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Preliminary Durability Performance Evaluation of Torus Base Mat in Pilgrim Station

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Date: March 27, 2007

Executive Summary: The objective of this report is a preliminary durability evaluation of the effect of the observed groundwater intrusion on the structural performance of the 8 ft thick Reactor Building base mat in Entergy's Pilgrim Station. Based on observations and documents shared by the Entergy team with the author, the following conclusions are drawn:

1. The groundwater migration through the 8ft. thick Reactor Building base mat is a highly localized phenomenon. It is caused by a 25ft hydraulic head difference, pushing groundwater through vertical joints and zones most likely weakened by tensions generated during setting and hydration following the construction. These localized zones are discontinuities equivalent to a vertical cylindrical hole of a maximum diameter of 4 mm (1/6th in). Such small discontinuities that originate from construction joints are inevitable in large-scale concrete engineering operations.

2. This highly localized nature of the zones through which water penetrates, does not compromise the overall structural performance of the Torus base mat: it does neither affect the bulk integrity of the concrete slab, nor the overall compressive and bending load bearing capacity of the reactor foundation.

3. Calcium leaching of the solid concrete is expected to take place in the localized zones through which water penetrates. While this localized calcium leaching does not affect the overall structural performance of the slab, it may contribute to further weakening the construction joints, and may eventually have degraded the grout in the annular space between the 3 in diameter hole and the 2 in diameter Williams rock anchors. A close-up inspection of the grout and bolt is recommended.

4. The lower pH-value of 9.3–9.4 of the water emerging from localized zones along the construction joints, compared to the typical pH~12 of concrete's bulk pore solution, is consistent with the calcium leaching observation. Its localized occurrence does not compromise the corrosion protection of the steel reinforcement in the slab. A refined corrosion indicator analysis is recommended to confirm the prevention or minimization of reinforcement and anchor bolt corrosion.

1. Objective

The objective of this report is a preliminary durability evaluation of the Torus Mat in Entergy's Pilgrim Station. This report is based on observations and documents shared by the Entergy team with the author during and following the visit on Monday, January 19, 2007 to Entergy's offices in the Pilgrim Station.

2. Observations[1]

The 8 ft thick Torus mat is part of the reactor building foundation, and surrounds the much thicker core vessel foundation. The Torus mat is divided into 16 Torus room bays, with bay #2 being the most south, and bay #10 the most north, where the ocean is situated.

At any point in time water may be observed on the floor of one or more Torus room bays, puddled at the low point under the invert of the Torus. The maximum water depth may be about ½ inch or more, but generally limited to the area directly beneath the Torus shell. The wetted areas of the floor have not extended out from under the Torus, and pumping for removal has never been required. Some of remaining bays having no water may have crystal residue indicating they were once wet. Several other bays show no evidence to suggest that they were ever wet. These are bays #16, 1, 2, 3 and 4, which are all situated on the south side of the reactor foundation, i.e. the furthest away from the sea.

Conditions associated with water seepage into the Torus room have been reported in the early 1980s but may have existed even before then. In the early 1980s seepage was reported at the junction of the drywell pedestal and the Torus room floor, in Bay #15. In the late 1990s, Torus room conditions were evaluated by Engineering. The most probable cause of water seepage was attributed to groundwater by-passing the waterproof membrane that encapsulates the Reactor Building 8 ft. thick base mat. A 25 ft. hydrostatic head forces water through the mat at discontinuities such as construction joints, anchor bolts holes or other features that result in reduced head losses. This conclusion was based on the following observations and operating experience with membrane designs similar to Pilgrim:

- A portion of the floor in Bay #10, adjacent to the Torus saddle common to Bay #11 (situated on the north side), was dried, cleaned and isolated with a berm. Within the berm is a Williams rock anchor installed in the early 1980s to secure the Torus saddles for pipe break accident uplift conditions. Within about a day, water reappeared on the floor within the berm. There were no visible cracks on the floor surface, suggesting that the water was coming up from the anchor hole drilled in the slab, or from beneath the torus saddle base plate.
- The water was sampled and not found to be contaminated to an extent that would indicate an active plant system leak. Some radioactive contamination was found but this was believed to be the result of plant system leaks that occurred much earlier in the plants operating history.

