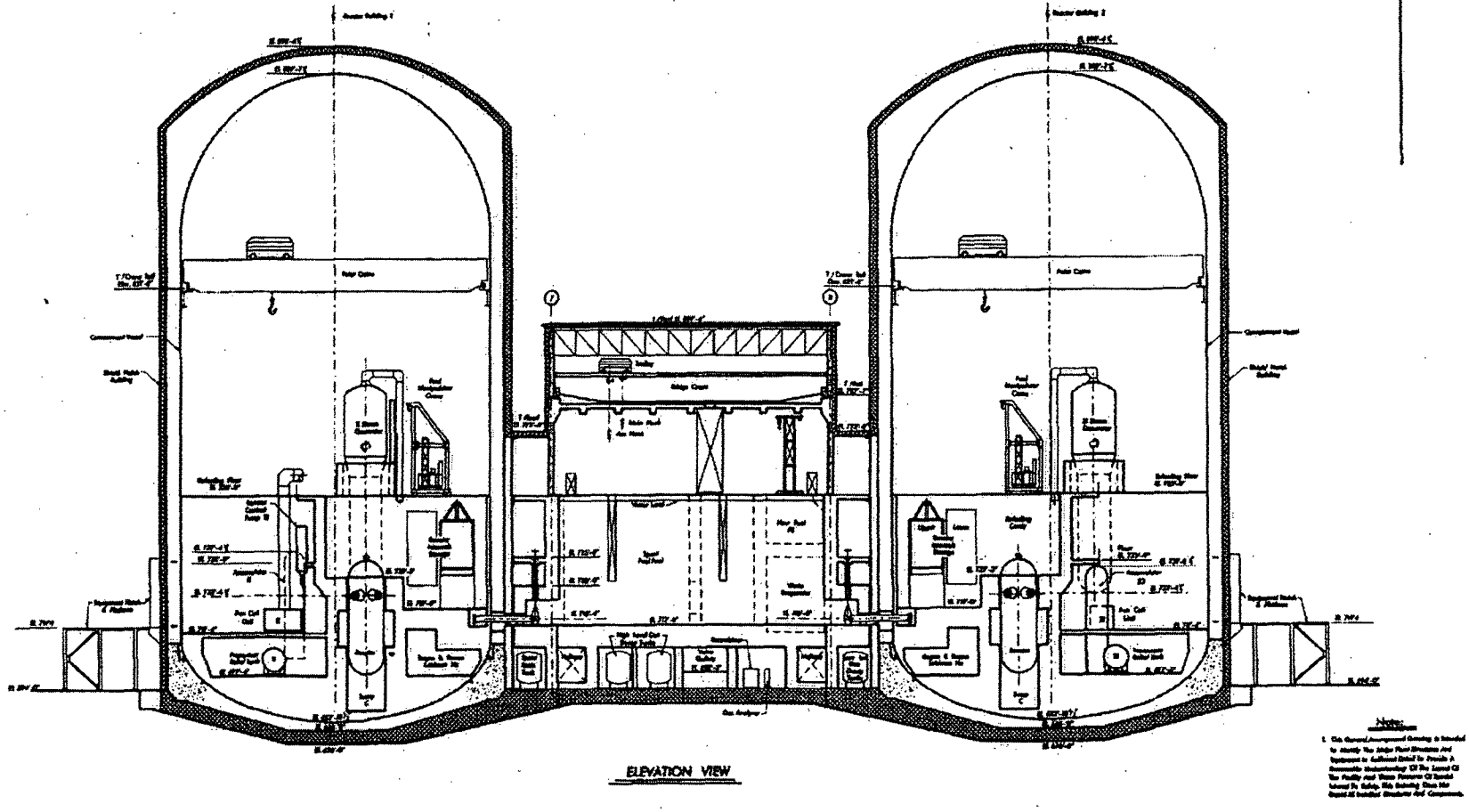
Prairie Island Refueling Cavity Leakage

Containment Design:



Containment Design Continued

- The containment vessel is 105'-0" inside diameter with a 1-1/2" thick 2:1 ellipsoidal bottom head, 1-1/2" thick shell, and ¾" thick hemispherical top head. SA-516-70 low temperature carbon steel.
- 3-1/2" thick insert plate at RHR sump (sump B) penetrations.
- Vessel provides primary containment with 5' annular gap between containment vessel and limited leakage reinforced concrete shield building.

Background:

- Indications of refueling cavity leakage on both units dating back to about 1987.
- Leakage events typically begin about two to four days after refueling cavity flood and end about three days after the pool is drained.
- Chemistry and leakage only during refueling cavity flood indicate refuel cavity water. No other feasible source.

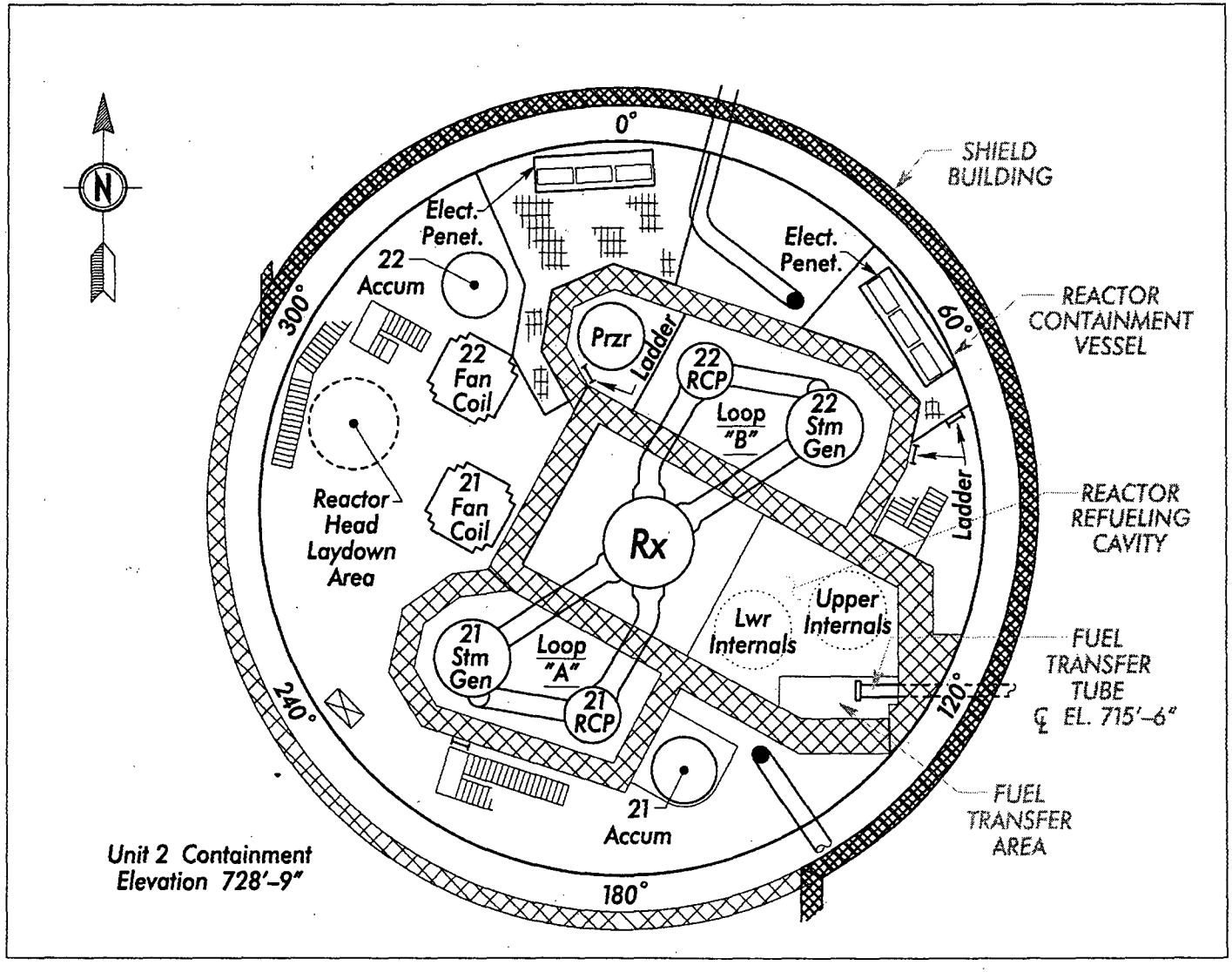
Timeline Summary:

- 1987 – 1998
  - Weld repairs completed on Unit 1 cavity in 1988
  - Routine pumping of Sumps B and C (both units, could be RV cavity seal or RHR valves)
- 1998
  - Vacuum box testing and dye penetrant exam of refuel cavity liners with weld repair of 3 pinhole leaks on unit 2
- 2002 – 2003 Instacote spray on strippable liner
  - Vendor experienced application problems
  - Leakage mitigated when properly applied
- 2004 – 2008 Caulk internals stands penetrations
  - Leakage mitigated when caulking performed underneath fasteners

Cause of Leakage:

