were you able to locate and/or repair the leaks, and if so, what methods were used to locate the leakage?
3. What was the source of the leakage?
4. If you have an ongoing problem with refueling cavity leakage, what kind of evaluation was done for the potential effect on the concrete and rebar?
5. Do you use any compensatory measures, such as a temporary, sprayed-on polymer coating, to prevent leakage?

Responses to the survey are summarized as follows:

Songs 2&3:
- Minor leakage.
- Visual inspections with no indications.
- No compensatory measures

Watts Bar:
- Leakage from refueling cavity liner and transfer canal.
- Did vacuum box, dye penetrant, and visual inspection of bottom 9' of transfer canal with no indications or repairs.

Wolf Creek:
- No leaks in refueling cavity. Minor leakage in spent fuel pool.

Ginna:

- Leakage noted from original construction.
- Vacuum box tested weld seams and found numerous small leaks due to weld porosity.
- Used anaerobic sealant on 475 feet of weld seam and reduced leakage by at least 50%.

Millstone 3: No known refueling cavity leakage.

Catawba: No known refueling cavity leakage.

Sizewell B: No known refueling cavity leakage.
Farley: No known refueling cavity leakage.

McGuire:

- 0.25 gph comes out under transfer canal between concrete and containment vessel.
- Have not located leak, but believe it is the liner plate near the RCC Change Fixture.
- Performed thickness UT of containment vessel with no indications.

Harris: No known refueling cavity leakage.

Point Beach:

- Refueling cavity leakage for "many years" on Unit 1.
- Source believed to be near transfer tube.

Indian Point:

- Stress Corrosion Cracking of liner plates results in significant leakage.
- Have used InstaCote, but not able to complete application in allotted time.
- Performed root cause evaluation and have evaluated boric acid effects on concrete similar to PINGP's evaluation.

Byron:

- Refueling cavity leakage estimated at 0.75 gpm.

Inclusion in the ISI summary report and the Prairie Island cavity leakage survey are the extent of known reports to external agencies.

VIII. Data Analysis

A. Information & Fact Sources

Interviews were conducted with the following groups:

- Engineers
- Laborers

The following data sources were used to obtain information in support of this root cause evaluation:

- Photographs
- Site Drawings
- Internal and External OE
- Work Orders
- Action Requests
- Laborer Notes
- Engineering Notes & Memos
- AES Evaluation

B. **Evaluation Methodology & Analysis Techniques**

The scope of this RCE includes five elements as follows:

- Determine the source(s) of leakage within the refueling cavities.
- Determine the leakage path(s) to the locations where leakage is indicated.
- Determine how long leakage has been present and if there were prior opportunities to identify leakage issues.
- Recommend action plan to correct (eliminate) leakage.
- Recommend action plan to address the effects of past leakage.

The first two elements are equipment related. Selected methodologies and techniques were:

- Personal statement
- Support/refute matrix
- Change Analysis
- Event and Casual Factor

The third element is organizational. Selected methodologies and techniques were:

- Personal statement

The last two elements are recommendations for future actions. The recommendations are the direct result of the root cause, contributing causes, and group consensus.

C. **Data Analysis Summary**

Determination of the sources(s) of the leakage within the refueling cavity:

During 2R24 refueling outage in December 2006, a troubleshooting plan was executed that included a determination that the source of leakage into Sump B was refueling cavity water, and could not be attributed to any other sources. A Support/Refute Matrix was prepared at that time and has been attached to this report as Appendix A. In summary, out of all the postulated sources, the chemistry of the water, especially the boron concentration and the concentration of radioactive iodine, was consistent only with refueling water. When taken together with the fact that the onset of leakage only occurs one or more days following refueling cavity flooding and stops a few days after draining, the origin of the water as the refueling cavity is confirmed positively. Thus, the ECCS systems, component cooling, steam and feedwater, and reactor coolant system are eliminated as possible sources of the leakage.

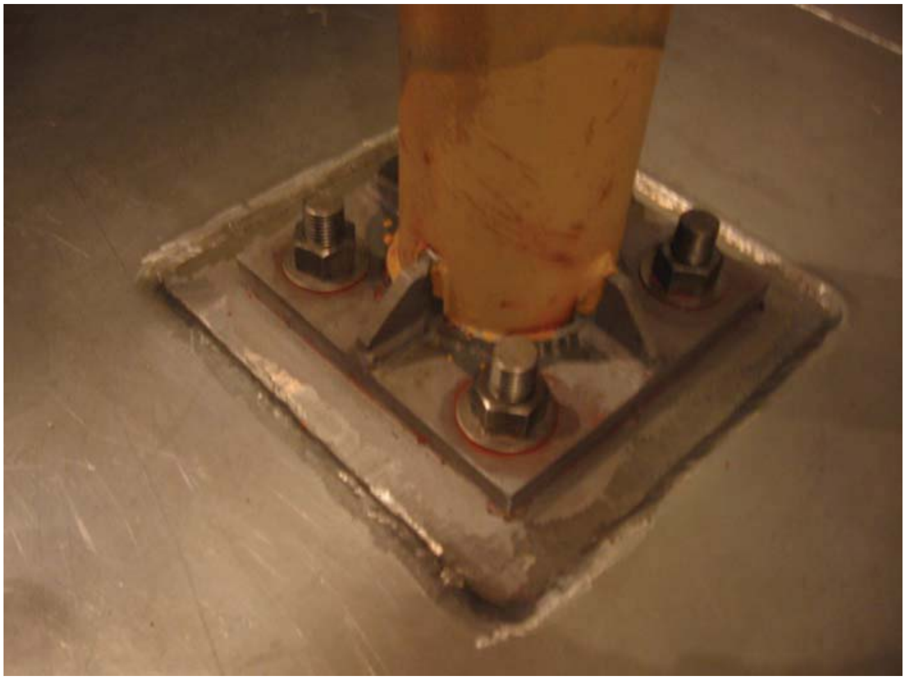
The primary leakage points within the refueling cavity are believed to be the anchor bolts of the upper and lower internals stands and the anchor bolts of the RCC Change Fixture. A Support/Refute Matrix was prepared and has been attached to this report as Appendix B along with a Change Analysis as Appendix C. Substantial efforts have been made since as early as 1988 to find and fix refueling cavity leaks, and these efforts continue to this day. While not being 100% successful, each effort yields information about where the leaks are not, so that by process of elimination, a short list can be developed of probable locations. In evaluating the large volume of historical data, it is important to differentiate between leakage into the reactor cavity (Sump C), and the leakage which manifests itself in Sump B, stress cracks in the bottom of the refueling cavity concrete (over the Regen Heat Exchanger Room), from the construction joint down in the Sump C thimble tube chase between concrete pours 4 and 5 (Figure 4), and from other stress cracks and construction joints in the walls common to the Steam Generator vaults and refueling cavity.

Leakage through the sandplug covers and the NIS detector well covers, or the seal for the vessel-to-cavity gap is normally associated with water in Sump C. Water from these sources flows into the NIS detector cooling and gap cooling ductwork and drains out in Sump C. Substantial leakage past NIS detector well covers is known to cause flow out of electrical conduits for the NIS instrumentation, and/or the sleeves for the detector positioning rods. Major leakage through the sandplug covers can cause water to come out the RCS piping sleeves that pass through the reactor bioshield. The sealing mechanism for the sandplug covers has not been reliable. As originally designed, the sandplug covers used no gasket, but rather a liberal application of RTV silicone sealant. The NIS Detector covers use an O-Ring, which is reliable but is subject to installation errors, in that it can be pinched if not seated properly in the groove. The vessel-to-cavity gap seal was originally an inflatable rubber boot that frequently leaked. The boot was replaced around 1999 with the Preferred Engineering segmented seal, which has proven less sensitive to installation technique, and has been virtually free of leakage. Limited leakage from the sandplug covers, NIS covers, and the cavity seal have historically been considered normal and are accepted as a nuisance since they are channeled and collected. There has been no credible path identified whereby leakage from these sources can migrate to the other locations where leakage has been observed such as Regen Heat Exchanger Room or Sump B. Once fluid has leaked past these mechanical joints it runs down the walls of Sump C, which is lined with carbon steel plate down to elevation 719’2-3/8” and stainless plate on down to 697’6” (see Dwg. NF-38488-4, -6). This liner is seal welded at each joint, so there is little opportunity for leakage into the space around and under the reactor vessel to migrate anywhere other than essentially straight down into the bottom of Sump C by gravity.

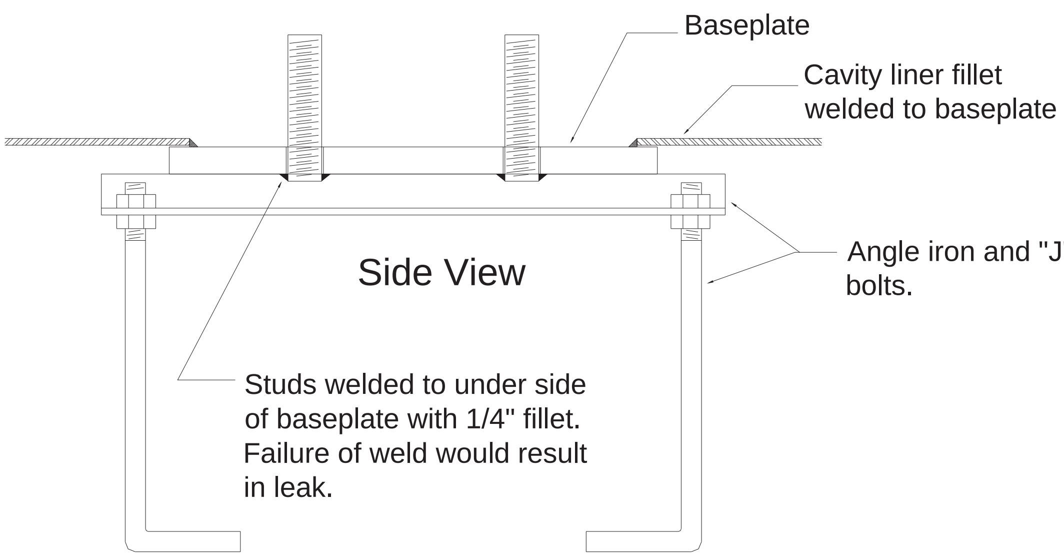
If there were postulated flaws in the Sump C liner, it is conceivable that capillary action could wick water through a flaw and behind the liner, where it could then follow a tortuous path through concrete joints to emerge below. However, without a driving pressure head such migration of water by capillary action would be expected to be insignificant, if it is credible at all. In any event, leakage through the mechanical joints in the upper cavity (sandplug covers, NIS covers, segmented seal) cannot be the source of the volumes and rates of leakage that are observed in the basement, and at most could contribute only a small fraction of what is observed.

All evidence suggests that the leakage which is seen coming out of the grout in Sump B, beneath the refueling cavity in the Regen Heat Exchanger Room and elsewhere, originates from flaws in the refueling cavity liner. Due to the efforts over the last several years to mitigate the leakage, the likely leak locations have been narrowed down considerably. In 1998 and 1999, extensive examinations were conducted of the seam welds between the liner plates and the embedment strips. NDE consisted of dye penetrant examinations and vacuum box testing of the accessible welds, and these exams ruled out the seam welds as the source of the leakage. The next step that was taken was to apply the polyurea strippable spray-on coating (brand name InstaCote) onto the cavity liner to attempt to mitigate the leaks. The first application was in the Unit 2 upper cavity and fuel transfer pit, including the bottom 6 feet of the vertical walls. The lower cavity was not coated. It was successful in stopping the leakage that outage. InstaCote was applied a second time during the following Unit 2 outage coating the lower cavity and transfer pit (the upper cavity was not coated). Again, the result was no leakage into Sump B or the Regen HX Room. Taken in combination, these results strongly indicate the leak is in the transfer pit for Unit 2. Based on this information, and following two consecutive failures of InstaCote application to effectively stop the leakage (attributed to insufficient coverage of the key locations), engineering made a decision to change methods and instead use a sealant (caulk) around only the suspect locations. This decision reflected the understanding that the liner plates and seam welds had already been shown to be sound, and therefore were not benefited by the application of the cavity coating. Over the last several outages on each unit, caulking has been applied to the anchor bolts of the upper and lower internals storage stands in the lower cavity and the RCC change fixture in the transfer pit. These locations were chosen as the leakage points because, unlike most of the embedment plates in the refueling cavity, the studs in these embedment plates are set into through-holes in the plates, creating a natural leak path along the threads (see following photographs and figures).

Revision 1 – Continued leakage in 1R26 indicates leakage of the Guide Tube supports.