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[1] John Dyckman, email March 20, 2007

- There were no active plant system leaks that could result in water on the Torus room floor.
- The seepage rate appears to be at steady state with evaporative losses, hence the floor surface within any bay never fills completely.

3. Methodology

Based on these observation, and additional information about the construction history of the reactor building foundation, the tasks of this preliminary durability performance evaluation are:

(1) To identify the most likely cause of the observed seepage into some Torus room bays, and

(2) To estimate the effect of this cause on the integrity and performance of the base mat foundation.

(3) Finally, some preliminary conclusions are drawn together with recommendations for further investigations.

4. Analysis

4.1 Correlating Construction History and Occurrence of Water Seepage

The job drawings of the construction sequence and photos taken during the construction indicate that the Torus mat was constructed first before the massive core foundation was put in place. In particular, the construction of the Torus mat was divided in four concrete segments, staring with the North-West Corner, followed by the South-East Corner, the North-East Corner and finally the South-West Corner. Finally, the central core foundation was poured. As such there are a total number of four construction joints between the four mat segments, in addition to the joint between the core foundation and the surrounding Torus base mat. It has been earlier suggested that those construction joints could be the preferential path for water seepage.

In order to check this suggestion, Figure 1 overlays in a plan view the pouring sequence with concrete joints and the bays in which water seepage has been observed. There appears to be a clear correlation between the construction sequence and the locus of occurrence of water. In particular:

(1) The water seepage observed in Bay #6 and #10, situated respectively on the North and the East side of the reactor foundation are situated in bays delineated to the inside by the core-mat construction joint, and separated in the center of the bay by one mat-to-mat construction segment joint.

(2) The water seepage observed in bays #7, #11 and #13 are all delineated to the center by a core-mat construction joint characterized by a kink forming a more-or-less sharp wedged geometrical discontinuity.

There appears to be, therefore, a strong indication in favor of the suggestion that the preferential paths for water seepage are construction joints. From a concrete material perspective, concrete construction joints are well-known to be the weak spot of any concrete engineering application, due to so-called "wall effect", leading during pouring of the fresh concrete to a higher water-concentration compared to bulk concrete. This higher water concentration available for cement hydration leads to a higher final porosity of the concrete in the immediate surrounding (typically a fraction of 1in) of the joints than in the concrete bulk. Since the flow of water occurs through this porosity, concrete construction joints form a preferential path for fluid conduction, as analyzed later on. With regard to the occurrence of water in specific bay areas, the following additional observations are made:

(1) In bay #6 and #10, it is most likely that the water seepage originates from the 'T' junction of the mat-mat joint with the core-mat joint.

(2) The fact that the core foundation was constructed only after the mat may have had some important implications on the stresses that were most likely generated during the concrete hydration. In fact, since hydration is an exothermic reaction, heat is generated during hydration, which leads to high temperature rises in massive concrete elements. This heat is transported through the concrete surface leading to a cooling over time of the concrete, until the concrete element reaches the ambient temperature [1]. Given the construction process, the base mat which had been poured first, must have been already in a state of cooling, when the much thicker core foundation was poured. Given the massive dimensions of the core foundation, the temperature in the core foundation is expected to have followed an almost adiabatic temperature rise. This temperature differential between the cooler mat and the hot core generates circumferential tension stresses in the mat immediately adjacent to the concrete joint. Indeed, a rough analysis of the stresses surrounding the core foundation shows that the circumferential (or hoop) stresses in the immediate vicinity of the joint are in tension if the temperature rise in the core had been twice the temperature rise in the mat. These stresses are amplified, in bay #7,#11,#13 by the presence of the wedge-shaped joint, leading to a significant stress amplification due to stress concentration which is typical for geometrical discontinuities. It is, therefore most likely that those wedge-shaped corners may have been additionally weakened during the differential hydration, forming some preferential path for water seepage.