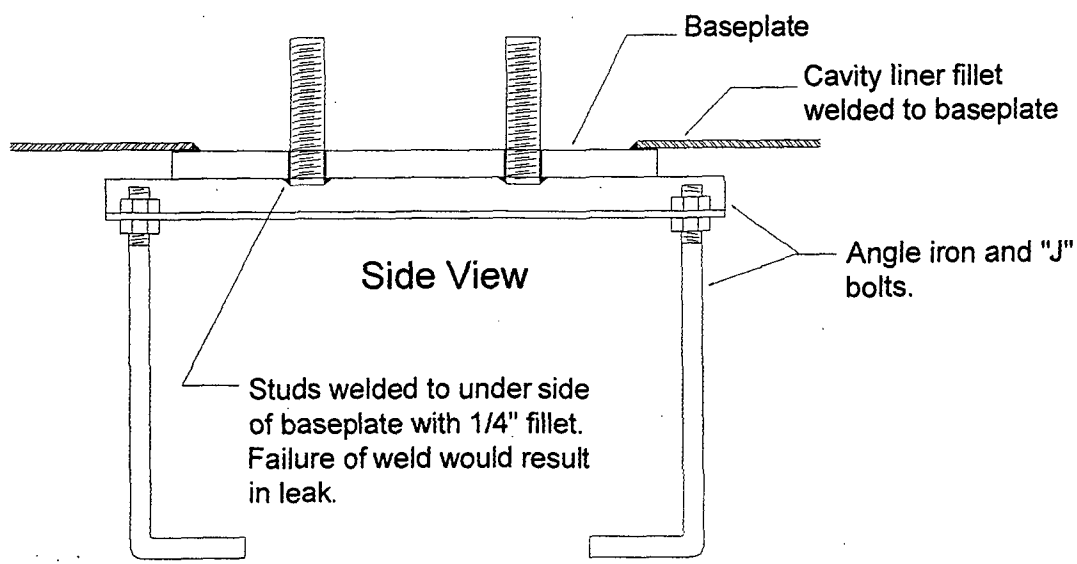
- Root Cause Evaluation determined leakage occurs at the internals stands and RCC change fixture anchors
  - Applies to both Unit 1 and Unit 2

Cause of Leakage:



Cause of Leakage Continued:

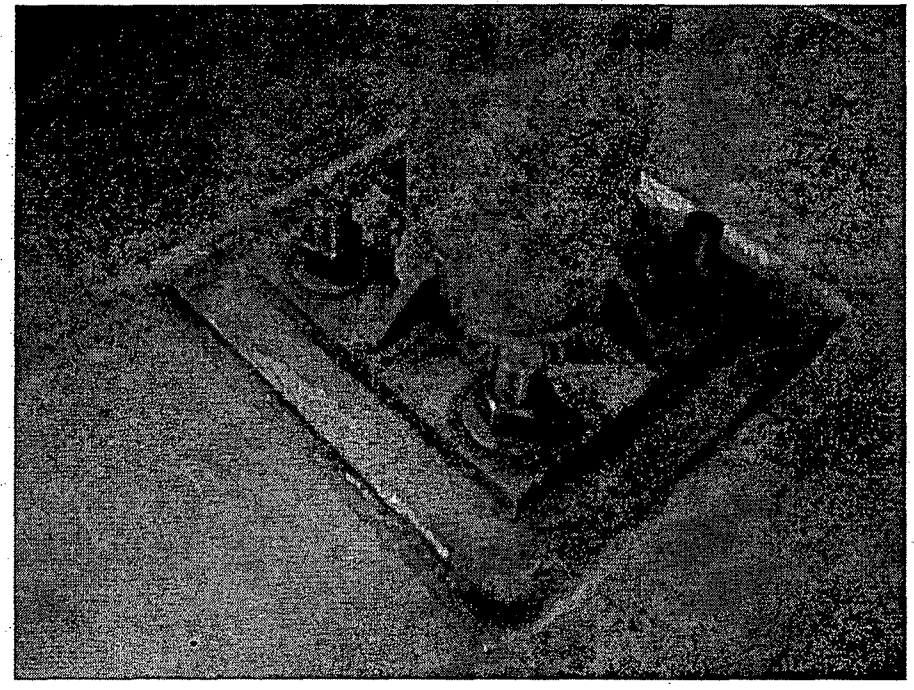
- Leakage through failed welds between Internals Stands baseplates and anchors.



General Arrangement of Internals Stands Supports

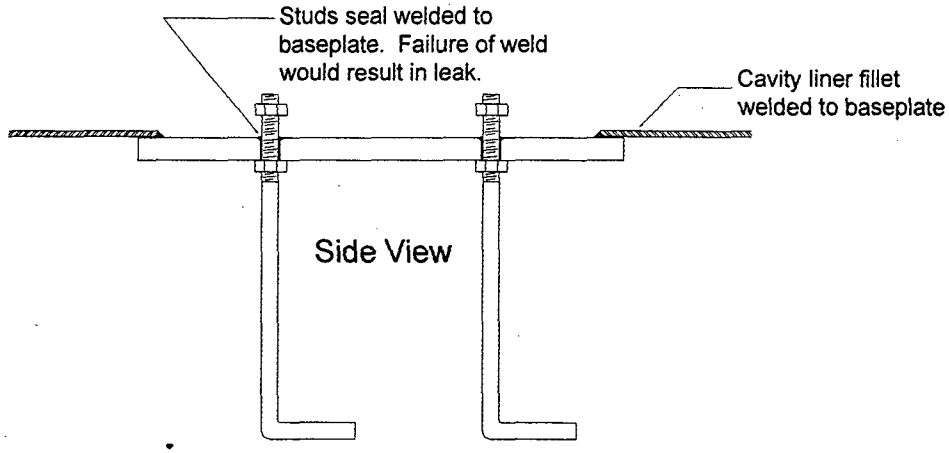
Cause of Leakage Continued:

- Typical Internals Stand Support



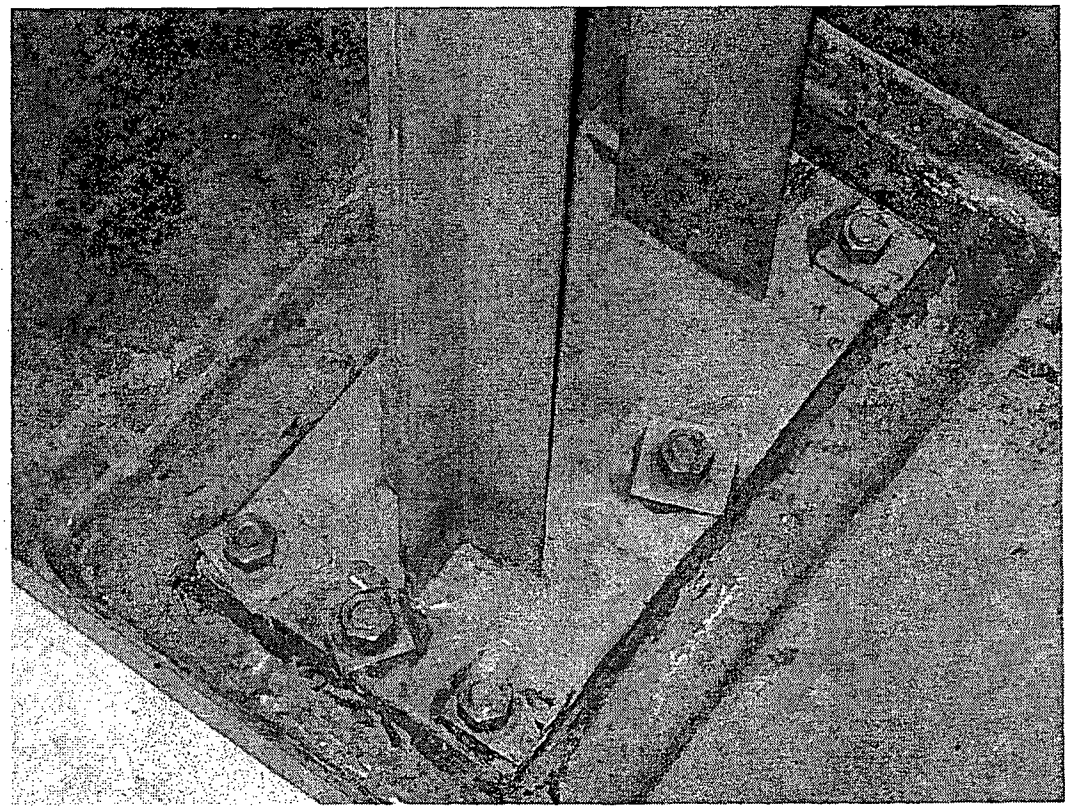
Cause of Leakage Continued:

- General Arrangement of RCC Change Fixture Support. Leakage through failed seal welds between anchors and baseplates.