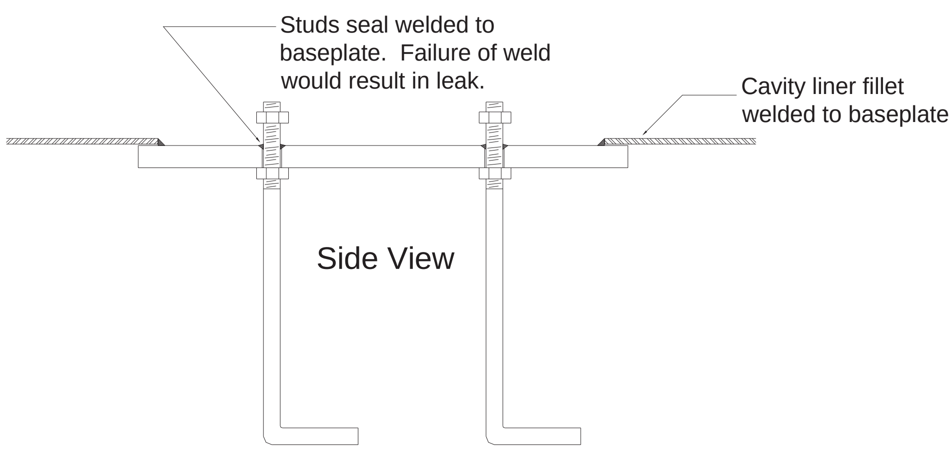


(Typical Internals Stand Support)

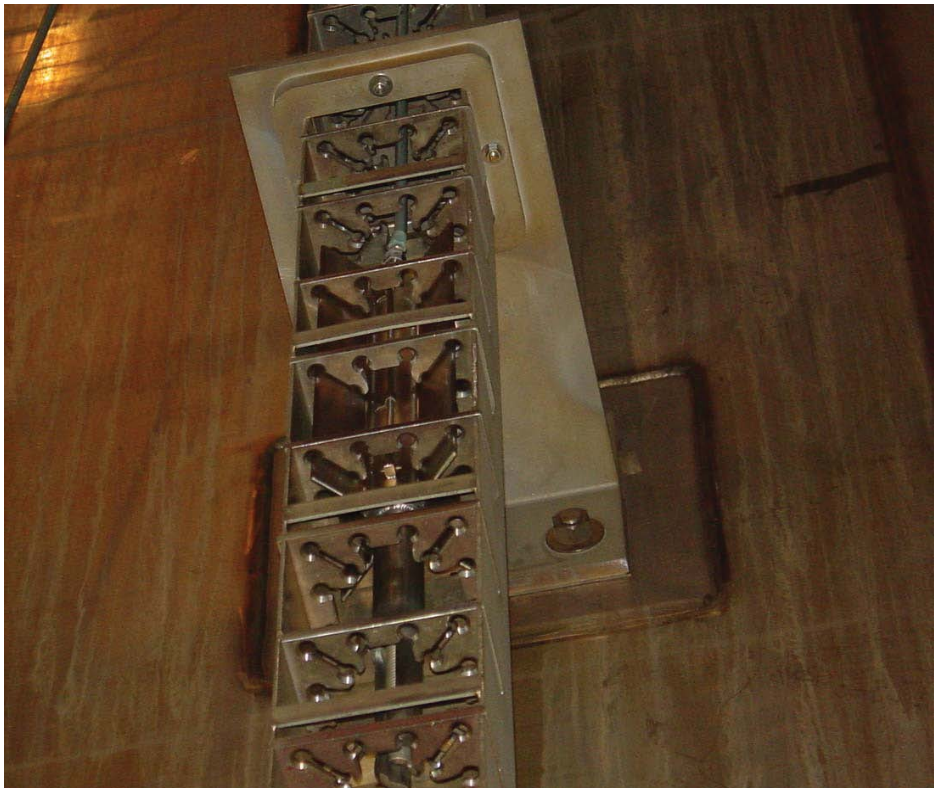


General Arrangement of Internals Stands Supports

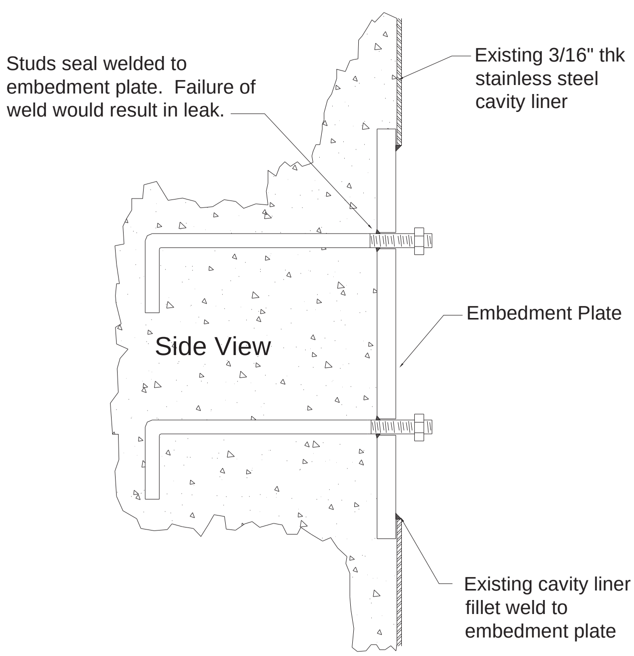
(Typical RCC Change Fixture Support)



General Arrangement of Change Fixture Supports



(Typical Guide Tube Support) Revision 1



General Arrangement of Guide Tube Supports *Revision 1*

The design drawings (NF-38488-2, XH-1-1260, XH-1001-94) specify that the studs be seal-welded to the embedment plates, on the underside for the internals storage stands, and on top (then ground flush) for the RCC change fixture. Due to inaccessibility the integrity of these seal welds has not been able to be verified to date, and is therefore suspect. Potential inservice failure mechanisms include chloride stress corrosion cracking of the stainless steel welds or fatigue cracking. Construction defects that could result in leakage include weld porosity or lack of fusion. Because these welds are generally inaccessible there has been no way to inspect them directly. In spite of these limitations, the results of the caulking over the last several outages on each unit have effectively confirmed the earlier suspicions of the leak locations. For two Unit 1 outages and one Unit 2 outage, caulking of the internals stands and RCC change fixture anchors alone has stopped all leakage not attributed to the NIS detectors or sandplug covers. In the same timeframe there have been several failures of the caulking to effectively stop cavity leakage. Each of these failures can be attributed to the inability (or failure) to do a complete job in removing and caulking under the nuts that anchor the internals stands and RCC change fixture. Reasons for inadequate caulking have included sequencing problems, where removal of the transfer tube blind flange has introduced standing water into the transfer pit, as well as access limitations to some of the hold-down studs, and fear of galling the anchors when attempting to remove the nuts. The transfer pit is a high radiation and often a high contamination area, making the caulking application challenging from several aspects, so it is understandable that inconsistent results occurred. However, the successful applications alone confirm the anchor studs as the most likely source of the leakage into the containment basement.

Determination of the leakage path(s) to the location where leakage is indicated:

The postulated leak paths are many and are based on a review of the methods and sequences used to construct the containment concrete structures, as well as the refueling cavity liner plates and embedments. The path required for the leakage to emerge from the basement concrete is fairly tortuous.

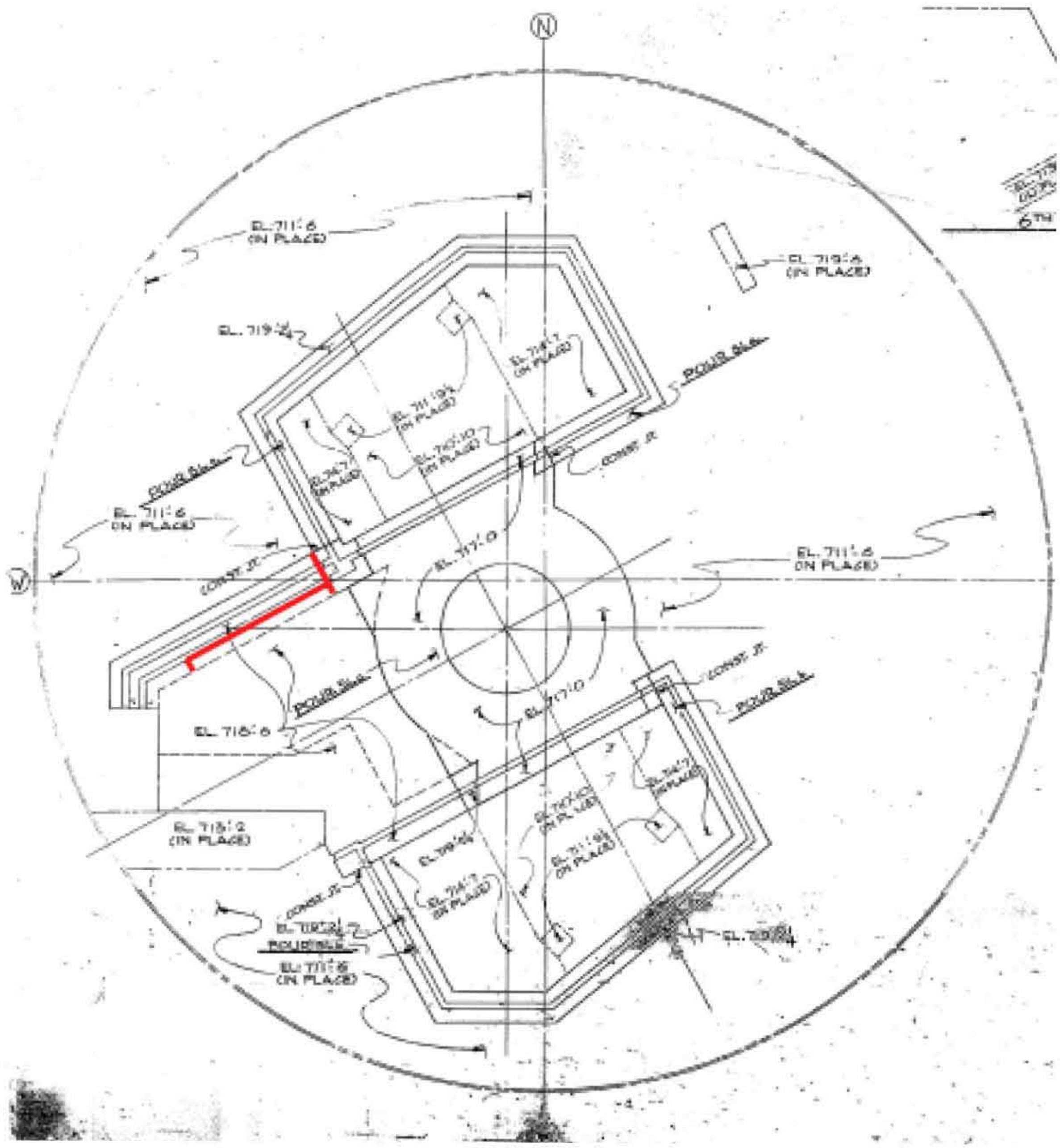
The path for leakage that emerges in the ceiling of the Regen HX Room is the simplest. It is postulated that leakage through the internals storage stand baseplates fills the space beneath the liner until it finds an entrance to a network of stress cracks in the continuous slab which comprises the floor of the refueling cavity. It then flows down through the cracks by gravity and emerges in the ceiling of the Regen Heat Exchanger Room. Total slab thickness that the leakage has to navigate is 3’8” (Figure 1).

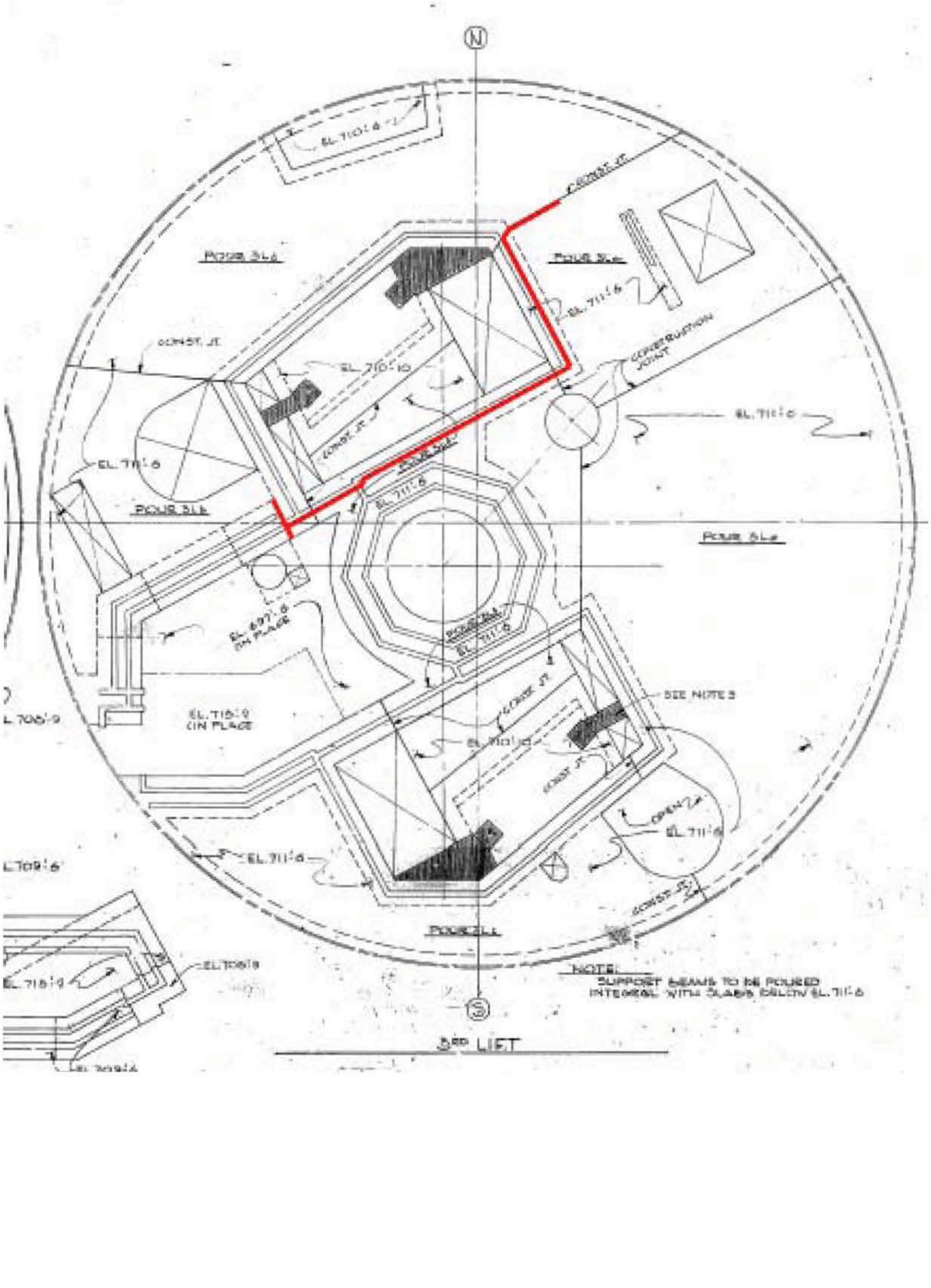
It is also theorized that this same leakage, once under the liner plate, can migrate between the liner and the concrete surface down under the liner of the transfer pit. This leak path requires that the flow find a way under the embedded angles that are set into the concrete to which the liner plate is welded. For water to flow from

under the liner of the lower cavity to under the liner of the transfer pit it would have to traverse under the embedded angles at the top edge of the transfer pit and the bottom corner. From there, it can go to the same places as leakage originating in the transfer pit itself.
The transfer pit has long been suspected as the origin of much of the leakage, and as a result of investigative efforts, the flaws in the pool membrane were concluded to be under the RCC change fixture baseplates. Once water has circumvented the embedment plates, it is theorized to flow between the liner plate and the concrete surface, and then under the embedded angle that forms the corner between the floor and the wall behind the transfer tube. Immediately behind the embedded angle is the concrete construction joint between "2nd Lift" (the floor slab of the transfer pit) and the "7th Lift" (the wall behind the fuel transfer tube) (Ref. NF-38443). The water can either flow through this joint, or fill up behind the wall liner plate, under the pressure head of the pool, and past the embedded angle which defines the inner edge of the sleeve in the concrete through which the fuel transfer tube passes.