(3) The fact that most water seepage observed occurred on the North side may well be related to the direction of water flow below the foundation, flowing towards the sea situated on the North side.

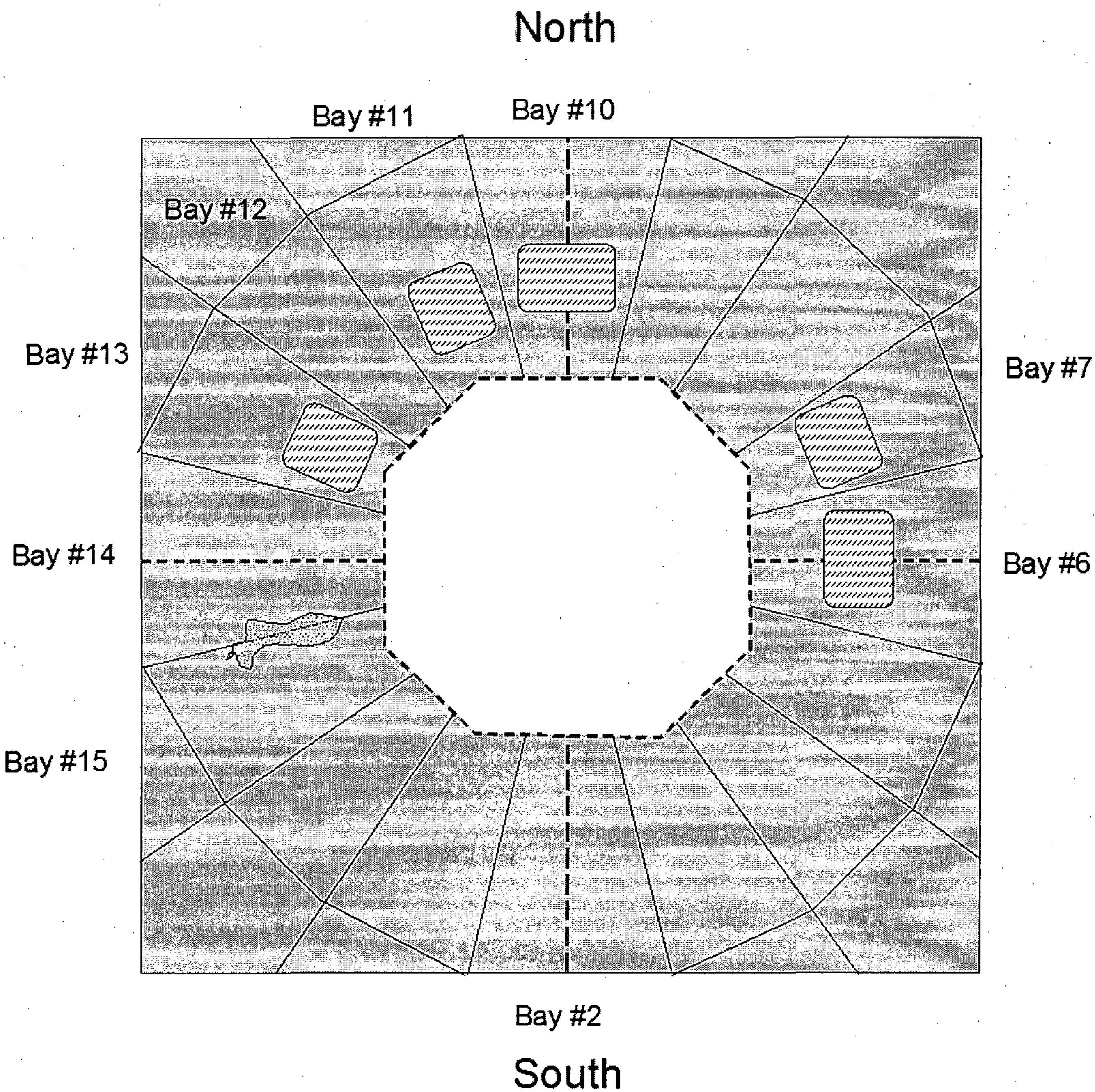

Figure 1: Correlating concrete construction sequence with water seepage occurrence: The dashed lines represent construction joints (re-constructed from shop-drawings), the patches represent observed water seepage in specific bays.