Cause of Leakage Continued:

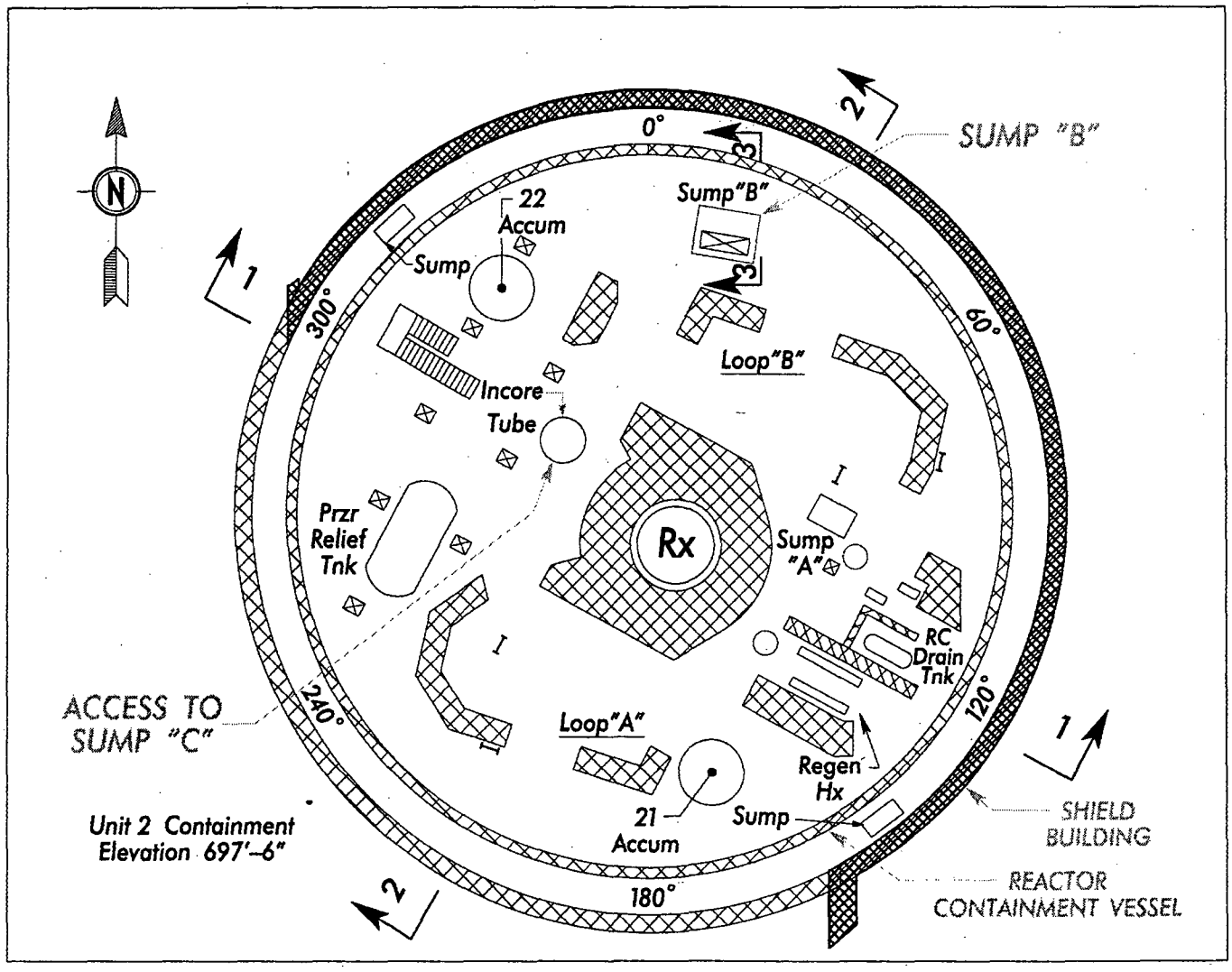
- Typical RCC Change Fixture Support



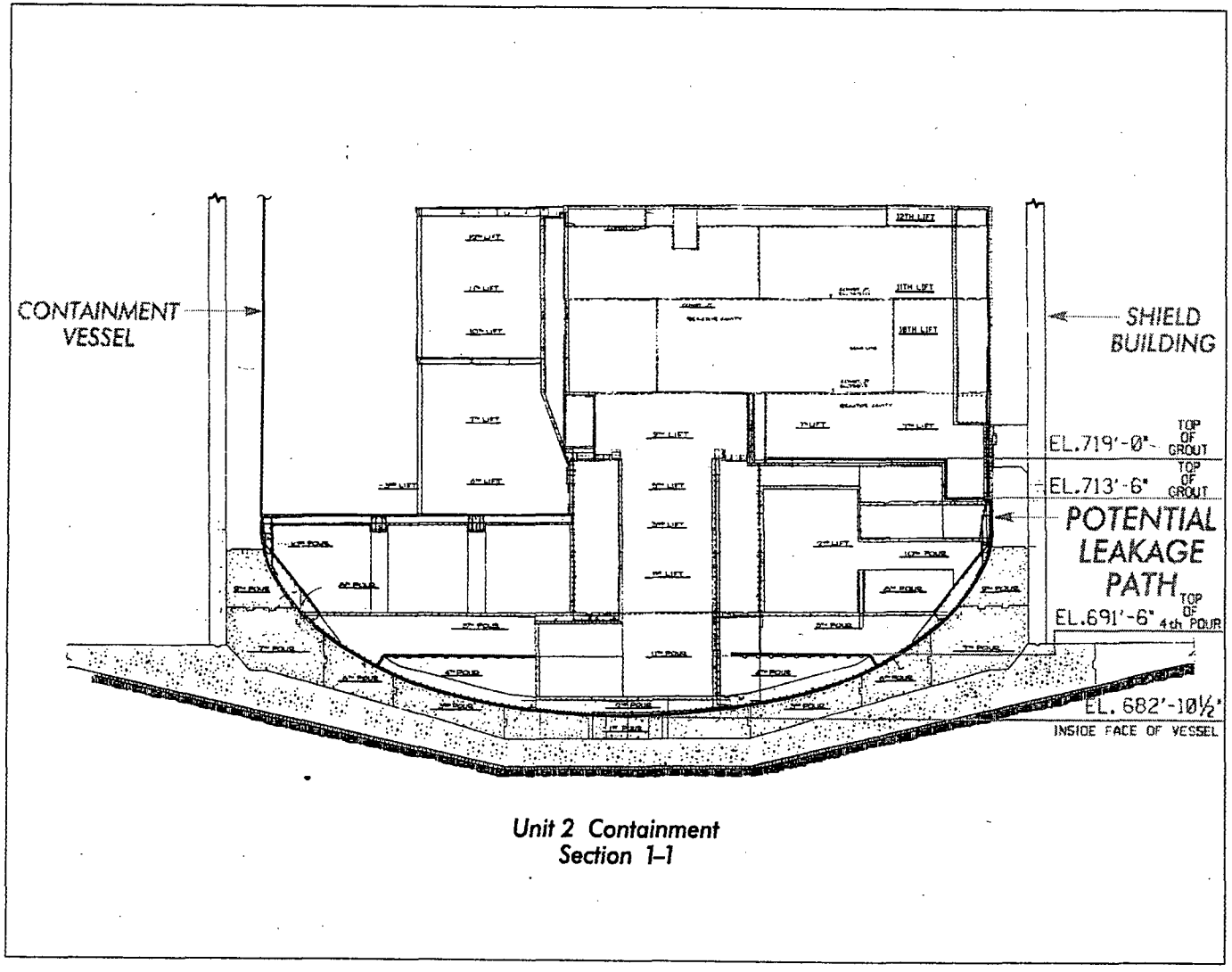
Leak Path:

- 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.

Leak Path:

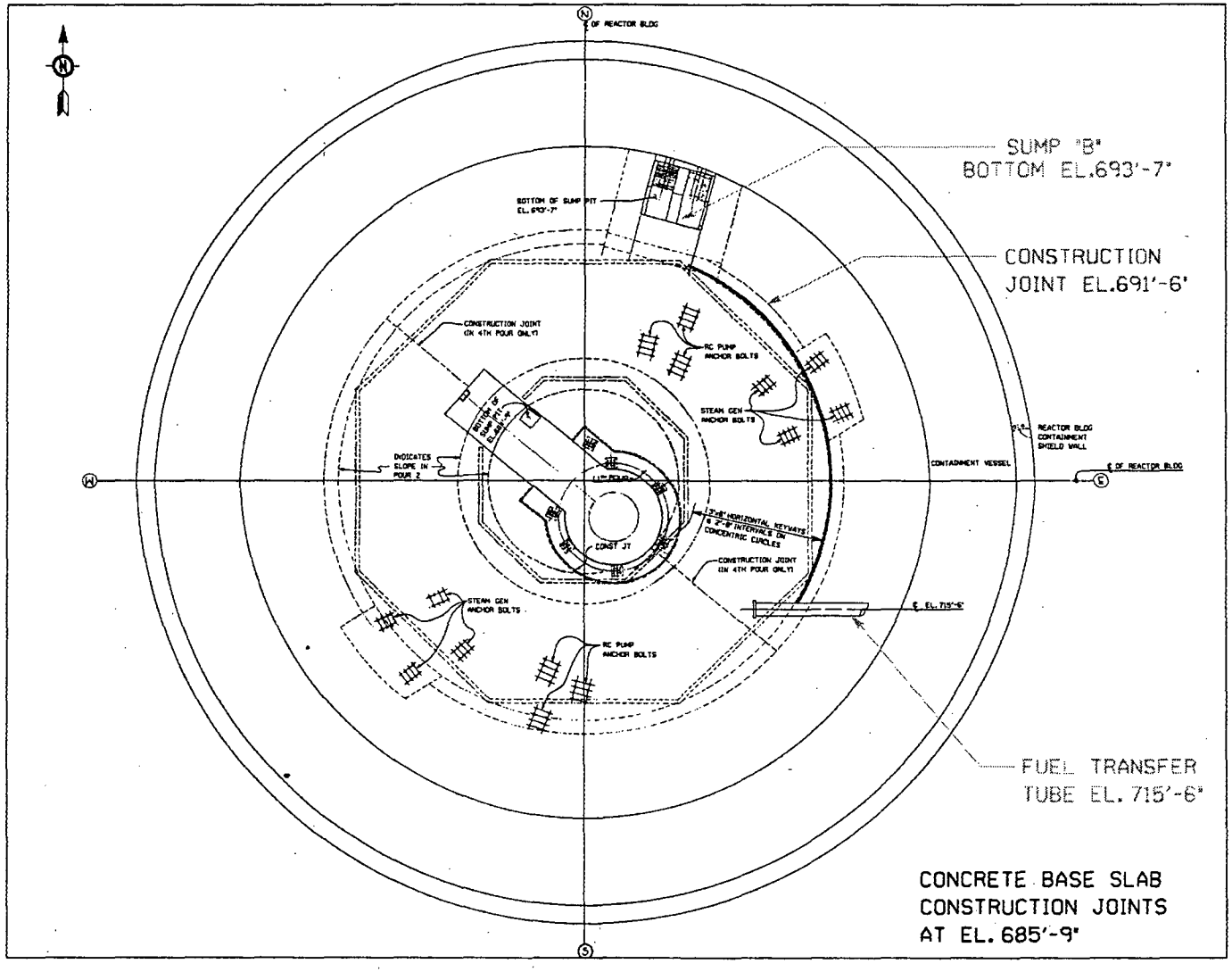

N
0°
60°
120°
180°
240°
300°
SUMP "B"
22
Accum
Sump
Sump"B"
Loop"B"
Incore
Tube
Przr
Relief
Tnk
Rx
Sump
"A"
RC
Drain
Tnk
Loop"A"
Regen
Hx
21
Accum
Sump
ACCESS TO
SUMP "C"
Unit 2 Containment
Elevation 697'-6"
SHIELD
BUILDING
REACTOR
CONTAINMENT VESSEL

Leak Path:



Unit 2 Containment
Section 1-1

Leak Path:


SUMP "B"
BOTTOM EL.693'-7"
CONSTRUCTION
JOINT EL.691'-6"
FUEL TRANSFER
TUBE EL. 715'-6"
CONCRETE BASE SLAB
CONSTRUCTION JOINTS
AT EL. 685'-9"
BOTTOM OF SUMP PIT
EL. 693'-7"
CONSTRUCTION JOINT
ON 4TH POUR ONLY!
RC PUMP
ANCHOR BOLTS
STEAM GEN
ANCHOR BOLTS
INDICATES
SLOPE IN
POUR 2
CONST JT
CONTAINMENT VESSEL
REACTOR BLDG
CONTAINMENT
SHIELD WALL
℄ OF REACTOR BLDG
℄ EL. 715'-6"

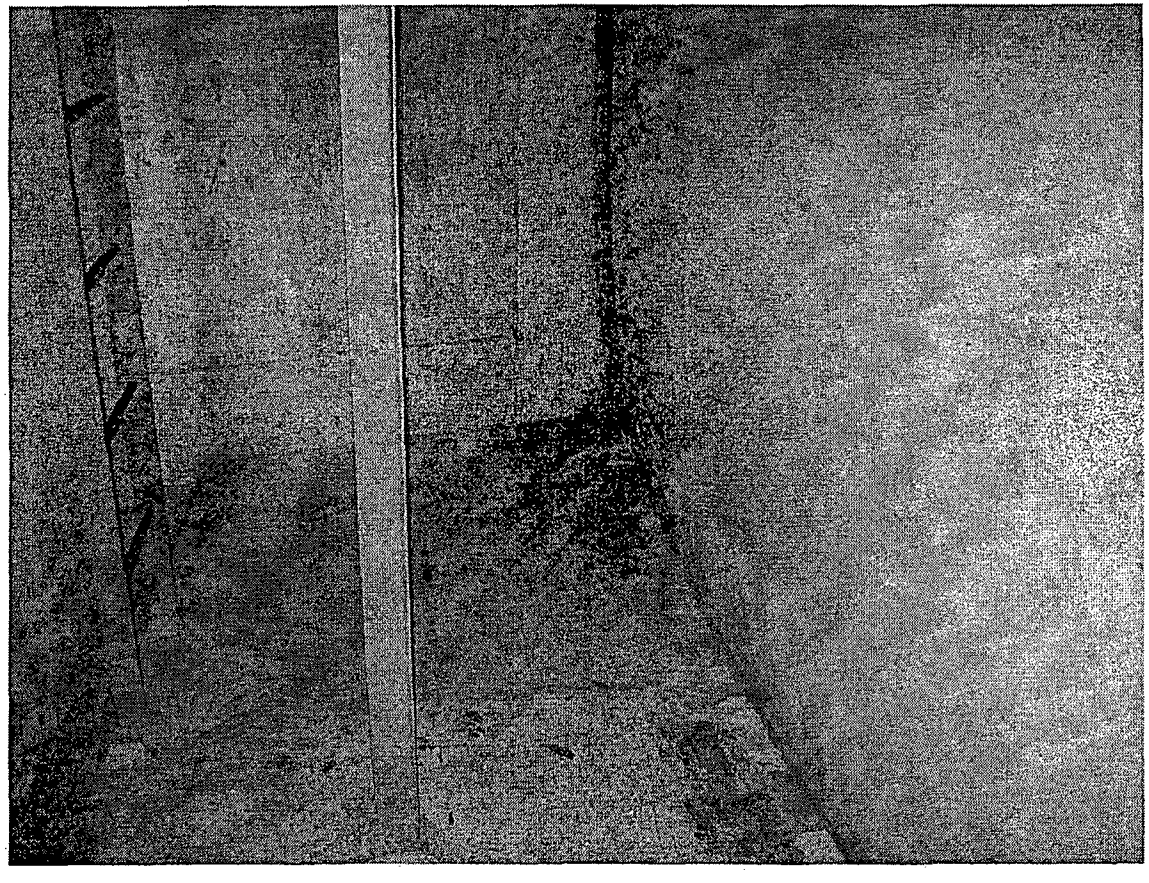
Prior Actions to Detect and Assess Degradation:

- 1998
  - Removed grout in Unit 2 Sump B for visual inspection of containment vessel
- 1998
  - Engineering Evaluation of Effects of Borated Water by Automated Engineering Services
- 2002
  - Removed grout in Unit 1 Sump B for visual inspection of containment vessel
- 2006
  - Review of 1998 Engineering Evaluation to assess exposure of containment vessel and structures from 1998 to December 2006
- 2008
  - Removed grout in Unit 2 Sump B with visual and UT examination of containment vessel. UT of containment vessel from annulus in area of expected leak path.

Inspection Results:

Visual and UT exam of containment vessel in sump B. No indications of degradation, some tool marking from concrete removal. Twelve UT readings all above 3.5 inch nominal plate thickness.

Inspection Results:



UT exam of containment vessel from annulus. Scanned 18' long x 2' high area with all readings above 1.5 inch nominal plate thickness.

Evaluation of Potential Degradation:

- Steel Containment Vessel
  - There are two general areas of the steel containment vessel that could be wetted by the leakage:
    - Area between the concrete and steel containment vessel between elevations 711' and 755' where the transfer pit and lower part of the refuel pool abut the steel containment vessel.
    - Area between the concrete and the steel containment vessel from elevation 711' and below, for the full circumference of the steel containment vessel.

Evaluation of Potential Degradation:

- Steel Containment Vessel
  - Tests at ambient temperature indicate the rates of corrosion of steel in aerated concentrated boric acid solutions range between 0.002 to 0.007 inches/year (Section 4.4.1 of the EPRI Boric Acid Corrosion Guidebook, Rev. 1).
  - 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. The test results provide an upper limit that can be used to 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.

Evaluation of Potential Degradation:

- Steel Containment Vessel
  - Because of the buffering effect of alkalinity from the concrete, the pH of the water in continuously wetted areas between the concrete and bottom head of the steel containment vessel is expected to have been in a range that inhibits corrosion of the steel, e.g., over about pH 12.
  - The expected amount of corrosion that has actually occurred in the wetted areas between the concrete and the inside surface of the steel containment vessel is less than 10 mils.

