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Review of Failure Modes Applicable to Prestressed Concrete Containments

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ABSTRACT

Prestressed concrete containment structures are subject to performance loss primarily due to aging and degradation. Many nuclear power plants (NPPs) have extended operating licenses beyond the design life of 40 years and some are considering operation for up to 80 years. The focus of this review is to determine which modes of performance loss, or 'failure modes', are most applicable to prestressed concrete containment vessels (PCCVs) beyond the age of 40 years. A list of failure modes taken from Crystal River Nuclear Plant Special Inspection Report is analyzed for applicability to aging nuclear containment structures. Each failure mode is described and discussed in detail. A table is provided to highlight the severity of each failure mode.

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EXECUTIVE SUMMARY

Prestressed concrete containment structures are subject to performance loss primarily due to aging and degradation. The focus of this review is to determine which modes of performance loss, herein referred to as 'failure modes', are most applicable to prestressed concrete containment vessels (PCCVs) beyond the age of 40 years. Many nuclear power plants (NPPs) have extended operating licenses beyond the design life of 40 years. Some are reaching the end of the extended license (60 years) and owners of these plants are considering application for extending the license to 80 years. A comprehensive review of potential failure modes for PCCVs—and prestressed concrete structures in general—is required. The list of failure modes (FMs) discussed herein is taken from Crystal River Nuclear Plant Special Inspection Report from the US Nuclear Regulatory Commission (NRC) [1]. Some portions of this review will reference specifics from the incident at Crystal River Nuclear Plant.

A summary of the events at Crystal River NPP is included here for the reader's benefit as is an image of the delamination crack that occurred (Figure 1). An excerpt from Crystal River Unit 3 (CR3) NRC Inspection Report:

> "Crystal River shut down for a planned refueling outage on September 26, 2009. One of the major work activities planned for this outage was a steam generator replacement. In order to take the old steam generators out and put the new steam generators in, the licensee created a construction opening in the side of the containment building. On October 2, 2009, while creating this opening, workers saw that there was a gap, or separation, affecting the outer layer of concrete of the building wall. The gap or separation in the concrete has been commonly referred to as a delamination.
>
> …
>
> The licensee's investigation concluded that the delamination was caused during the creation of the opening in containment. As part of preparing the containment building for making the opening, tendons in the containment building wall were detensioned. The main cause of the delamination was attributed to the scope and sequence of this tendon detensioning. Tendon detensioning began after the plant was shut down in Operating Mode 5, when containment operability was not required."

Figure 1. Delamination crack running from horizontal tendon to horizontal tendon, parallel to the wall surface, approximately 10 inches deep (photo taken after partial concrete demolition). [1]

In addition to the analysis of the delamination at CR, the Expanded Material Degradation Assessment (EMDA) Report, NUREG/CR-7153 Vol. 4, "Aging of Concrete and Civil Structures," dated October 2014, identifies low-knowledge but high-significance concrete and concrete degradation issues related to subsequent license renewals (SLR) [2]. Creep and potential creep fracture is one of the identified issues that is applicable for PCCVs owing to sustained multi-axial loading. In addition to the EMDA report, the Organization of Economic Cooperation and Development / Committee on the Safety of Nuclear Installations (OECD/CSNI) has identified aging effects for concrete containment structures in a CSNI Activity Proposal Sheet (CAPS). Creep, shrinkage, drying, and moisture transport are specifically identified as some of the several significant aging topics for study. The topics mentioned in the EMDA report and the CAPS are all discussed in this document along with other potential issues.

Many of the FMs discussed in this document are related to issues that affect strength or integrity of the concrete, particularly in tension. In real plant situations, degradations are often coexistent, sometimes even linked, and are cumulative. Looking at concrete tension, some FMs contribute to demand (i.e., increased tensile stress), and others contribute to diminished capacity (e.g., age and wear-and-tear created microcracking). Combinations of FMs will typically result in exaggerated damage and earlier functional failure; however, a very few combinations of other FMs can result in a net zero change in functional capacity. For example, tendon over-tensioning can cause high localized stresses, but concrete creep over time can redistribute the high localized stresses to the surrounding area and lower the stresses to a manageable level.