It should be noted that those phenomena (higher porosity of concrete close to joints, microcracks around geometrical discontinuities) are almost inevitable in massive concrete engineering applications due to the high exothermic nature of cement hydration. It is for this reason that concrete design codes specify a minimum amount of steel reinforcement, which needs to bridge concrete construction joints. This reinforcement ensures the structural performance of the slab, despite some localized concrete material weakness along construction joints. This reinforcement, however, cannot eliminate neither the higher material porosity, nor the occurrence of microcracks. It may eventually limit the microcrack opening and propagation; thus ensuring the structural performance of the concrete foundation.

4.2 Seepage through Concrete Bulk and Construction Joints

The most likely source of the water seepage observed on the Torus floor is due to groundwater infiltration driven by the hydraulic head of the pore fluid under gravity forces. For purpose of analysis, the following assumptions are made:

- The porosity of the 8 ft concrete mat is assumed to be fully saturated by liquid water. This seems to be a reasonable assumption, given that the 8 ft thick concrete slab would take some centuries[2] to dry to a level in equilibrium with the ambient humidity conditions inside the Torus room (see, for instance, [2,3]).

- The 8 ft concrete slab is sufficiently homogeneous throughout its thickness. This allows one to condense the flow into a single material parameter, the intrinsic permeability of concrete. For bulk concrete, typically values for the intrinsic permeability reported in the open literature vary between 10^{-17}–10^{-16} m^2, depending on the concrete mix proportion and curing conditions (see, for instance, [4]). The concrete composition and massiveness of the Torus base mat is indicative of an intrinsic permeability of 10^{-17} m^2.

Under these assumptions the mass flux rate through the 8 ft concrete slab can be estimated using Darcy's Law. For reference, we first estimate the mass flux rate through the concrete bulk. For an hydraulic head difference of 24.5 ft between the bottom of the slab and the surface and an intrinsic permeability of 10^{-17} m^2, these calculations yield a mass flux (per unit surface) through the concrete bulk of Q=0.02 kg/ (m^2day) which amounts to 6.2 kg/ (m^2yr). Such a small amount of water (which generates daily a water film 17μm thin) is expected to evaporate almost instantaneously, and it is a clear indication that the water flux through the concrete bulk porosity cannot be at the origin of the observed water seepage. It hints towards a very localized nature of the water penetration. Furthermore, the small value is a benchmark value for a first-order estimate of the size of the joint openings through which the water flow occurs.

Indeed, it was observed that in a previously dried area water reappeared within a day or two generating a water film on-average 1/4 in thick[3]. This observation translates into a

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[2] Drying of concrete is an extremely slow process. It takes some 10 years to dry a slab of 12 cm thickness exposed on both sides to ambient conditions. The drying duration increases with the square of the thickness. Hence, over the last 35 years, the drying front in the torus room may have reached a depth of $x = (35/10)^{0.5} \times 6 = 11.2$ cm = 4.4 in, which is negligible (5%) compared to the base mat thickness of 8 ft. In return, this drying may have caused some microcracking (almost invisible to the eye) in the concrete surface, expanding roughly half the depth of the drying front [3]. This microcracking scales with the mass loss and is little affected by an increase of the amount of steel reinforcement.

[3] John Dyckman, email March 16, 2007.

water flux of Q=3.2-6.4 kg/(m^2day), which is substantially greater than the water flux through the concrete bulk.

One can attempt to link this high flux rate to the space through which the flow occurs, by considering the flow of water through a cylinder of radius a in a cross section A (see, for instance [5]). In this simple model representation of the flow along the joints, the cylinder represents the joint opening, while the cross section represents the wetted surface in consequence of the flow through the cylinder. These calculations provide an upper-bound estimate of the cylinder radius representing the characteristic size of the joint opening, and yield values for the pore throat radius in functions of the wetted surface area. The results which are displayed in Figure 2, indicate that the equivalent cylindrical "joint" opening, is on the order of 1-2 mm (~1/25 – 1/12 in) for wetted surface areas of 5-20 m^2 (~50–200 ft^2) which was observed in some bay areas.