Evaluation of Potential Degradation:

- Steel Containment Vessel
  - Expected containment vessel corrosion is 10 mils with a conservative upper limit of 0.25 inch.
  - This amount of corrosion is a fraction of the 1.5" plate thickness and does not raise a risk of leakage through the containment vessel in the event of an accident.
  - Since the affected areas of the containment vessel are fully encased in concrete on both sides (below elevation 711') loads imposed on the vessel in the potentially thinned areas are minimal. Thinning by 0.25 inches would not be expected to challenge the ability of the containment vessel to retain accident pressure.

Evaluation of Potential Degradation:

- Concrete
  - The type and rate of attack caused by continuous exposure to boric acid for long periods has recently been quantified for two other plants.
  - The results can be applied to the Prairie Island case.

Evaluation of Potential Degradation:

- Concrete
  - The main effect of exposure of concrete to long term borated water leaks is the potential for degradation of the concrete that would start at the wetted surface and proceed inward.
  - Such degradation would involve dissolution of the cement binder by the acid and would leave unbonded aggregate with no strength.
  - Our evaluation of potential degradation at Prairie Island referenced an evaluation that was based on aggregates which were igneous in origin and included no aggregates that are soluble in acids, i.e., contain no carbonates.

Evaluation of Potential Degradation:

- Concrete
  - The aggregates that were used at Prairie Island were mostly igneous in origin, but did include about 5% carbonates that are soluble in acids.
  - About 10 to 15% of concrete is normally cement. All of this cement is soluble in acids.
  - The addition of about 5% soluble aggregate increases the percent of soluble material in concrete to 15 to 20% at Prairie Island considering both cement and carbonate-form aggregates.

Evaluation of Potential Degradation:

- Concrete
  - While it is not certain that this increase in soluble fraction will increase the rate of degradation, it is considered that any increase can be conservatively bounded by increasing the rate of degradation by a factor of two.
  - Applying this conservatism, an exposure of 15 days for each outage and assuming that the number of outages is 25 leads to a maximum depth of attack into the concrete after 36 years of 0.31 inches.

Evaluation of Potential Degradation:

- Concrete
  - The effects of 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 there is a four inch layer of grout that is not relied upon for strength. For the thicker walls of the refueling pool, the concrete cover was specified to be 5 inches. 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 walls, loss of 0.31 inches represents a loss of less than 1% and is insignificant from a structural and functional standpoint.
    - The variable thickness wall at the containment end has areas that appear to be approximately 10 inches in thickness at the transfer tube. Further evaluation of this area will be performed.

Evaluation of Potential Degradation:

- Concrete
  - 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.
  - 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.

Evaluation of Potential Degradation:

- Concrete
  - 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 further evaluation is required in the area with thinnest concrete near the transfer tubes.

Evaluation of Potential Degradation:

- Rebar
  - 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, 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.

Evaluation of Potential Degradation:

- Rebar
  - Corrosion of rebar can be initiated at chloride concentrations of 1000 ppm or more, depending on the level of carbonation and other factors.
  - Since the chloride concentration in the borated water observed in Sump B at Prairie Island is about 7 ppm or less, 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.

Evaluation of Potential Degradation:

- Rebar
  - Dissolution of calcium hydroxide from the concrete around rebar at cracks in the concrete could develop conditions that might lead to increased rates of corrosion of the rebar.
  - However, tests performed for another plant and other tests described in available literature indicate that corrosion in such situations has been negligible, even when the low pH borated water reaching the cracks was continuously refreshed.
  - It is thought that conditions at the rebar remain sufficiently alkaline to passivate the surface, despite the presence of refreshed borated water.

Evaluation of Potential Degradation:

- Rebar
  - Carbonation is a process in which carbon dioxide from the atmosphere either directly, or after dissolution in water, converts the calcium hydroxide in the concrete to calcium carbonate.
  - Carbonation can result in the pH decreasing from over 12.5 to about 8.3. In this lower pH range, corrosion of rebar can occur, although generally at a low rate.
  - Carbonation progresses through concrete at a relatively low rate. For a medium strength concrete in an indoor environment, carbonation will have reached a depth of about 25 mm in 25 years. Fitting an equation to the data and extrapolating to a time of 36 years indicates that the depth of carbonation will be about 30 mm, or 1.2 inches.

Evaluation of Potential Degradation:

- Rebar
  - 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.
  - The thickness of the cover on structural concrete in the reactor building may vary 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.

Evaluation of Potential Degradation:

- Rebar
  - Corrosion of the periodically wetted 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 typical indications of corrosion of rebar and their absence shows 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.

Evaluation of Potential Degradation:

- Rebar
  - The rate of corrosion of carbon steel in borated water at near-neutral pH is at most about 0.007 inches per year.
  - 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 0.007 = 0.014 inches, which is insignificant.

Evaluation of Potential Degradation:

- Rebar
  - 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.
    - The concrete cover in the area in contact with the lower shell of the containment is specified as 1-1/2 inches.
    - If this area has remained moist, carbonation will occur at about 2/5 of the rate that would occur in an indoor dry environment (the presence of moisture inhibits penetration of the carbon dioxide into the concrete).
    - 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.

Evaluation of Potential Degradation:

- Rebar

  - 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.
  - For example, if one assumes that the area was wetted half the time, and that carbonation occurred at twice the estimated rates (2.4 inches in 36 years in an indoor air environment and 0.96 inches in a moist air environment), the average rate of carbonation would be 1.7 inches in 36 years, such that carbonation would have reached the rebar in (1.5/1.7)(36) = 31.8 years.

Evaluation of Potential Degradation:

- Rebar
  - Thus, corrosion at a neutral pH rate would be limited to only 36-31.8 = 4.2 years. At the upper limit rate of 0.007 inches per year, the depth of corrosion would be (4.2)(0.007) = 0.029 inches, which corresponds to a 6% reduction in rebar area and is not considered significant since the actual thinning is expected to be much less.
  - Since the water is stagnant in this area, dissolution of calcium hydroxide from non-carbonated concrete just beyond the carbonation front is expected to raise the pH to a protective level, such that actual corrosion rates will be much lower than the conservatively assumed value of 0.007 inches/year.

Evaluation of Potential Degradation:

- Reinforced Concrete – Overall Conclusions
  - 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.
  - The reinforced concrete structures in the lower regions of the reactor buildings remain capable of meeting design requirements.

Evaluation of Potential Degradation:

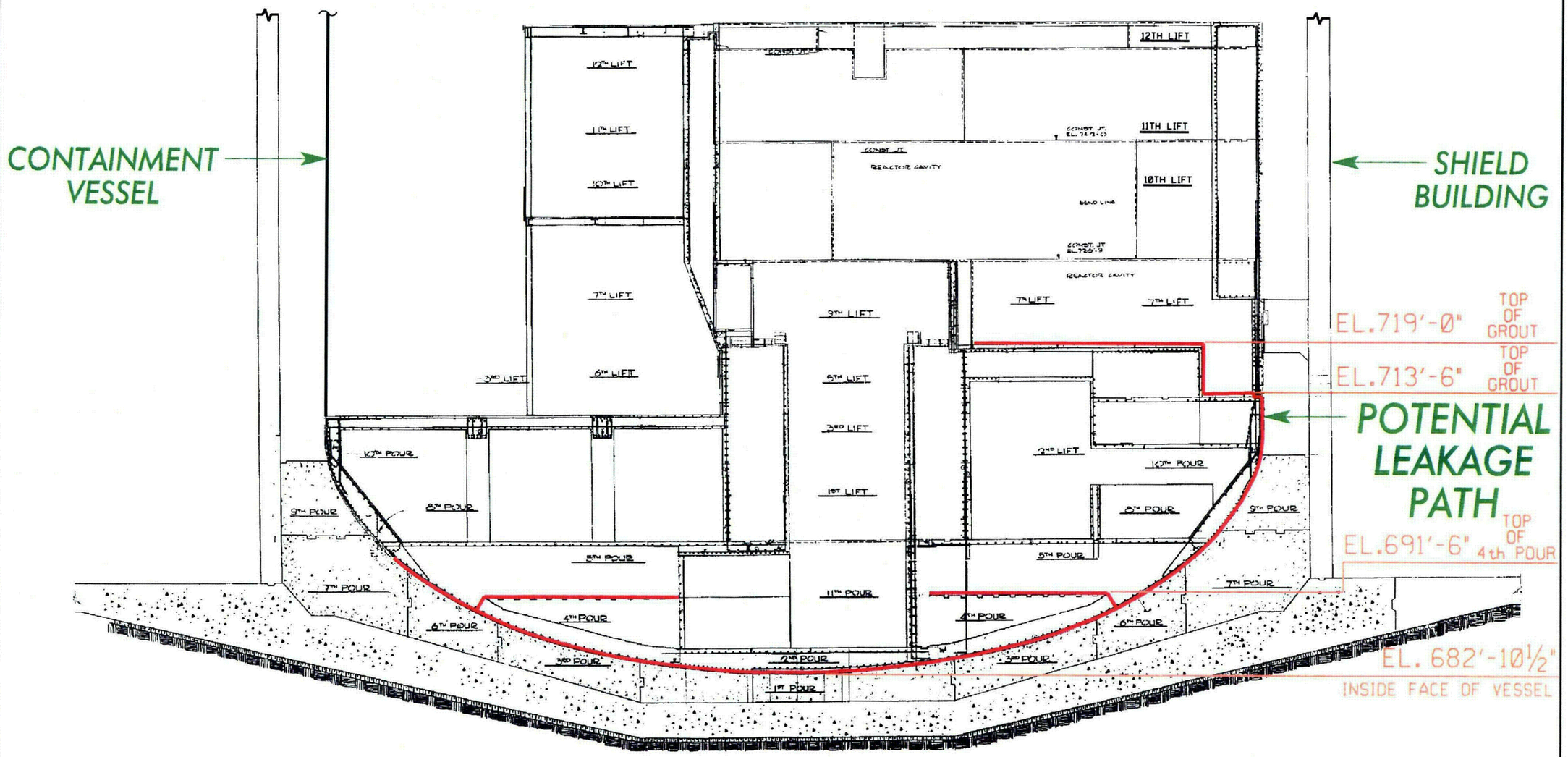
- Reinforced Concrete – Overall Conclusions
  - Exception
    - If degradation of concrete inside the liner should occur in the area around the transfer tube, it could represent a significant fraction of the wall. Accurately determining the concrete thickness in this area was not possible with the drawings readily available.
    - Based on rough scaling, the thickness could reach a minimum of approximately 10 inches. The estimated maximum degradation thickness of 0.31 inches would be about 3%, which could be significant if the concrete in this area is highly loaded.
    - This issue will be resolved by further evaluation.