Once the leakage makes it through either of these two paths, it will encounter the inner surface of the containment vessel shell, after which it can flow by gravity down between the concrete of the "10th pour", "8th pour", "5th pour", "4th pour", and "2nd pour" and the containment shell, in whatever gaps exist where the concrete is not intimately bonded to the steel, possibly all the way down until it reaches the low point of the inside surface of the ellipsoidal bottom head. As the water accumulates after the onset of leakage, it will progressively fill up the void spaces between the basement concrete and containment shell until the level rises to an elevation where the water can escape. As the level rises, construction joints in the concrete such as between the 4th and 5th pour fill with water, and in the case of Unit 2, this water comes out in the corner of the Sump C thimble chase. If the level climbs high enough, it is known to escape around the RHR suction lines in Sump B of both units and bleed through the grout. When the level climbs higher, the water has been known to leak out of construction joints between adjacent segments of the "8th pour", the sloping walls of the basement, and at floor level. Refer to the figures at the end of this section.

Other locations from which leakage is observed to emerge from concrete includes the El. 711'6" floor slab on the "backside" of the refueling cavity towards the stairwell, which is quite remote from the refueling pool. The path for leakage to get into this floor slab is somewhat tortuous, and demonstrates how mobile the refueling water can be once it gets into the network of joints and cracks in the concrete. See the figures that follow this section. The floor of the lower refueling cavity is at El. 718'8", this corresponds with the top of this pour and a construction joint in the refueling cavity walls. Once water has accumulated under the liner of the lower cavity, it need only flow under one of the corner embedments, an angle iron, before it would encounter the construction joint at 718'8". There are full-length keyways set into the top of each wall at each construction joint that would have the tendency to channel water lengthwise down a joint by forming a sort of drain trough. Water has not been observed emerging from the refueling cavity wall construction joints, as would be expected since this is the shortest path for leakage to take. It is believed this may be due to the effect of the full-length keys. The effect of the keyways in this case appears to be to channel the leakage towards the 12 RCP vault until it encounters the vertical construction joint where the refueling cavity slab pour meets the RCP vault wall pour, “5La”. The top of this pour is at 719’2-1/4”, higher than the floor of the lower cavity, so gravity would encourage the leakage to turn down through the vertical joint. The vertical joint ends at 711’6”, so the flow is forced to turn again. The construction joint at El 711’6”, the mezzanine level, is continuous from the refueling cavity, through the reactor bioshield concrete, and down the steam generator vault wall. Once flow reaches the northeastern limits of the steam generator vault wall, the path is somewhat unclear, because there were no photos found of the crack through which this leakage emerges in the basement. However, drawings do show that there is a construction joint between adjacent pours of the floor slab at El 711’6”. It is known that water is not seen on the surface of the floor at this location of the mezzanine level, only emerging from the underside of the slab. Leakage must flow through a path within the slab thickness itself, such as the joint between pours “3La” and “3Ld” before dripping out of a fissure. Note that this path can also explain sightings of leakage from the outside of 12 vault walls near 12 accumulator and within 12 vault on the floor at El. 710’. A similar path exists to explain leakage into 22 vault, which has been reported on Unit 2.


N
W
EL. 711'-6
(IN PLACE)
EL. 719'-6
(IN PLACE)
POUR SLA.
CONST. JT.
EL. 717'-0
EL. 718'-6
EL. 713'-2
(IN PLACE)


N
CONST. JT.
CONSTRUCTION JOINT
EL. 711'-6
EL. 710'-10
SEE NOTE 3
EL. 715'-0 (IN PLACE)
NOTE:
SUPPORT BEAMS TO BE POURED INTEGRAL WITH SLABS BELOW EL. 711'-6
S
3RD LIFT

Determine how long this leakage has been present and if prior opportunities were present to identify the leakage issues:

Evidence of formal response to leakage goes back to at least 1988 based on a Unit 1 work order (8807239) to "Find leaking cavity liner welds and repair". Another Unit 1 work order was written in 1989 (8902434) to fabricate vacuum boxes to test the reactor cavity welds for leakage.

The leakage became a significant issue during the 1998 Unit 2 refueling outage (CAP00051045) when water was found entering sump B from around the RHR suction pipe sleeve. This leakage resulted in the Automated Engineering Services (AES) evaluation of potential degradation, removal of the grout in sump B, and vacuum box testing of the refueling cavity liner.

Similar leakage was experienced during the 1999 Unit 1 refueling outage (CAP00057041) when water was found leaking into sump B, from the ceiling above the regen heat exchangers, and other locations. The refueling cavity was inspected using vacuum box and dye penetrant (WO990156). The grout was removed in the Unit 1 Sump B in 2002.

In response to the Davis-Besse SOER 02-4 the site identified refueling cavity leakage as the highest ranking site issue. An ACE was written, but there were no corresponding corrective actions included in the ACE.

The issue was most recently raised with the Unit 2 leakage in 2006 and fall 2008, and has since become a license renewal issue.

From approximately 1998 through 2008 actions to mitigate leakage have included weld repair of pin-hole leaks of the refueling cavity seams, installation of a strippable liner and caulking of cavity penetrations. Potential degradation has been assessed by evaluation, and monitored by grout removal in Sump B and ultrasonic thickness measurement of the containment vessel from the annulus.

Site documentation indicates leakage from approximately 1988 through 2008 with numerous Action Requests and several attempts to mitigate leakage with intermittent success. Procurement of the AES evaluation and the ranking of refueling cavity leakage as a top site issue in response to the Davis-Besse SOER strongly suggest the site recognized both the significance of the leakage and the potential for equipment degradation. There have clearly been numerous prior opportunities to identify the leakage issues.

Recommendation for action plan to correct (eliminate) refueling cavity leakage:

There are two basic components to eliminating leakage. The first is leak detection (locating the leakage points) and the second is leak repair.

There are several methods that could potentially be used to locate leaks (provided here for completeness) including:

- Pressurize the backside of the liner and snoop (soap bubble check).
- Pressurize the back side of the liner with a traceable gas.
- Vacuum box seams.
- Vacuum box with specialized boxes to accommodate penetrations.
- Dye Penetrant.
- Controlled filling or draining to determine elevation of leaks.
- Acoustic emissions (similar to listening for steam leaks).

There are several methods that could potentially be used to seal leaks including:

- Spray on coating (InstaCote) or other sealant.
- Caulking
- Seal welding
- Encapsulation

Because leakage is often less than a gallon per hour it is believed mitigation will require an essentially bubble tight refueling cavity liner with all pin-hole leaks permanently repaired. The recommended repair plan for PINGP includes the following steps:

1. Unbolt and set aside all mechanically fastened fixtures (RCC Change Fixture, internals stands, and guide tube supports).
2. Vacuum box penetrations and embedment plates to locate existing leaks for record purposes.
3. Weld repair all detected leaks and preemptively seal weld all other penetrations (including non-leaking penetrations). Vacuum box all penetrations after welding is complete.
4. Vacuum box, and/or PT weld seams and weld repair as needed to ensure absence of SCC.
5. Pressure test or PT Transfer tube bellows attachment welds and weld repair as needed.

It is recognized that that some flexibility should be allowed as improvements to the repair methodology will likely be identified as the repair is designed and planned.

Recommendation for action plan to address the effects of past refueling cavity leakage:

The action plan to address the effects of past leakage should consist of analytical evaluation to assess the potential for current or future degradation of the containment vessel and structures, and continued monitoring for degradation. A second independent evaluation of the effects of refueling cavity leakage on the containment vessel, concrete and reinforcing bar is in progress. If needed (the evaluation is inconclusive or not well supported), the evaluation should be supplemented by independent tests to better assess the degradation rate of steel and concrete using both submersion and wet/dry cycles. If the evaluation indicates a potential for significant degradation, the site should further research potential NDE techniques to examine large areas of the containment vessel wall such as guided wave UT and/or concrete sounding to better confirm no significant degradation of the concrete structures.

The concrete should be removed in sump B and one other location where practical (such as sump C) to facilitate visual and UT exam of the containment vessel.

D. **Failure Mode Summary**

There is a high level of confidence that the leakage emanates from the penetrations in the lower refueling cavity and transfer pit. Potential leakage points include the upper internals stand, lower internals stand, and RCC Change Fixture supports. Construction drawings indicate the penetrations were seal welded to the associated embedment plates. As a result, it is believed these welds either failed or were never leak tight. Potential inservice failure mechanisms include chloride stress corrosion cracking of the stainless steel welds or fatigue cracking. Construction defects that could result in leakage include weld porosity or lack of fusion. Because these welds are generally inaccessible there has been no way to inspect them directly.

Figure 1.

Shows the location of Sump B on the North side of containment and Regen Heat Exchangers directly below the lower cavity.

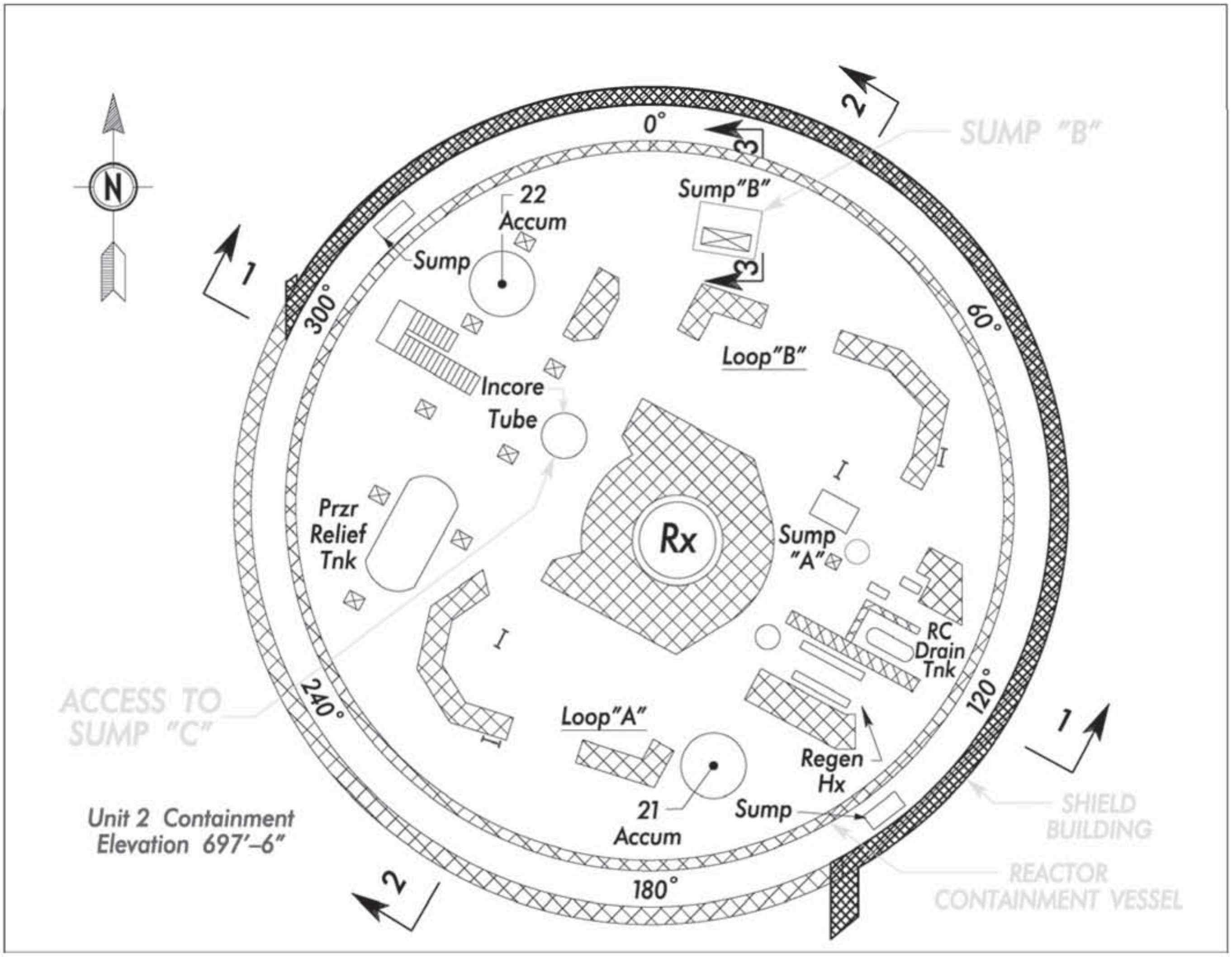


Figure 2.

Shows the location of the upper and lower internals stands, and transfer pit.