It should be noted that this rough model overestimates the joint opening because it cumulates all possible joint openings into one single cylindrical shape. On the other hand, it provides an upper-bound estimate of the order of magnitude of the joint opening, which is expected to be in the sub-millimeter range, but substantially greater than the typical capillary pore size of concrete which is in the micrometer range.

In all cases, the order of magnitude estimations of the water flow generated by the hydraulic head difference is clear evidence of a mal-functioning of the water-stop PVC membrane originally designed to control seepage at concrete construction joints.

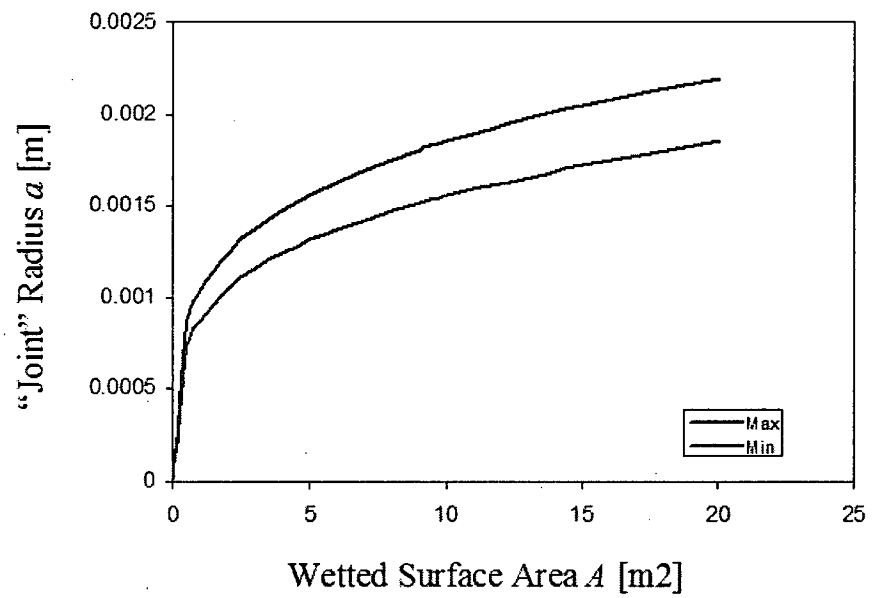

Figure 2: Estimated equivalent cylindrical joint size as a function of the wetted surface area. The upper curve is based on water re-appearance within one day, the lower curve on water re-appearance in two days.

4.3 Effect of Calcium Leaching

When concrete is put in contact with water having a lower calcium concentration than the equilibrium calcium concentration, calcium is leached from the concrete into the pore solution. The equilibrium concentration of calcium in the pore solution is roughly 480 mg/L (see e.g. [6-7]), meaning that if the calcium concentration in the pore solution is below this threshold value calcium is dissolved ("leached") from the solid into the pore solution. The consequence of leaching is a substantial increase in the porosity (due to the dissolution of Portlandite) and a substantial loss in mechanical stiffness and strength properties [6,8].

Water collected from the Torus room and analyzed chemically[4] showed a calcium concentration of 230 mg/L, which is smaller than the equilibrium calcium concentration. As a consequence, it cannot be excluded that calcium leaching occurred along the preferential path of groundwater intrusion. In favor of this suggestion is the observation that evaporation residues furthermore show a 31mw% of calcium[5].