Corrective Actions – Leakage Source:

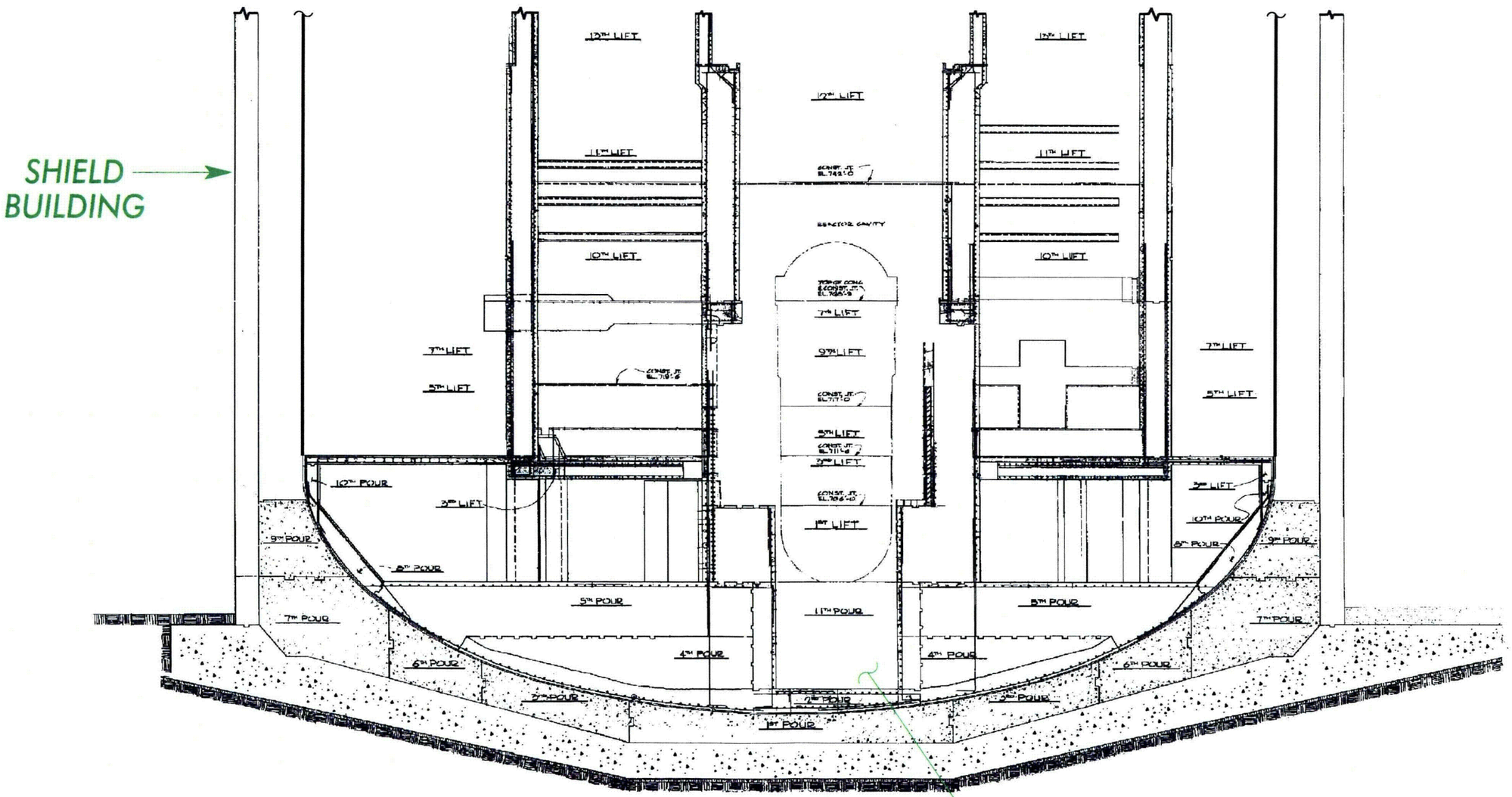
- Eliminate leakage at the internals stands and RCC Change Fixture anchors through repair and/or modification

Corrective Actions – Containment Impacts:

- Remove concrete from sump below reactor vessel (sump C) - during subsequent outage following refueling cavity repairs
  - Inspect (UT) containment vessel near low point
  - Evacuate any remaining water
- Complete a margin assessment of the vessel, concrete and rebar to determine amount of allowable degradation
- Perform more extensive evaluation/analysis of structural requirements and potential degradation in area around transfer tubes