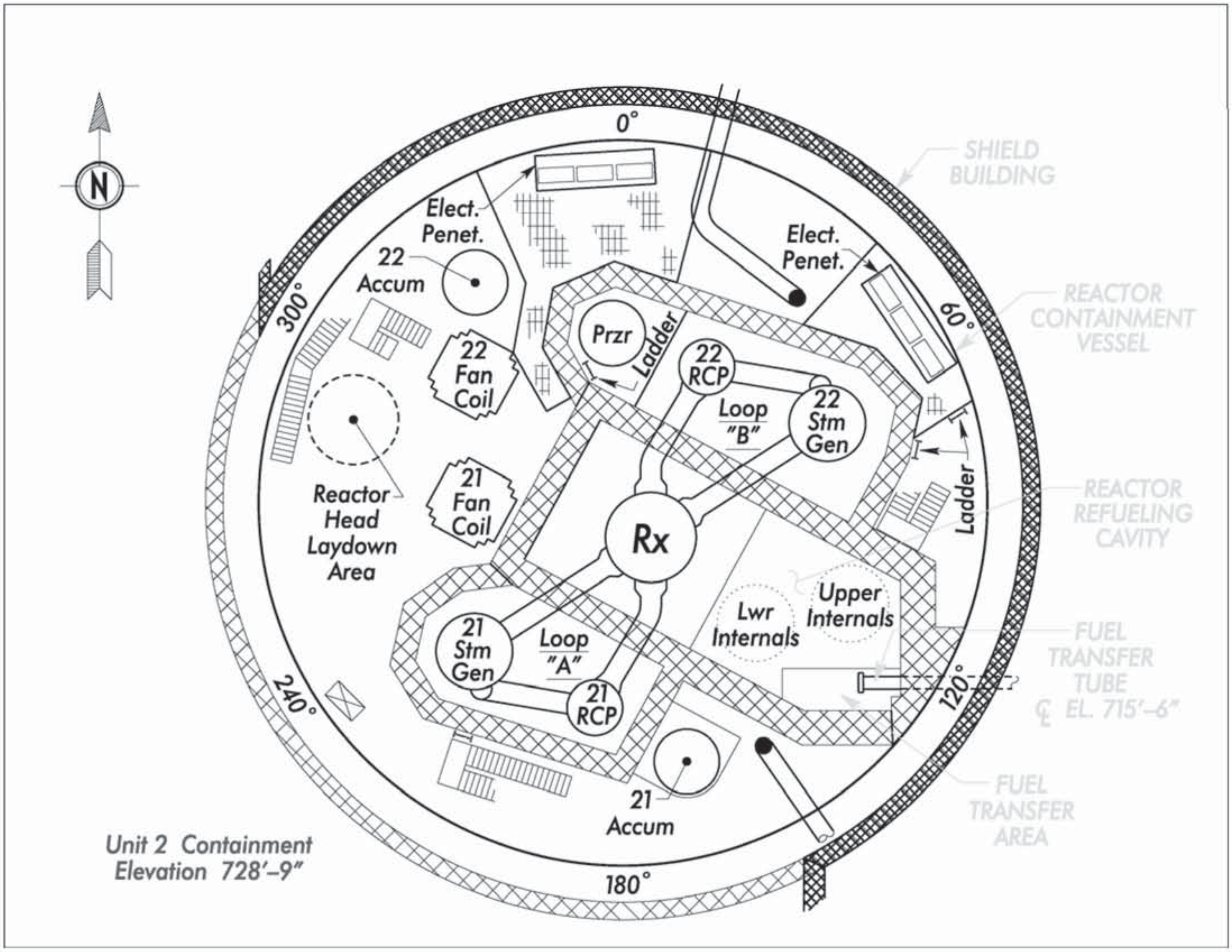


Figure 3.

Shows the horizontal leak path from the transfer pit to Sump B.

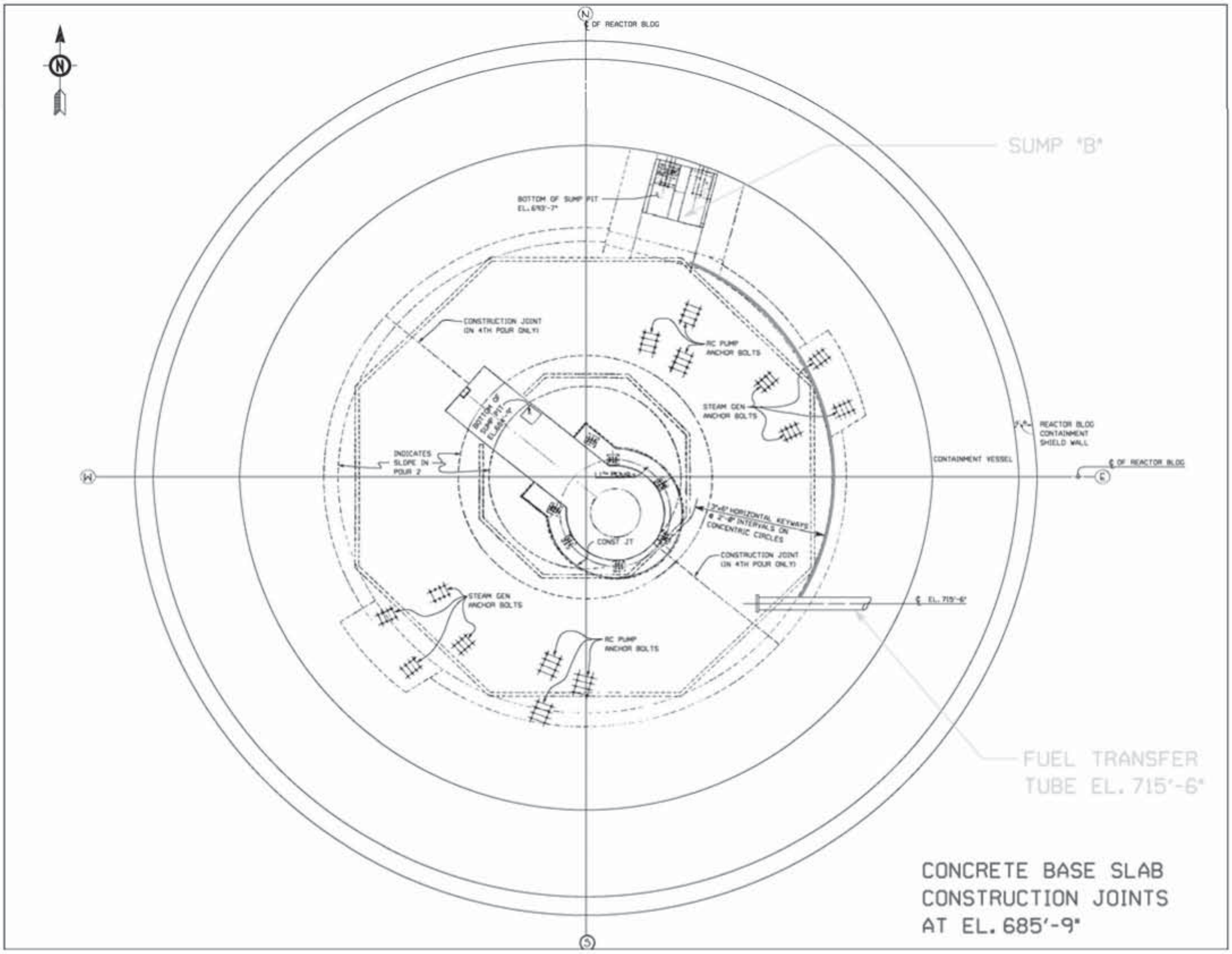


Figure 4.

Shows the vertical leak path with potential leakage between the concrete and containment vessel to the low point of the bottom head.

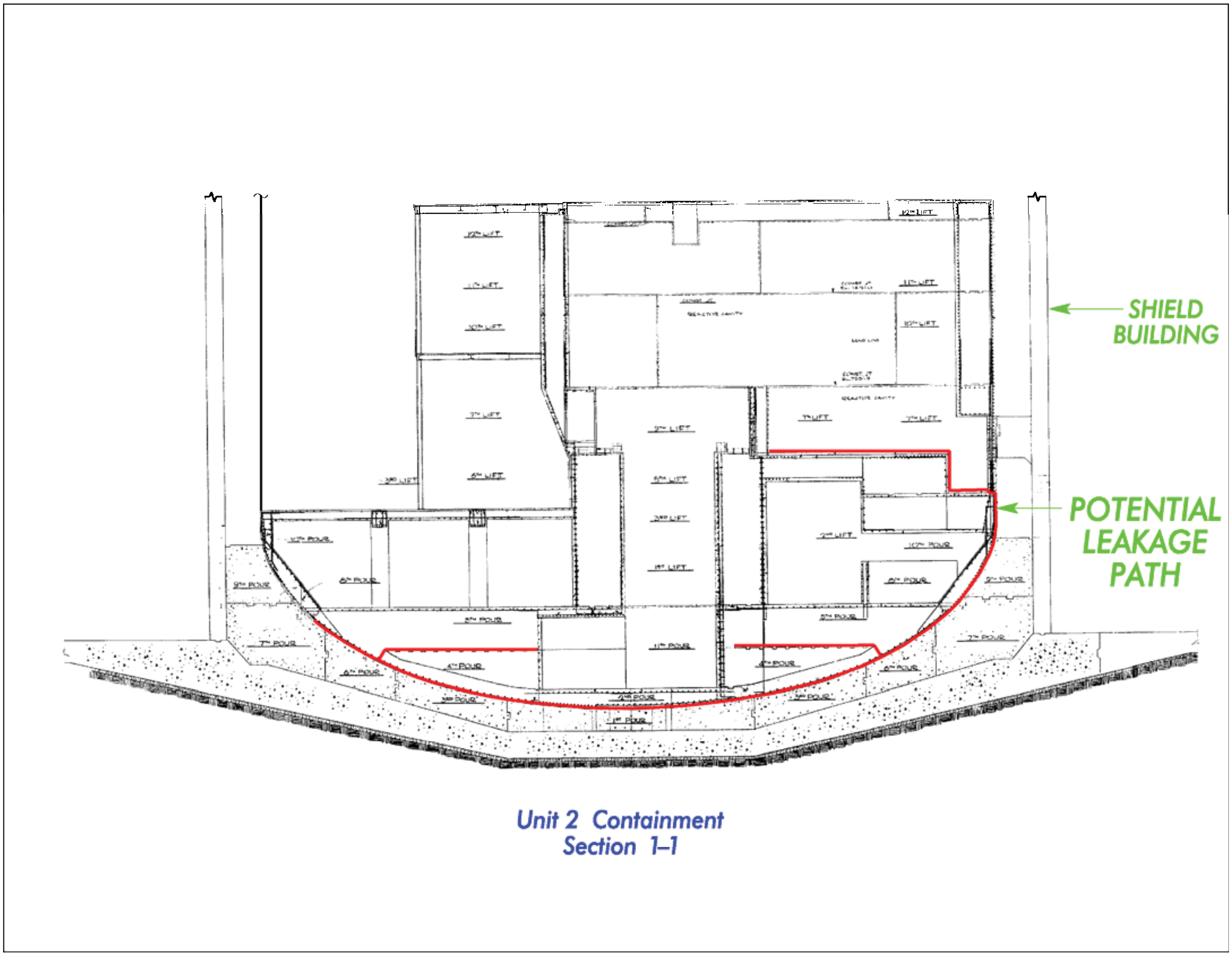
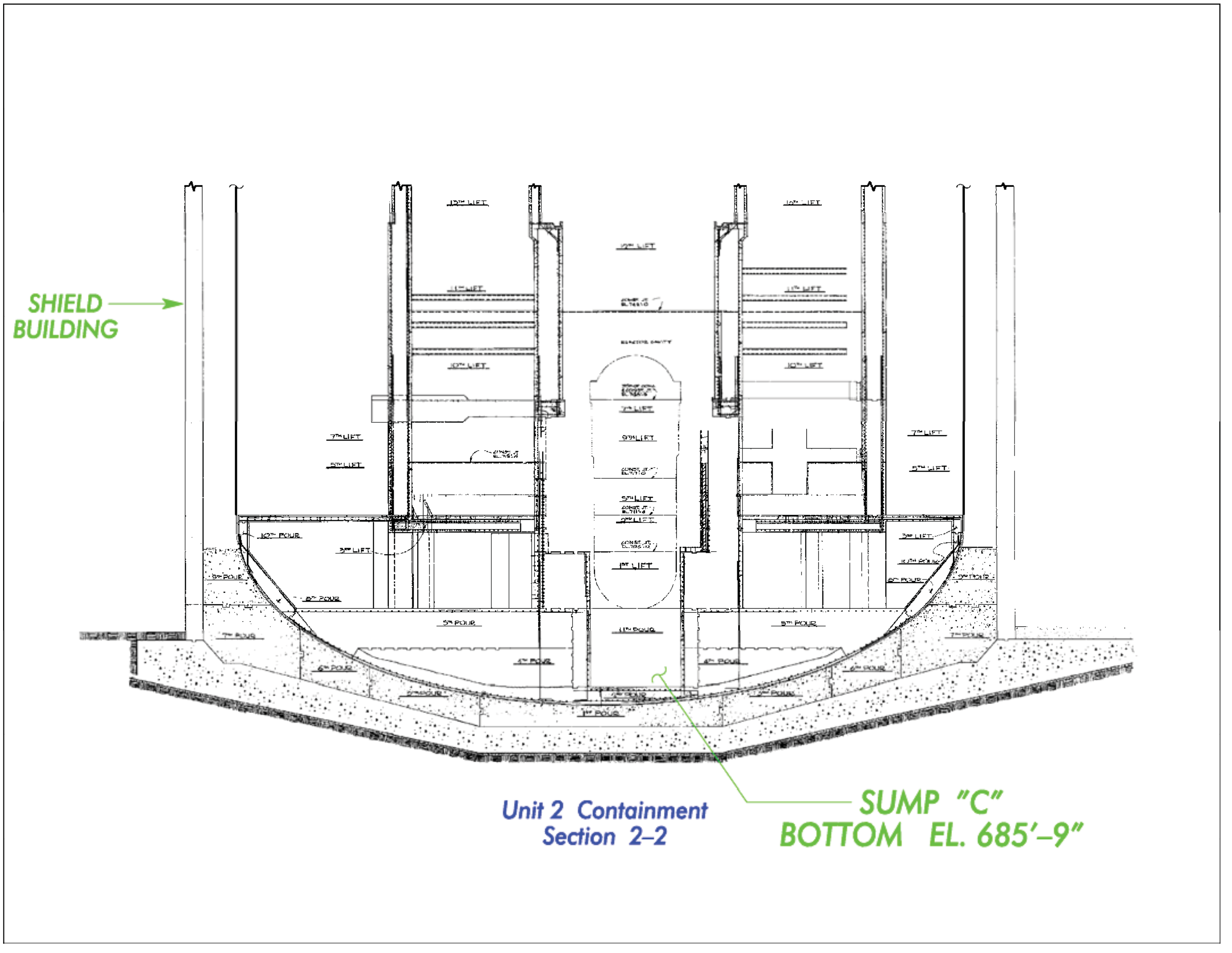


Figure 5.

Shows the location of Sump C around and under the reactor vessel.



IX. Root Cause and Contributing Causes

Root Cause:

Leakage through the anchor bolts of the internals stands and RCC Change Fixture.

The evidence shows with a high level of confidence leakage emanates from the anchor bolts of the internals stands and RCC Change fixture based on the following:

- Extensive vacuum box testing of cavity weld seams indicated no significant leaks
- The seal welds of the anchors have never been inspected.
- The seal welds of the anchors would be more prone to cracking than seam welds due to high residual stress, mechanical stress and potential contact with chlorides
- Leakage has on three occasions been mitigated by removing the anchor nuts and caulking
- There is a direct correlation between failure to remove the anchor nuts and leakage.