Fortunately, calcium leaching is a very slow process: the calcium leaching front advances 0.115 mm/√day; which means that over the last 35 years the leaching may have dissolved the calcium in a layer maximum 13 mm (~1/2 in) thick. In other words, in the life span of the power plant, calcium leaching has no effect on the bulk integrity and structural performance of the concrete foundation. On the other hand, it cannot be excluded that calcium leaching may have contributed to the weakening of the construction joints over the years. In fact, the calcium leaching may have contributed to the joint opening through which groundwater (at a lower calcium concentration than the equilibrium concentration) penetrates. The way by which calcium leaching is most likely to affect the joint opening is sketched in Figure 3, showing dissolution fronts originating from the bottom side around a joint (left). The figure shows that the dissolution generates a vertical wedge-shaped dissolution pattern around the joint, which propagates upward through the slab in a self-similar fashion. These dissolution fronts scale linearly with the water-velocity in the joint and the joint opening [9]; which means that the higher the water flow through the joint, the more advanced the vertical position of the degraded zone.

Measurements of the flow rate through the joints could make it possible to estimate the current height of the leaching front in the 8 ft base mat. In the absence of such measurements, it is not possible to exclude that leaching by groundwater may have reached the grout of the Williams rock anchored (2ft below surface), leaching the calcium of the grout in the annular space between the 3 in diameter hole and the 2 in Williams rock anchor.

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[4] Northeast laboratory Services Report, dated 03/19/2007.

[5] Northeast Laboratory Services Report, dated 03/15/2007.