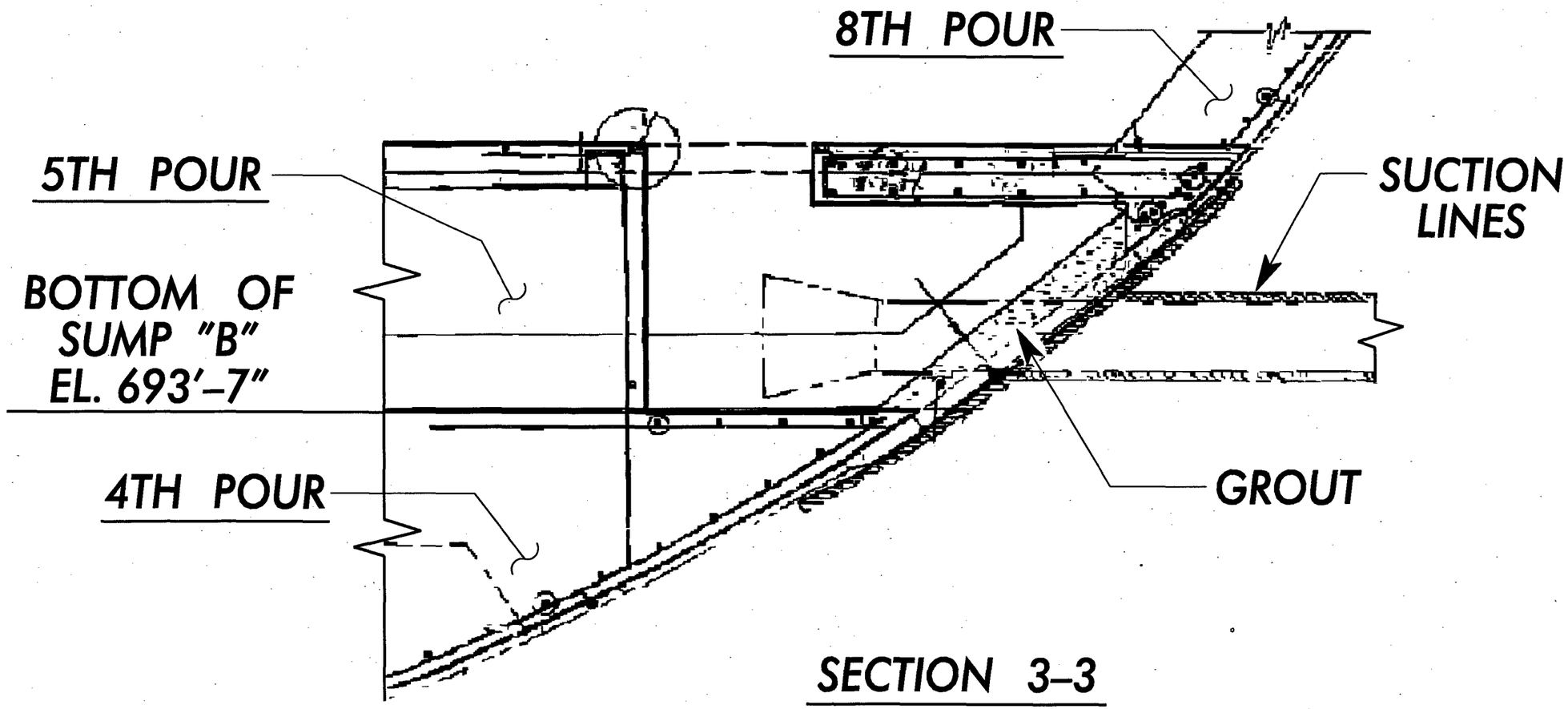


Unit 2 Containment
Section 1–1

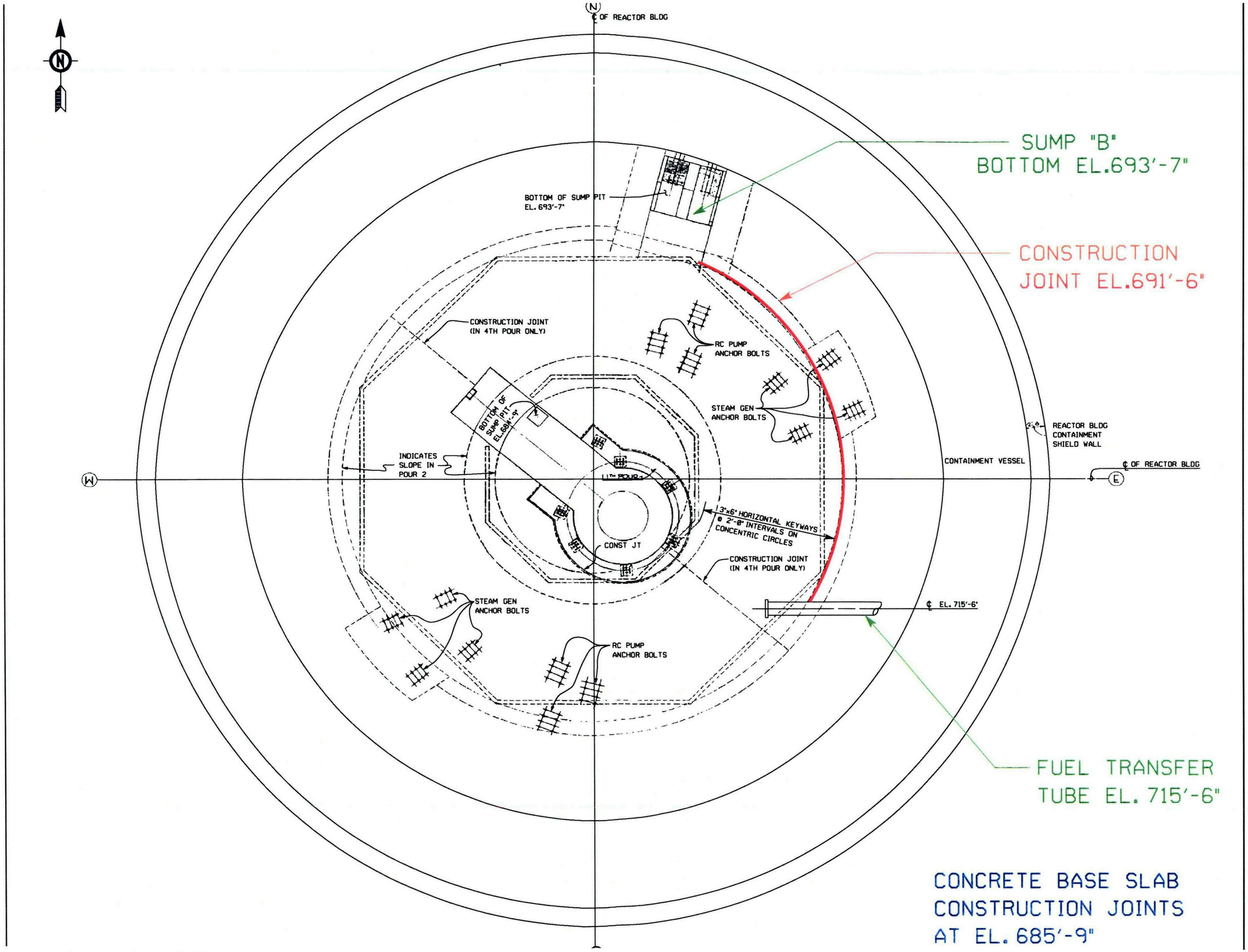


Unit 2 Containment
Section 2–2

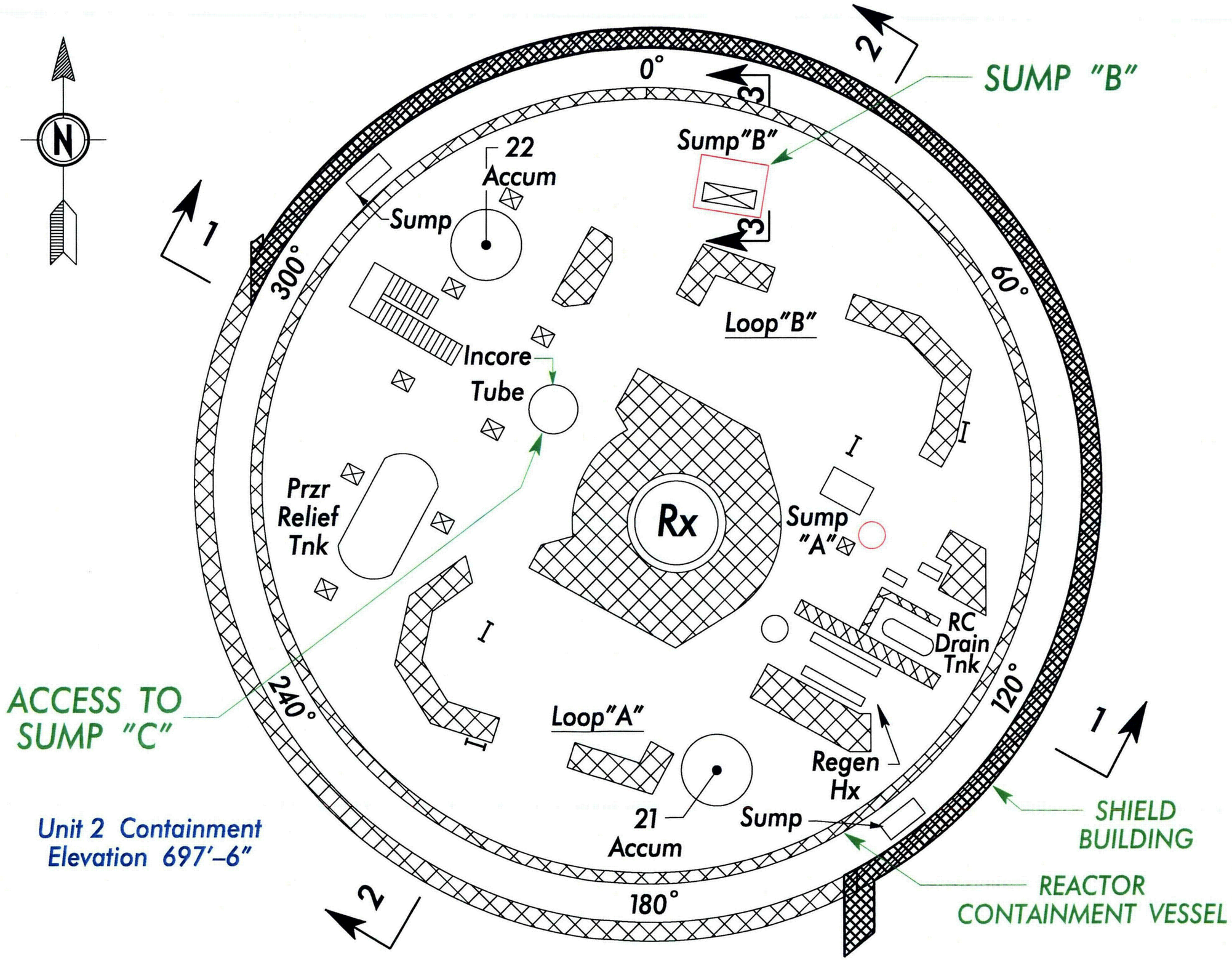
SUMP "C"
BOTTOM EL. 685'–9"