Contributing Causes: None

Other Factors:

On three occasions leakage can be correlated to failure to remove the nuts when caulking the anchor bolts.

On two occasions the InstaCote liner failed to mitigate leakage as a result of inadequate thickness on the baseplates and anchors.

Failure to remove the nuts and inadequate InstaCote application resulted in failure to mitigate the leakage. However, these factors are not considered contributing causes as they did not contribute to or cause leakage.

X. Corrective Actions

The search of available OE did not identify any industry events with the same root cause (leakage attributed to failure of the seal welds around anchor bolts or other cavity liner penetrations). As a result, none of the corrective actions are based on OE.

It was further determined that previous actions to mitigate leakage at Prairie Island and other sites, such as InstaCote and caulking, only addressed the symptoms of leakage and not the cause. In addition, these mitigation methods were only intermittently successful. As a result, these actions were not considered for corrective actions. The human performance, procedure adherence and vendor oversight aspects of these failures to mitigate leakage are already addressed by three recent RCE's: 1141755 NRC Cross Cutting Issues, 1165133 Human Performance and Cross Cutting NRC Violations, and 1166830 Inadequate CAP Resolution of Significant Issues. Expanding on these issues in this RCE would be redundant.

Corrective Actions to Prevent Recurrence (CAPRs)

CAPR#.1 Develop and implement repairs that permanently eliminate leakage through the anchor bolt penetrations of the Unit 1 refueling pool. Action to be assigned to NSSS Engineering with a due date of 10/16/2009.

CAPR#.2 Develop and implement repairs that permanently eliminate leakage through the anchor bolt penetrations of the Unit 2 refueling pool. Action to be assigned to NSSS Engineering with a due date 05/22/2010.

It is recommended the repair plan for the above actions include the following steps:

1. Unbolt and set aside all mechanically fastened fixtures (RCC Change Fixture, internals stands, and guide tube supports).
2. Vacuum Box penetrations and embedment plates to locate existing leaks. Weld repair and vacuum box completed welds
3. Preemptively seal weld and vacuum box all penetrations.
4. Vacuum Box, and/or PT weld seams and repair as needed to ensure no leakage due to stress corrosion cracking.
5. Pressure test or PT transfer tube bellows attachment welds and weld repair as needed.

Alternate approaches can also be considered provided the repair permanently and completely mitigates future leakage.

Compensatory actions are not required as the site has indicated to the NRC that repairs will be implemented in upcoming outages 1R26 and 2R26.

Other Corrective Actions

CA#.1 Perform an evaluation to assess potential degradation of the containment vessel, containment building concrete, and reinforcing steel to date (in progress). Evaluation should bound potential thinning or reduction in strength of key components. Action to be assigned to Program Engineering with a due date of 04/30/2009.

CA#.2 Review the evaluation from CA#.1 and determine if the site should sponsor additional testing to more accurately determine degradation rates. Also determine if the site should further research potential NDE techniques to examine large areas of the containment vessel wall such as guided wave UT and/or concrete sounding to better confirm no significant degradation of the concrete structures. Action to be assigned to Program Engineering with a due date of 07/28/2009.

CA#.3 Perform a margin assessments of the containment vessel and containment structures to determine the minimum wall requirements of potentially corroded areas of the vessel and allowable concrete degradation including the area around the transfer tube. Action to be assigned to Program Engineering with a due date of 02/28/2010.

CA#.4 After repair (CAPR#.1), remove the concrete from the low point of the Unit 1 Sump C to allow visual and UT thickness examination of the containment vessel and facilitate the evacuation of any remaining water from between the bottom head of the containment vessel and interior concrete. A sample of concrete close to the containment vessel shall be assessed for strength and chemically analyzed for changes caused by borated water. Any water seeping into the excavation shall be analyzed for pH and ionic species. Reinforcing bar exposed by the excavation shall be visually examined for indications of degradation. Action to be assigned to Program Engineering with a due date of 06/04/2011.

CA#.5 After repair (CAPR#.2), remove the concrete from the low point of the Unit 2 Sump C to allow visual and UT thickness examination of the containment vessel and facilitate the evacuation of any remaining water from between the bottom head of the containment vessel and interior concrete. A sample of concrete close to the containment vessel shall be assessed for strength and chemically analyzed for changes caused by borated water. Any water seeping into the excavation shall be analyzed for pH and ionic species. Reinforcing bar exposed by the excavation shall be visually examined for indications of degradation. Action to be assigned to Program Engineering with a due date of 02/25/2012.

Effectiveness Reviews

EFR#.1 Monitor and document the absence of Unit 1 leakage in typical areas including the Sump B and Regen Hx room for the first pool flood after repair in 1R26. Continued leakage would indicate either the wrong root cause of ineffective repairs. Action to be assigned to NSSS Engineering with a due date of 10/16/2009.

EFR#.2 Monitor and document the absence of Unit 1 leakage in typical areas including the Sump B and Regen Hx room for the first outage after repair in 1R27. Continued leakage would indicate either the wrong root cause of ineffective repairs. Action to be assigned to NSSS Engineering with a due date of 06/04/2009.

EFR#.3 Monitor and document the absence of Unit 1 leakage in typical areas including the Sump B and Regen Hx room for the second outage after repair in 1R28. Continued leakage would indicate either the wrong root cause of ineffective repairs. Action to be assigned to NSSS Engineering with a due date of 11/17/2012.

EFR#.4 Monitor and document the absence of Unit 2 leakage in typical areas including the Sump B and Regen Hx room for the first pool flood after repair in 2R26. Continued leakage would indicate either the wrong root cause of ineffective repairs. Action to be assigned to NSSS Engineering with a due date of 05/22/2010.

EFR#.5 Monitor and document the absence of Unit 2 leakage in typical areas including the Sump B and Regen Hx room for the first outage after repair in 2R27. Continued leakage would indicate either the wrong root cause of ineffective repairs. Action to be assigned to NSSS Engineering with a due date of 02/25/2012.

EFR#.6 Monitor and document the absence of Unit 2 leakage in typical areas including the Sump B and Regen Hx room for the second outage after repair in 2R28. Continued leakage would indicate either the wrong root cause of ineffective repairs. Action to be assigned to NSSS Engineering with a due date of 11/25/2013.

EFR#.7 Access results of Unit 1 leakage monitoring and any additional actions initiated as a result of monitoring. Close action or initiate new actions as appropriate. Action to be assigned to NSSS Engineering with a due date of 11/17/2012.

EFR#.8 Access results of Unit 2 leakage monitoring and any additional actions initiated as a result of monitoring. Close action or initiate new actions as appropriate. Action to be assigned to NSSS Engineering with a due date of 11/25/2013.

XI. **References**

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XII. **Attachments**

Appendix A: Support/Refute Matrix for Source of leakage

Appendix B: Support/Refute Matrix for Leak Locations

Appendix C: Change Analysis

Appendix D: Event and Causal Factor Chart

Appendix A
Support/Refute Matrix for Source of Leakage

Unit 2 Sump B - 2R24 -Support/Refute Matrix

Work Order #: ___None___ Date: ____12/2/2006_
Equipment ID: __Unit 2 Sump B_ Site/Unit: ___PI Unit 2
Troubleshooting Team Lead: __Downing__
Troubleshooting Team Members: ___C Koehler, J Horner, _L Drenth, L Lenertz, D Patel, D Fricke, W Pasch, D Herling
Other Knowledgeable Individuals: L. Johnson
Description of Concern Water Leakage into Sump B coincidental with Refueling Pool flood
Additional Info ACE 8718, OTH 6284, CA 7475, Design Change 83L787,

Credible water sources	Info needed to evaluate	Eval that supports/refutes Failure Mode	Actual Failure Y/N (?)	Explains All Symptoms Y/N(?)
Refuel Pool	• Chemistry • When the leak is active	• Chemistry has Borated water along with Iodine and trace of other nuclides • Leak is active during refueling.	Y	Y
RHR	• Chemistry • Is leak active when RHR pumps in service	• Chemistry has Borated water along with Iodine and trace of other nuclides • ERCS has both pumps off during on 11/26 and leak was active. Leak did not change when pumps were put into service.	N	N
Component Cooling	• Chemistry	• No chromates in water and water is Borated.	N	N
Secondary Side	Chemistry	• Water is Borated	N	N
Safety Injection	• Location	• Up on Steel structure no leak path	N	N
Steam Generator	• Location	• Up on Steel structure no leak path	N	N
Accumulator	• Location	• Up on Steel structure no leak path	N	N
RCS Piping	• When leak is active • Is leak at a detectable rate through monitoring	• Leak is not active when plant is online • This is a detectable leak	N	N

Credible water sources	Info needed to evaluate	Eval that supports/refutes Failure Mode	Actual Failure Y/N (?)	Explains All Symptoms Y/N(?)
Core	• When leak is active • Is leak at a detectable rate through monitoring	• Leak is not active when plant is online • This is a detectable leak	N	N
NIS covers	• Is leakage present in junction boxes	• No leakage near any junction box	N	Y
Through Refueling Cavity liner into Construction joint at El 713, migrate through construction joints to escape path in Sump B or C	Refuel Pool chemistry – • 2500 PPm Boron • Iodine and trace nuclides • 20 ppb Fe Sump B Seepage Chemistry • 2500 PPM Boron • Iodine and trace of other nuclides • 292 ppb Fe Leak is active during refueling Reactor Building Unit #2 General Section Concrete Reinforcement NF-38484-1	Presence of Iodine confirms that the source of the leakage is the Refueling Pool. From there, the only credible leak path found is the case where water leaks through the liner in the lower cavity or transfer pit and once it is below the liner it can leak through the construction joint at El. 713, which puts the water between the concrete and the steel liner. The leakage can then run down the liner to the basement, unobserved behind the concrete. Once it is below the basement concrete, it can migrate around the circumference of containment and through construction joints and come out wherever there is an escape path such as in Sump C at the joint between the 4^{th} and 5^{th} pours, and in the annulus around the RHR Suctions in Sump B. Increase in Iron indicates motion of water past a source of Fe, such as the Containment Liner or Structural Rebar	Y	Y

Appendix B
Support/Refute Matrix for Leak Locations

Leak Origin	Supporting Evidence	Evidence to Refute	Credible Leak Source to CTMT Vessel Steel?
Liner plate seam welds	• Imperfections have previously been identified in these welds and repaired both at this plant and other plants in the industry.	• All accessible seam welds in each unit have been vacuum box tested or dye penetrant tested, with the exception only of inaccessible or difficult weld configurations, notably the transfer tube to bellows welds. • Caulking of the internals stand and RCC change fixture baseplates has been adequate to seal the cavity leaks at least twice on Unit 1 and once on Unit 2.	**No**
Defects in liner plate or embedment plate base metal	• Much of the base metal has not been checked for leaks by any method. • Instacote has failed to seal the cavity on two occasions, one on each unit. • Refueling cavity construction was QA type III. • Stainless steel is subject to Stress corrosion cracking when exposed to chlorides and fluorides, which may be present in concrete.	• Base material defects in rolled plate that would extend though the wall would be expected to be very rare. • Stress corrosion cracking at room temperature is fairly rare, and these materials are not under high stress, thus removing a necessary element of SCC. • Instacote of the cavity floors and walls has been effective in sealing the cavity. • Caulking of the internals stand and RCC change fixture baseplates has been adequate to seal the cavity leaks at least twice on Unit 1 and once on Unit 2.	**No**

Leak Origin	Supporting Evidence	Evidence to Refute	Credible Leak Source to CTMT Vessel Steel?
Sandplug covers (x 6)	• Sandplug cover leakage is known to occur due to a history of extensive corrosion of the carbon steel sand boxes and support frames. • Boric acid residue is evident at the low points of the embedded pipe sleeves for the RCS main loop piping, visible from the RCP and Steam Generator vault ends, with evidence of leakage down the vault walls from these sleeves. • Leakage into Sump C down the walls of the reactor cavity is evident from rust stains and boric acid residue. • The reactor gap cooling ductwork shows significant surface rust. • Sandplug covers are sealed only by a layer of RTV caulking.	• No credible path has been established whereby leakage past the sandplug covers can find a path to emerge in Sump B, the Regen HX room ceiling, or the other concrete joints where it is seen. • There is no pressure head driving force acting on the fluid once it has entered the reactor cavity gap. Straight down into the gap cooling ductwork is the path of least resistance. • Caulking of the internals stand and RCC change fixture baseplates has been adequate to seal the cavity leaks at least twice on Unit 1 and once on Unit 2.	**No**
NIS Detector Covers (x 8)	• NIS detector cover leakage has occurred several times during plant life, due to installation errors of the O-ring in the O-ring groove, or failure to tighten the cap screws on the covers.	• No credible path has been established whereby leakage past the NIS detector covers can find a path to emerge in Sump B, the Regen HX room ceiling, or the other concrete joints where it is seen. • There is no pressure head driving force acting on the	**No**

Leak Origin	Supporting Evidence	Evidence to Refute	Credible Leak Source to CTMT Vessel Steel?
	• When leakage has occurred, it is normally a very significant flow rate, and it empties out several places like the electrical junction boxes for the nuclear instrumentation and the pushrods for positioning the detectors.	fluid once it has entered the reactor cavity gap. Straight down into the NIS detector cooling ductwork is the path of least resistance. • Caulking of the internals stand and RCC change fixture baseplates has been adequate to seal the cavity leaks at least twice on Unit 1 and once on Unit 2 • NIS detector cover leakage is not thought to be a chronic problem since it appears only intermittently when the O-rings sealing mechanism has failed.	
Reactor-to-cavity gap seal	• Leakage has occurred at this and other plants through the reactor-to-cavity gap seal.	• Since the replacement of the inflatable boot seal with the Preferred Engineering segmented seal, leakage through this path has been highly reduced. • No credible path has been established whereby leakage past the reactor-to-cavity gap seal can find a path to emerge in Sump B, the Regen HX room ceiling, and the other concrete joints where it is seen. • There is no pressure head driving force acting on the fluid once it has entered the reactor cavity gap. Straight down into the gap cooling ductwork is the path of least resistance.	**No**