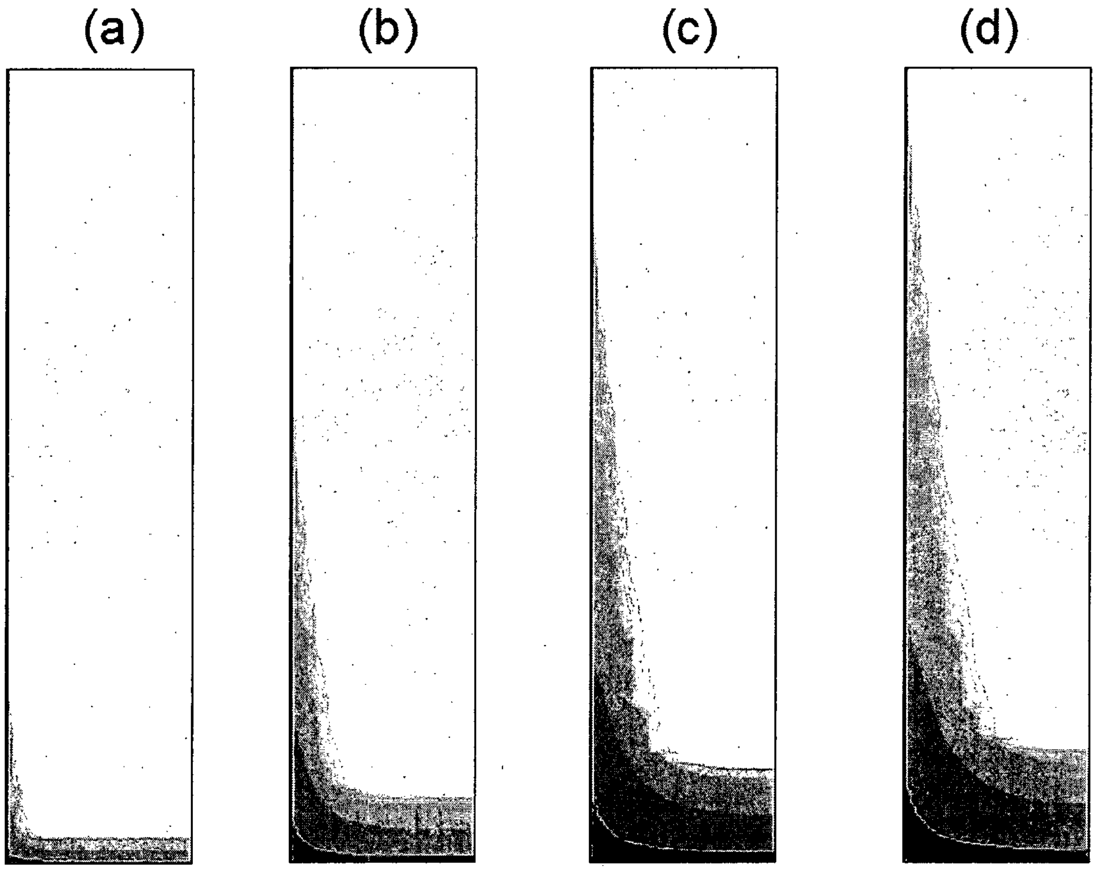

Figure 3: Dissolution Fronts around a joint through which water flows with a lower calcium concentration than the equilibrium concentration. For a flow velocity of V=10 cm/d and a joint opening of 0.4 mm, (a) 27 years; (b) 158 years; (c) 318 years; (d) 438 years. The vertical height in this figure is 5 cm (reproduced from [9]).

4.4 Effect of pH Value

Compared to the groundwater (pH ~ 6.7)[6], the water collected in the Torus bay has a pH value of 9.3 – 9.4[7]. This pH value is below the typical pH~12 value found in the highly basic interstitial pore solution of concrete, and it is consistent with the observation of a lower-than-equilibrium calcium concentration in the water seepage. Given the very low flow rates through the bulk of the concrete slab, it is reasonable to expect that a high pH~12 value prevails in the pore solution of the concrete bulk, while the slightly lower pH value of 9.3 – 9.4 only occurs locally in the water penetrating through the joint openings. In all cases, both pH values are in a range that should prevent or minimize reinforcement corrosion. To ascertain this suggestion, a refined chemical analysis of the water may be helpful, one in which not only the pH value is measured (which represents the H^+ cation concentration), but as well other quantities, such as the Cl^-/OH^- concentration ratio in water. Such corrosion indicators have recently been identified to

[6] SAIC Report dated July 17, 2006.
[7] Northeast laboratory Services Report, dated 03/19/2007

provide a more comprehensive measure of the onset of corrosion, as it requires a critical amount of Cl^- to start the corrosion (see, for instance, [10] and references cited herein).

5. Summary of Analysis and Recommendation

The analysis of observations and documents relating to the groundwater intrusion into some bays of the Torus room allows for the following preliminary conclusions:

1. The observed groundwater penetration is a highly localized phenomenon. It is caused by the high hydraulic head difference, pushing groundwater through vertical joints and zones most likely weakened by tensions generated during setting and hydration following the construction. These zones are discontinuities equivalent to a vertical cylindrical hole of a maximum diameter of 4 mm (1/6th in).

2. The calcium concentration of the collected groundwater is smaller than the equilibrium calcium concentration in cementitious materials. As a consequence calcium leaching is expected to take place. The highly localized nature of the water penetration ensures that this leaching has no effect neither on the bulk integrity of the concrete, nor on the overall structural performance of the reactor foundation. (In fact, a vertical cylinder of 4 mm diameter in a ~142 ft x 142 ft foundation slab, will not compromise neither its compressive load distribution function nor the bending capacity of the slab.)

3. Thus, the effects of calcium leaching are localized around the vertical joints and other vertical discontinuities present in the slab. Depending on the flow velocity, leaching may have affected the grout in the annular space between the 3 in diameter hole and the 2 in diameter Williams rock anchor, compromising the grout's stiffness and strength. It is recommended to inspect whether the grout has been chemically degraded.

4. The lower pH-value of the collected groundwater is consistent with the observation of a lower-than-equilibrium calcium concentration. Since the phenomenon is localized around some weak spots along the construction joints, it is unlikely that this locally lower pH value substantially increases the risk of reinforcement corrosion. To further prevent and minimize the risk of reinforcement corrosion, a refined chemical analysis is recommended to measure relevant corrosion indicators, such as the Cl^-/OH^- concentration ratio, and to compare those corrosion indicators with now well-established corrosion thresholds [10]. A close-up inspection of the Williams rock anchors may complement this evidence of a non-detectable corrosion risk.

In summary, the analysis provides evidence that the observed groundwater penetration does not compromise the structural performance of the Torus base mat. It is recommended that any corrective measurement should be based on a prior identification of the exact location of the weak points along the construction joints, and a detailed analysis of the degradation state of both the grout and the bolt of the William rock anchor system.

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