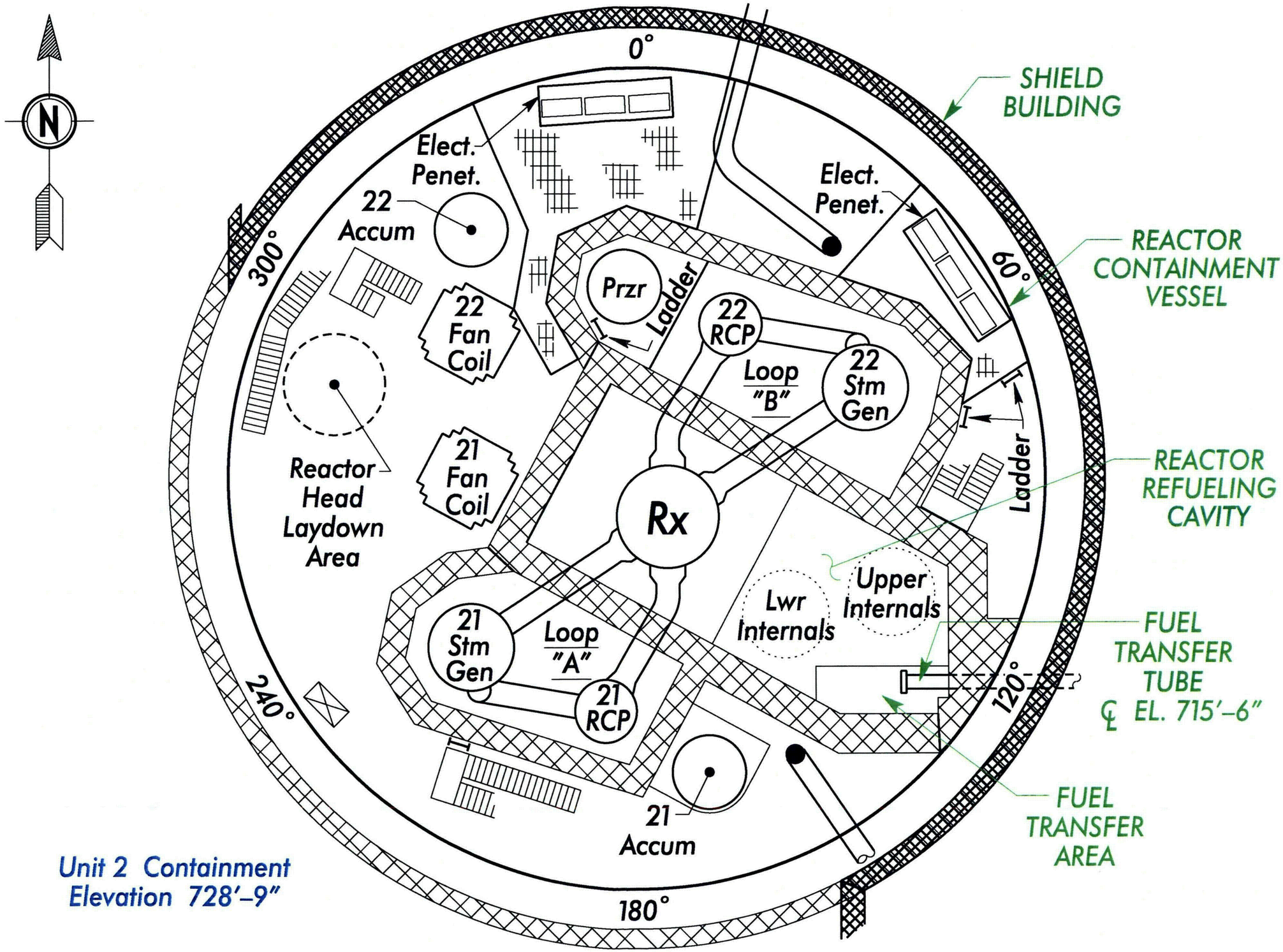

8TH POUR
5TH POUR
SUCTION LINES
BOTTOM OF SUMP "B" EL. 693'-7"
4TH POUR
GROUT

SECTION 3-3



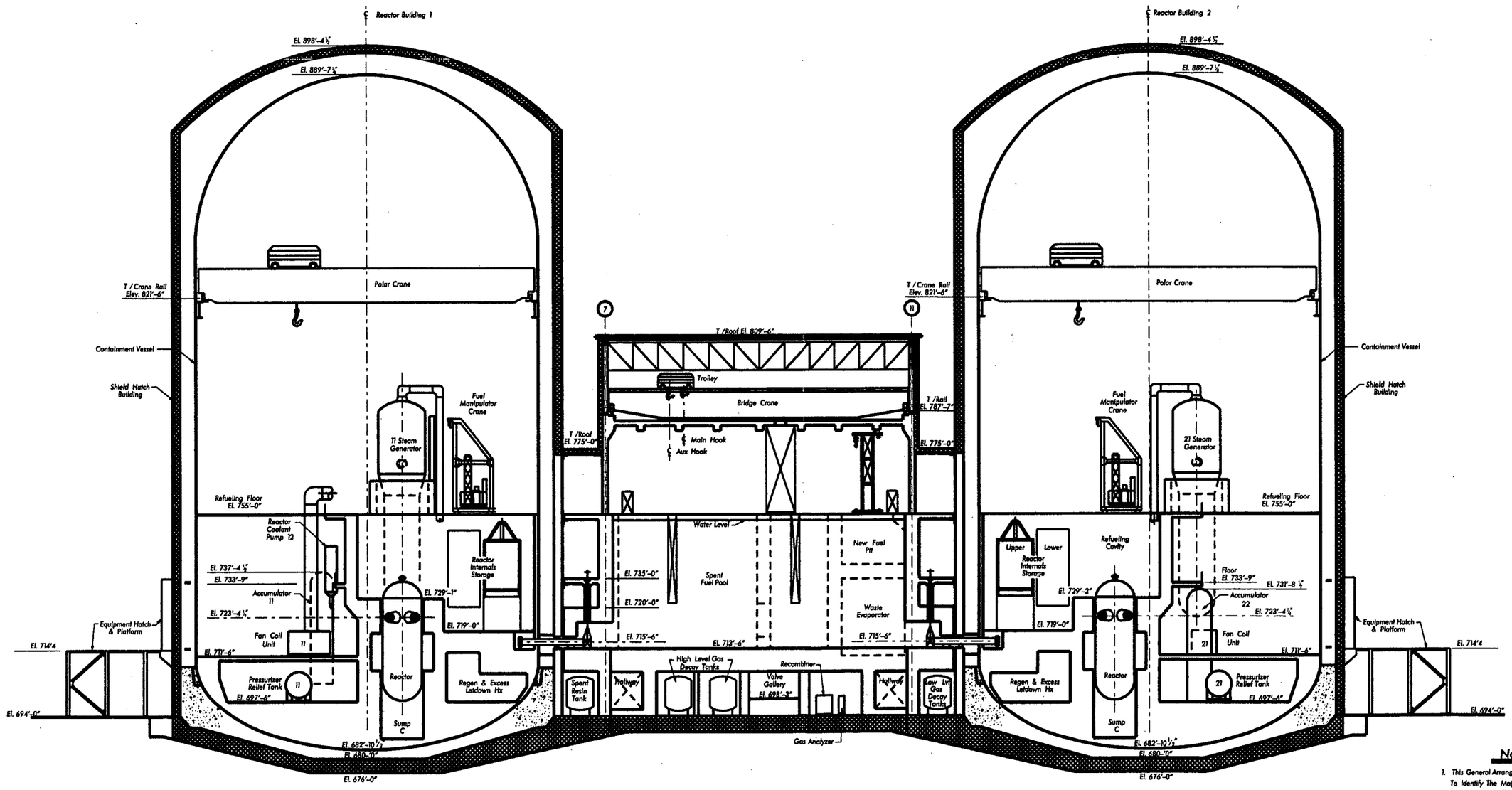
CONCRETE BASE SLAB
CONSTRUCTION JOINTS
AT EL. 685'-9"


N
0°
60°
120°
180°
240°
300°
1
2
3
SUMP "B"
Sump"B"
22
Accum
Sump
Loop"B"
Incore
Tube
Przr
Relief
Tnk
Rx
Sump
"A"
RC
Drain
Tnk
Loop"A"
Regen
Hx
21
Accum
Sump
ACCESS TO
SUMP "C"
SHIELD
BUILDING
REACTOR
CONTAINMENT VESSEL
Unit 2 Containment
Elevation 697'-6"



Unit 2 Containment
Elevation 728'-9"

REVISIONS



ELEVATION VIEW

Note:

1. This General Arrangement Drawing Is Intended To Identify The Major Plant Structures And Equipment In Sufficient Detail To Provide A Reasonable Understanding Of The Layout Of The Facility And Those Features Of Special Interest To Safety. This Drawing Does Not Depict All Installed Structures And Components.

– Aux. Bldg. Radiological Controlled Area

DWN KK	DATE 1-4-01	SIGNIFICANT NO.	8630					
CHECKED		GROUP	1	2	3	4	5	CL 6
PROJECT NO.								
APP'D & CERT.								
FILMED								

UNIT 1 & 2 ELEVATION VIEW
LOOKING SOUTH
RADIOLOGICAL CONTROLLED BOUNDARIES

NORTHERN STATES POWER COMPANY
PRAIRIE ISLAND NUCLEAR GENERATING PLANT
RED WING, MINNESOTA

SCALE 3/32" = 1'-0

FIGURE 12.3-6 REV 23