Leak Origin	Supporting Evidence	Evidence to Refute	Credible Leak Source to CTMT Vessel Steel?
		• Caulking of the internals stand and RCC change fixture baseplates has been adequate to seal the cavity leaks at least twice on Unit 1 and once on Unit 2.	
Fuel Transfer Tube	• The transfer tube bellows to cavity liner weld is a complicated geometry and is in a difficult location to access and has not been checked by vacuum box or dye penetrant. • One of the bellows field welds is located behind a shield and cannot be inspected without removing the shield, but which could hypothetically be a leak source. • Refueling water leakage is often noted in areas of the containment basement directly below the transfer tube, such as the walls near the RCDT. • Instacote was applied to areas which included the accessible transfer tube field welds, and was successful in preventing all refueling cavity leakage on two occasions.	• Instacote, when applied to the transfer tube field welds, failed to stop refueling cavity leakage to Sump B, the Regen HX Room ceiling, and the RCDT area walls on two separate occasions. • Caulking of the internals stand and RCC change fixture baseplates has been adequate to seal the cavity leaks at least twice on Unit 1 and once on Unit 2.	**No**

Leak Origin	Supporting Evidence	Evidence to Refute	Credible Leak Source to CTMT Vessel Steel?
Internals Storage Stand Baseplates (x 8)	• These embedment plates have the hold down studs threaded into through-holes in the plates, creating a natural leak path through the threads. The drawings call for a ¼” fillet weld (continuous leak proof) on the underside of the plates, but these welds are inaccessible for inspection. • The welds could have been damaged during the installation of the storage stands. • These welds would have been made by the superstructure contractor who was erecting the containment concrete structures and steel, not the refueling cavity liner contractor, so this could have been an overlooked detail. • Caulking of the internals stand baseplates and the RCC change fixture baseplates has been adequate, in isolation, to seal the cavity leaks at least twice on Unit 1 and once on Unit 2.	• The design is clear that the embedment plates are to have the studs seal welded with a continuous leakproof weld. A leak at this location presumes either a deviation from design, a lack of quality in the weld, or an inservice failure of the weld, of which all scenarios may be considered improbable. • Three times, once on Unit 1 and twice on Unit 2, when the storage stand baseplate feet were caulked, the refueling cavity still leaked. This was attributed to worker practices or deviations from the intent of the procedure, which may have left a path through the RCC change fixture baseplates in the upender pit or under the nuts of the internals stand feet, but nonetheless the caulking which was attempted of the internals storage stand baseplates alone did not quell the leakage. • During the first application of Instacote in 2R20, the lower cavity, including the storage stand baseplates, was not coated, and yet the Instacote application was effective in stopping the cavity leakage that outage.	**Yes**

Leak Origin	**Supporting Evidence**	**Evidence to Refute**	**Credible Leak Source to CTMT Vessel Steel?**
RCC Change Fixture Baseplates (x 3)	• These embedment plates have the hold down studs/concrete anchor J-bolts threaded into through-holes in the plates, creating a natural leak path through the threads. The drawings call for a seal weld of unspecified size to be applied between the stud and embedment plate in a groove created by the countersunk hole, and then ground smooth, but these welds are generally inaccessible for inspection, being located under the RCC change fixture feet, and have never been tested due to difficulty in configuring a vacuum box to this geometry. Given the crevice where this weld meets the studs, dye penetrant may not be practical due to the likelihood of bleedout creating false calls. • These welds would have been made by the superstructure conctractor who was erecting the containment concrete structures and steel, not the refueling cavity liner contractor, so this	• The design is clear that the embedment plates are to have the studs seal welded to the embedment plates. A leak at this location presumes either a deviation from design, a lack of quality in the weld, or an inservice failure of the weld, of which all three scenarios may be considered to some degree improbable. • Twice, both times on Unit 2, when the RCC change fixture baseplate feet were caulked, the refueling cavity still leaked. This was attributed to worker practices or deviations from the intent of the procedure, which may have left a path through the internals storage stand baseplates under the nuts, but nonetheless caulking of the RCC change fixture baseplates alone did not quell the leakage.	**Yes**

Leak Origin	Supporting Evidence	Evidence to Refute	Credible Leak Source to CTMT Vessel Steel?
	could have been an overlooked detail, or the leak-tighness may not have been of foremost concern. • The welds could have been damaged during the installation of the RCC Change Fixture. • Caulking of the internals stand and RCC change fixture baseplates has been adequate to seal the cavity leaks at least twice on Unit 1 and once on Unit 2. • During Unit 1, 1R23 when the storage stand baseplates were caulked but the RCC change fixture baseplates were not, leakage was considered to be reduced, but was not stopped. • During the first application of Instacote in 2R20, the lower cavity, including the storage stand baseplates, was not coated, only the upper cavity and the fuel transfer pit, and yet the Instacote application was effective in stopping the cavity leakage that outage.		

Leak Origin	Supporting Evidence	Evidence to Refute	Credible Leak Source to CTMT Vessel Steel?
RCC Guide Tube Embedments (x 4) in cavity wall.	• These embedment plates have the studs/anchor J-bolts inserted or threaded through holes in the plates, creating a natural leak path through the threads. The drawings call for a ¼" fillet weld all around on the backside of the plates, but these welds are inaccessible for inspection, visually or otherwise, and have never been tested due to difficulty in configuring a vacuum box to this geometry. • These welds would have been made by the superstructure conctractor who was erecting the containment concrete structures and steel, not the refueling cavity liner contractor, so this could have been an overlooked detail. • No attempt has been made by PINGP staff to mitigate this location due to its height above the floor of the cavity, which makes accessibility for any type of caulking or coating application much more difficult.	• The design is clear that the embedment plates are to have the studs welded on the backside all around with a ¼" fillet. A leak at this location presumes either a deviation from design, a lack of quality in the weld, or an inservice failure of the weld, of which all three scenarios may be considered improbable. • Although no action has ever been taken to try to seal these locations, we have had several leak-free outages. This is difficult to explain if these are a leak source, unless there is some intermittent self-sealing mechanism beyond our understanding.	**Yes**

Leak Origin	Supporting Evidence	Evidence to Refute	Credible Leak Source to CTMT Vessel Steel?
	• Leakage through this path could explain why our best efforts elsewhere are at times unsuccessful. • ***Revision 1 – Continued leakage in 1R26 of 7 drips per minute indicates at least one small leak remains. Leakage stopped when the cavity was lowered suggesting leakage at one of the two upper supports.***		
Other embedment plates for tool brackets, guide stud storage, drive rod storage, fuel transfer cart rails.	• These brackets and attachments are the mechanisms by which loads are transmitted to the structure, so they are subject to stress and strain. Such stresses could hypothetically result in cyclic displacements and consequently fatigue cracking of welds or base metal resulting in a leak path.	• The miscellaneous racks and brackets in the cavity other than those described above, consist of a plain embedment plate with j-bolts or anchor studs welded to the back to be embedded in the concrete, with the members comprising the bracket elements or rack shapes welded to the front side. There is no possible leak path through the solid embedment plates. The liner plates are welded to the embedment plates with fillet welds that are generally accessible and that have been tested by vacuum box or PT at some point in earlier leak investigations.	**No**

Appendix C
Change Analysis

Problem Statement: Analyze if the sealing efforts had an affect on the cavity leakage.

Unit 2

Out-age	Previous Condition	Current Condition	Change Difference	Assessment
2R19	No sealing attempt	Vacuum box testing and PT of accessible seams and fasteners.		Found sandplug cover fastener leaks and three small discontinuities in liner plate seam welds were repaired. No verification was done to confirm this resolved the leakage.
2R20	Repaired welds and sandplug fastener leaks	InstaCote applied to upper cavity deck and around the reactor vessel to 6 ft up the walls and floor of the up-ender pit.	InstaCote on the upper deck and transfer pit.	No cavity leakage reported indicating leak points in either the upper cavity and/or transfer pit were sealed
2R21	InstaCote applied to upper cavity deck and around the reactor vessel to 6 ft up the walls and floor of the up-ender pit.	InstaCote of transfer pit and lower cavity.	InstaCote on lower cavity. No InstaCote on upper cavity	No cavity leakage reported indicating leakage in transfer pit.
2R22	InstaCote of transfer pit and lower cavity.	InstaCote of transfer pit and lower cavity.	No change	Not completely effective, light coating on internals stand contributed to some leakage in sump B. NIS well cover O-ring leaks contribute to leakage in sump C.
2R23	InstaCote of transfer pit and lower cavity.	Caulk potential leak paths on base-plates and fasteners of the internals stand and in up-ender pit. Including caulking under nuts.	Used caulking instead of InstaCote.	No indication of cavity leakage indicating leakage is at anchor studs and not other locations.
2R24	Caulk potential leak paths on base-plates and	Caulk potential leak paths on base-plates and	Removal of nuts and reapplication of caulking under	Not completely effective, leakage only reported in sump B indicating nuts must be removed

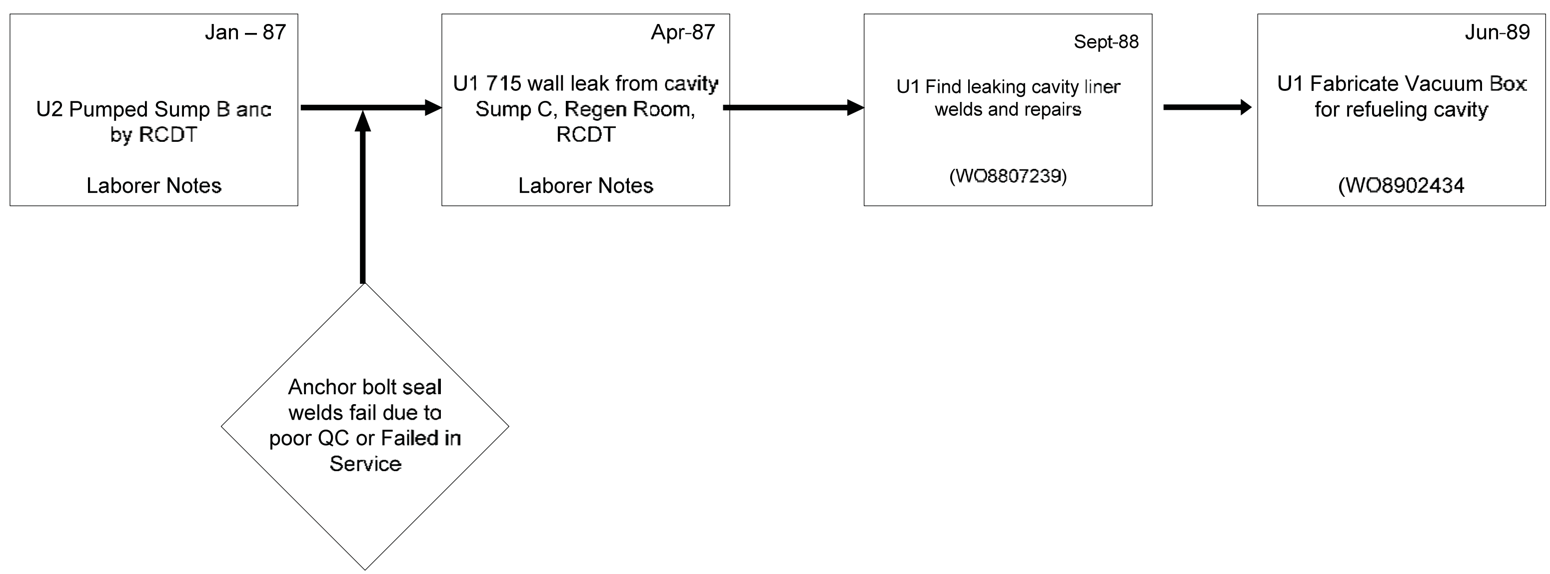
Out-age	Previous Condition	Current Condition	Change Difference	Assessment
	fasteners of the internals stand and in transfer pit. Including caulking under nuts.	fasteners of the internals stand in up-ender pit. No caulking performed under nuts.	nuts was not done.	to seal anchor studs.
2R25	Caulk potential leak paths on base-plates and fasteners of the internals stand in transfer pit. No caulking performed under nuts.	Caulk potential leak paths on base-plates and fasteners of the internals stand in up-ender pit. No caulking performed under nuts.	No change	Not completely effective, leakage reported from the ceiling of the Regen Room, 22 Vault and Sump B.

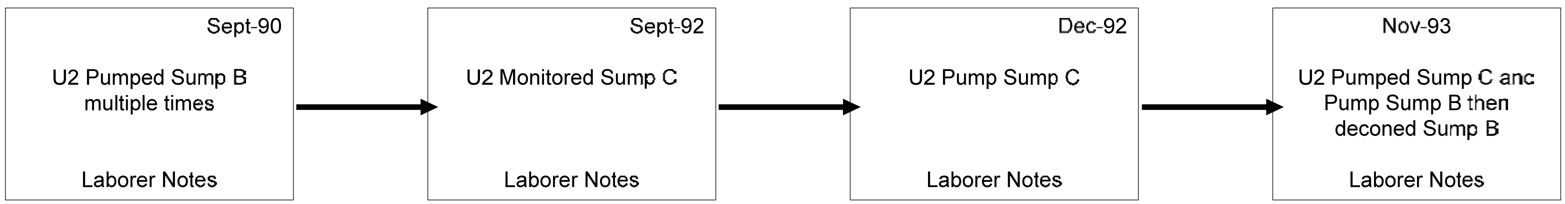
Unit 1

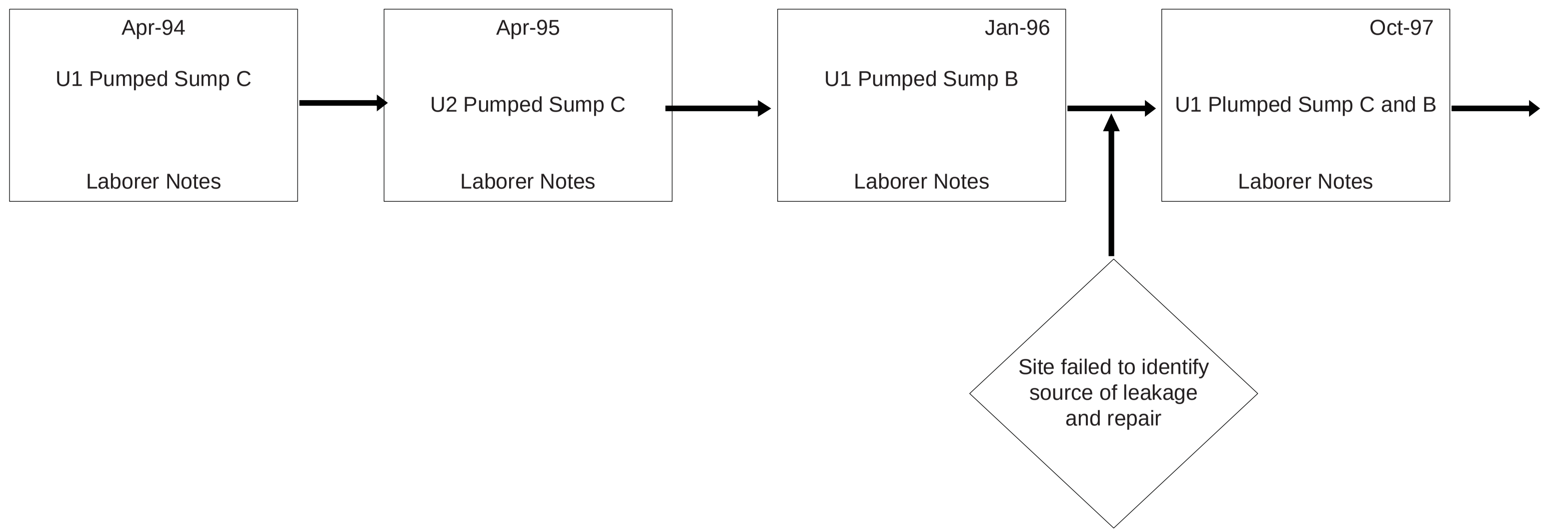
Outage	Previous Condition	Current Condition	Change Difference	Assessment
1R20	No sealing attempts	Vacuum box testing and PT of accessible seams and fasteners	Repaired sand plug fastener leaks	Not completely effective, leakage reported in Sump B
1R21	Repaired sandplug fastener leaks	No additional action taken	No change	No cavity leakage reported.
1R22	Repaired sandplug fastener leaks.	InstaCote of up-ender pit and lower cavity.	Use of InstaCote on up-ender pit and lower cavity.	Not completely effective, leakage reported in the ceiling of the Regen Room and Sump B.
1R23	InstaCote of transfer pit and lower cavity.	Caulking of the internals stands including under the nuts of the stands. No caulking in the transfer pit.	Use of caulking in the lower cavity. No caulking in transfer pit.	Leakage significantly reduced. Not caulking transfer pit resulted in some leakage.
1R24	Caulking of the internals stands including under the nuts of the stands. No caulking in the transfer pit.	Caulking of the internals stands and in the transfer pit including under the nuts of the stands.	Caulking of the stands in the transfer pit.	No cavity leakage reported indicating leakage of anchor studs in the transfer pit.

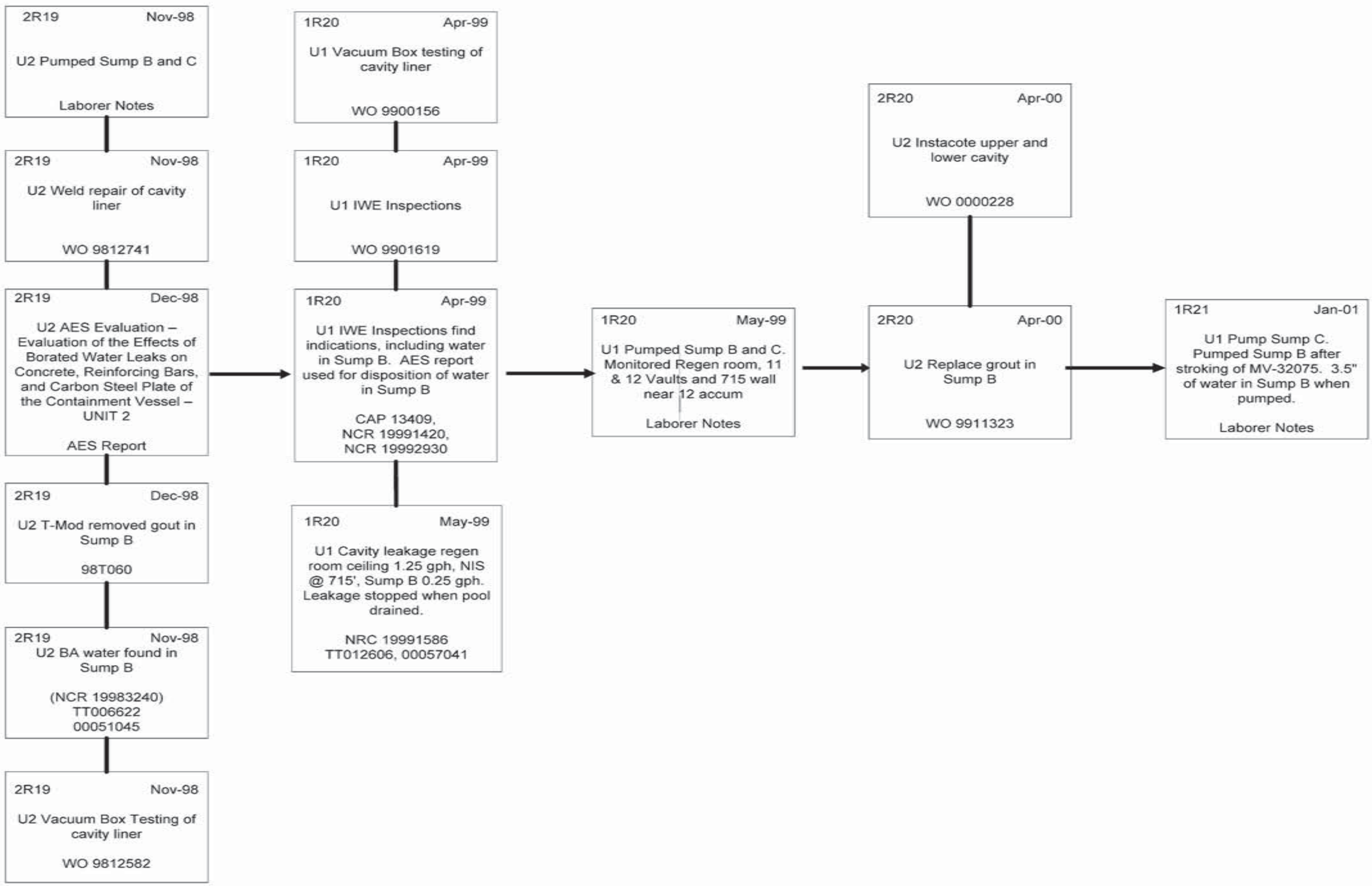
Outage	Previous Condition	Current Condition	Change Difference	Assessment
1R25	Caulking of the internals stands and in the transfer pit including under the nuts of the stands.	Caulking of the internals stands and in the transfer pit including under the nuts of the stands.	No change	No record of leakage with the exception of a significant sand plug cover leak into Sump C.

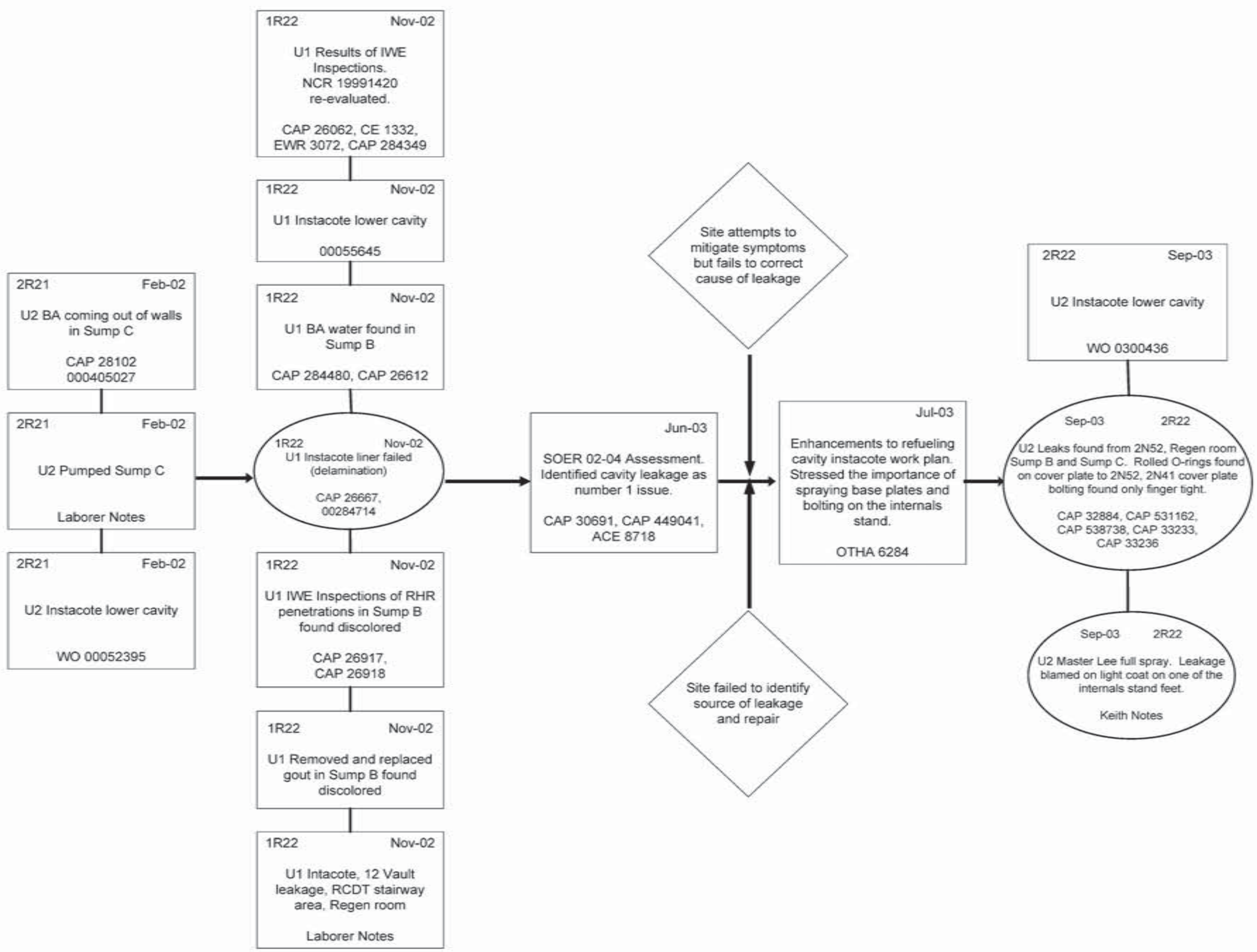
Appendix D
Event and Causal Factor Chart

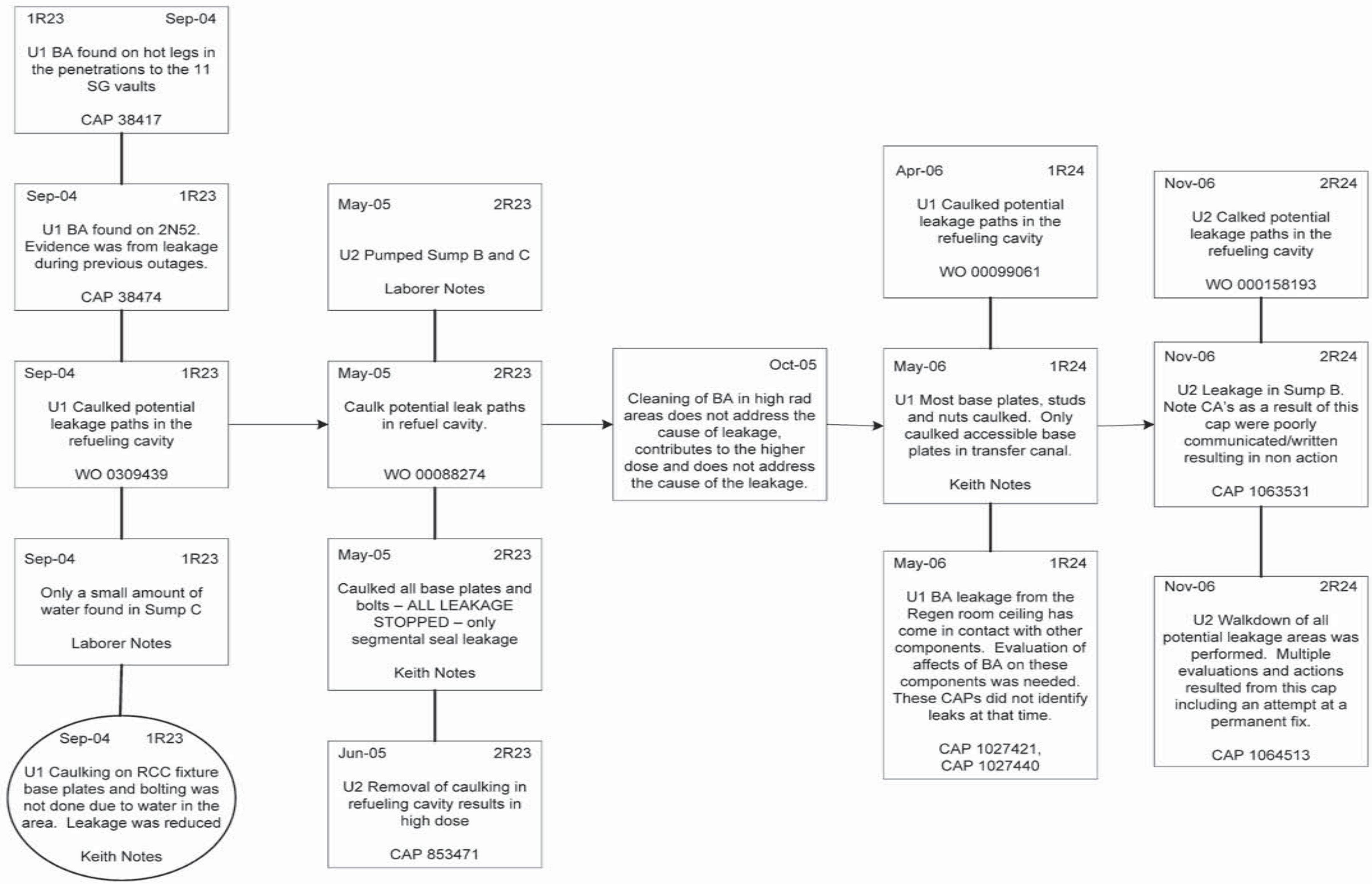


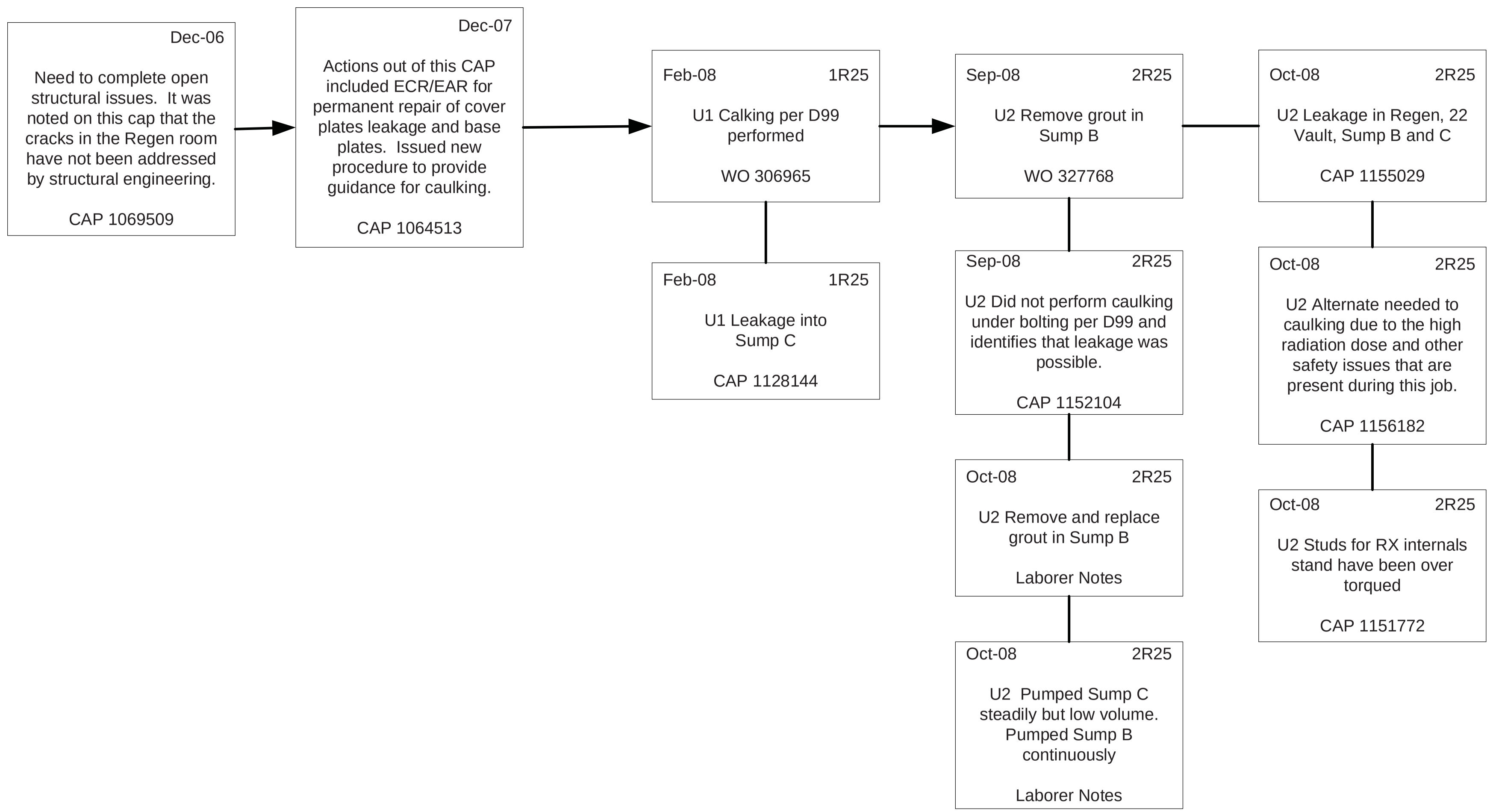

Sept-90
U2 Pumped Sump B multiple times
Laborer Notes
Sept-92
U2 Monitored Sump C
Laborer Notes
Dec-92
U2 Pump Sump C
Laborer Notes
Nov-93
U2 Pumped Sump C anc Pump Sump B then deconed Sump B
Laborer Notes

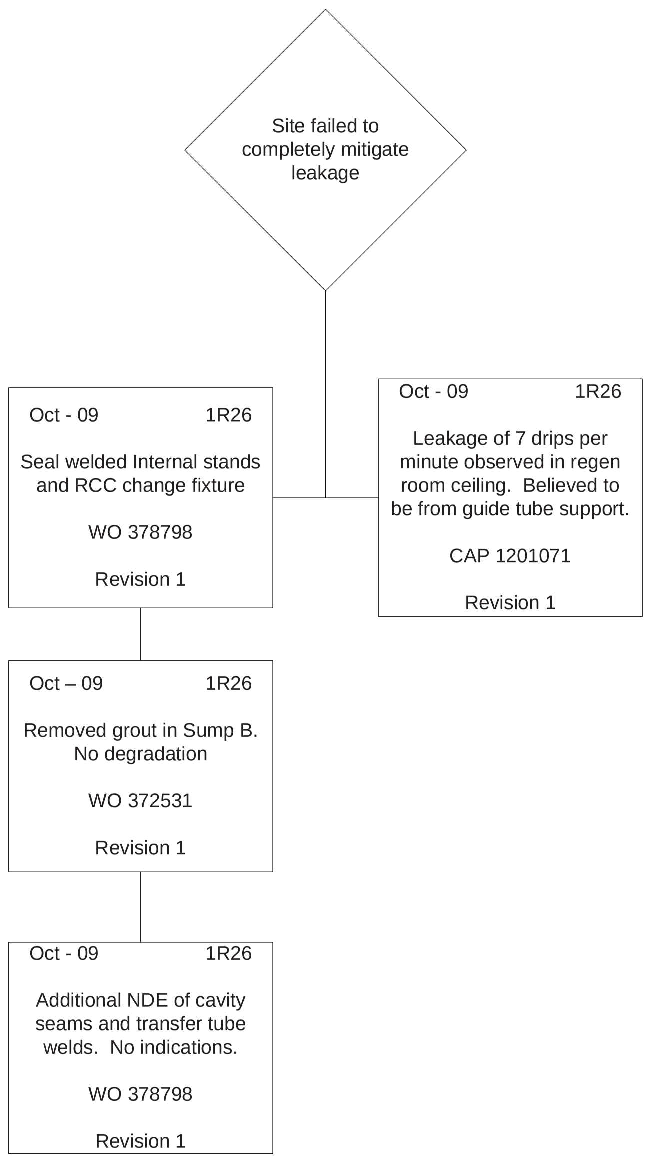

Apr-94
U1 Pumped Sump C
Laborer Notes
Apr-95
U2 Pumped Sump C
Laborer Notes
Jan-96
U1 Pumped Sump B
Laborer Notes
Oct-97
U1 Plumped Sump C and B
Laborer Notes
Site failed to identify source of leakage and repair


2R19 Nov-98
U2 Pumped Sump B and C
Laborer Notes
2R19 Nov-98
U2 Weld repair of cavity liner
WO 9812741
2R19 Dec-98
U2 AES Evaluation – Evaluation of the Effects of Borated Water Leaks on Concrete, Reinforcing Bars, and Carbon Steel Plate of the Containment Vessel – UNIT 2
AES Report
2R19 Dec-98
U2 T-Mod removed gout in Sump B
98T060
2R19 Nov-98
U2 BA water found in Sump B
(NCR 19983240)
TT006622
00051045
2R19 Nov-98
U2 Vacuum Box Testing of cavity liner
WO 9812582
1R20 Apr-99
U1 Vacuum Box testing of cavity liner
WO 9900156
1R20 Apr-99
U1 IWE Inspections
WO 9901619
1R20 Apr-99
U1 IWE Inspections find indications, including water in Sump B. AES report used for disposition of water in Sump B
CAP 13409,
NCR 19991420,
NCR 19992930
1R20 May-99
U1 Cavity leakage regen room ceiling 1.25 gph, NIS @ 715', Sump B 0.25 gph. Leakage stopped when pool drained.
NRC 19991586
TT012606, 00057041
1R20 May-99
U1 Pumped Sump B and C. Monitored Regen room, 11 & 12 Vaults and 715 wall near 12 accum
Laborer Notes
2R20 Apr-00
U2 Instacote upper and lower cavity
WO 0000228
2R20 Apr-00
U2 Replace grout in Sump B
WO 9911323
1R21 Jan-01
U1 Pump Sump C. Pumped Sump B after stroking of MV-32075. 3.5" of water in Sump B when pumped.
Laborer Notes


1R22 Nov-02
U1 Results of IWE Inspections. NCR 19991420 re-evaluated.
CAP 26062, CE 1332, EWR 3072, CAP 284349
1R22 Nov-02
U1 Instacote lower cavity
00055645
2R21 Feb-02
U2 BA coming out of walls in Sump C
CAP 28102 000405027
1R22 Nov-02
U1 BA water found in Sump B
CAP 284480, CAP 26612
2R21 Feb-02
U2 Pumped Sump C
Laborer Notes
1R22 Nov-02
U1 Instacote liner failed (delamination)
CAP 26667, 00284714
2R21 Feb-02
U2 Instacote lower cavity
WO 00052395
1R22 Nov-02
U1 IWE Inspections of RHR penetrations in Sump B found discolored
CAP 26917, CAP 26918
1R22 Nov-02
U1 Removed and replaced gout in Sump B found discolored
1R22 Nov-02
U1 Intacote, 12 Vault leakage, RCDT stairway area, Regen room
Laborer Notes
Jun-03
SOER 02-04 Assessment. Identified cavity leakage as number 1 issue.
CAP 30691, CAP 449041, ACE 8718
Site attempts to mitigate symptoms but fails to correct cause of leakage
Site failed to identify source of leakage and repair
Jul-03
Enhancements to refueling cavity instacote work plan. Stressed the importance of spraying base plates and bolting on the internals stand.
OTHA 6284
2R22 Sep-03
U2 Instacote lower cavity
WO 0300436
Sep-03 2R22
U2 Leaks found from 2N52, Regen room Sump B and Sump C. Rolled O-rings found on cover plate to 2N52. 2N41 cover plate bolting found only finger tight.
CAP 32884, CAP 531162, CAP 538738, CAP 33233, CAP 33236
Sep-03 2R22
U2 Master Lee full spray. Leakage blamed on light coat on one of the internals stand feet.
Keith Notes


1R23 Sep-04
U1 BA found on hot legs in the penetrations to the 11 SG vaults
CAP 38417
Sep-04 1R23
U1 BA found on 2N52. Evidence was from leakage during previous outages.
CAP 38474
Sep-04 1R23
U1 Caulked potential leakage paths in the refueling cavity
WO 0309439
Sep-04 1R23
Only a small amount of water found in Sump C
Laborer Notes
Sep-04 1R23
U1 Caulking on RCC fixture base plates and bolting was not done due to water in the area. Leakage was reduced
Keith Notes
May-05 2R23
U2 Pumped Sump B and C
Laborer Notes
May-05 2R23
Caulk potential leak paths in refuel cavity.
WO 00088274
May-05 2R23
Caulked all base plates and bolts – ALL LEAKAGE STOPPED – only segmental seal leakage
Keith Notes
Jun-05 2R23
U2 Removal of caulking in refueling cavity results in high dose
CAP 853471
Oct-05
Cleaning of BA in high rad areas does not address the cause of leakage, contributes to the higher dose and does not address the cause of the leakage.
Apr-06 1R24
U1 Caulked potential leakage paths in the refueling cavity
WO 00099061
May-06 1R24
U1 Most base plates, studs and nuts caulked. Only caulked accessible base plates in transfer canal.
Keith Notes
May-06 1R24
U1 BA leakage from the Regen room ceiling has come in contact with other components. Evaluation of affects of BA on these components was needed. These CAPs did not identify leaks at that time.
CAP 1027421, CAP 1027440
Nov-06 2R24
U2 Calked potential leakage paths in the refueling cavity
WO 000158193
Nov-06 2R24
U2 Leakage in Sump B. Note CA's as a result of this cap were poorly communicated/written resulting in non action
CAP 1063531
Nov-06 2R24
U2 Walkdown of all potential leakage areas was performed. Multiple evaluations and actions resulted from this cap including an attempt at a permanent fix.
CAP 1064513


Dec-06
Need to complete open structural issues. It was noted on this cap that the cracks in the Regen room have not been addressed by structural engineering.
CAP 1069509
Dec-07
Actions out of this CAP included ECR/EAR for permanent repair of cover plates leakage and base plates. Issued new procedure to provide guidance for caulking.
CAP 1064513
Feb-08 1R25
U1 Calking per D99 performed
WO 306965
Feb-08 1R25
U1 Leakage into Sump C
CAP 1128144
Sep-08 2R25
U2 Remove grout in Sump B
WO 327768
Sep-08 2R25
U2 Did not perform caulking under bolting per D99 and identifies that leakage was possible.
CAP 1152104
Oct-08 2R25
U2 Remove and replace grout in Sump B
Laborer Notes
Oct-08 2R25
U2 Pumped Sump C steadily but low volume. Pumped Sump B continuously
Laborer Notes
Oct-08 2R25
U2 Leakage in Regen, 22 Vault, Sump B and C
CAP 1155029
Oct-08 2R25
U2 Alternate needed to caulking due to the high radiation dose and other safety issues that are present during this job.
CAP 1156182
Oct-08 2R25
U2 Studs for RX internals stand have been over torqued
CAP 1151772


Site failed to completely mitigate leakage
Oct - 09 1R26
Seal welded Internal stands and RCC change fixture
WO 378798
Revision 1
Oct - 09 1R26
Leakage of 7 drips per minute observed in regen room ceiling. Believed to be from guide tube support.
CAP 1201071
Revision 1
Oct – 09 1R26
Removed grout in Sump B. No degradation
WO 372531
Revision 1
Oct - 09 1R26
Additional NDE of cavity seams and transfer tube welds. No indications.
WO 378798
Revision 1