Every instance of a potential issue in a PCCV should be analyzed by an expert to determine the severity of the situation.

An important note in this report is that the list of failure modes from CR3 does not include liner failure. Many PCCVs around the world, including all in the United States, require a steel air-tight liner on the inside of the PCCV that doubles as the inner formwork of the structure. The list of 75 failure modes from CR3 does not include liner failure since the concrete delamination event would not be directly associated with a liner degradation mechanism. However, concrete containments with a steel liner during a slow pressurization often functionally fail along the following event path:

(1). Increased deformation associated with overstress or damage to a strength element of the containment wall;
(2). Excess straining of the liner in the region of the increased deformation;
(3). Through-wall cracking of the concrete;
(4). Local tearing of the liner and thus leakage through the liner and concrete.

With this in mind, a brief discussion is included here on liner failure. From the Nuclear Containment Steel Liner Corrosion Workshop: Final Summary and Recommendation Report [3]:

> "Corrosion of containment liners has been observed on both the inside surfaces and on the outside surface that is in contact with the concrete building structure. Corrosion initiated on the interior liner surface has been observed with degraded moisture barriers or protective coatings when water has accumulated at the inner surface of the liner. Corrosion initiated on the outer surface of the liner, or the surface that is in contact with the concrete containment building wall, has been associated with foreign material left embedded in the concrete. The current known cases of through-wall corrosion of steel containment liners in domestic plants are restricted to instances of embedded foreign material in containment buildings with reinforced concrete construction. The higher density of the rebar in reinforced concrete containment may increase the probability that embedded foreign material was inadvertently left in place during original construction as compared to prestressed containments. Microcell-accelerated localized corrosion appears to be the corrosion mechanism for outer diameter corrosion (OD-corrosion) of steel containment liners. Corrosion is initiated by the presence of an embedded foreign material at the concrete/liner interface that may act as a crevice former and alters the local chemistry preventing passivation of the steel liner. A microcell is formed because the local anodic area where active corrosion is occurring is coupled to a large cathodic surface that consists of multiple layers of rebar and passive sections of the liner immediately adjacent to the anodic area. Once initiated, localized corrosion can continue to propagate over a period of many years because the thick sections of concrete have sufficient water content and the ionic conductivity necessary to support the electrochemical corrosion reactions. While other mechanisms could be

explored further, there is no evidence that they have contributed to OD-corrosion. Although not observed in operating plants to date, one potential long-term degradation mechanism that could have effects on OD-corrosion is ettringite (mineral formed during the hydration of cement) formation and dissolution coupled with the presence of an embedded foreign material and high containment temperatures; this could lead to conditions that promote corrosion of the liner."

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AAR	Alkali aggregate reactions
ASME	American Society of Mechanical Engineers
ASR	Alkali silica reactions (specific type of AAR)
BPVC	Boiler Pressure-Vessel Code
CAPS	CSNI Activity Proposal Sheet
CR3	Crystal River unit 3
CSNI	Committee on the Safety of Nuclear Installations
DBA	Design basic accident
DEF	Delayed ettringite formation
EMDA	Expanded Material Degradation Assessment
FM	Failure mode
GUTS	Guaranteed ultimate tensile strength
HCP	Hardened cement paste
ILRT	Integrated leak rate test
LOCA	Loss of coolant accident
NDE	Nondestructive evaluation
NPP	Nuclear power plant
NSSS	Nuclear steam supply system
OECD	Organization of Economic Cooperation and Development
PCCV	Prestressed concrete containment vessel
SIT	Structural integrity test
SLR	Subsequent license renewal

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1. CONTAINMENT DESIGN AND ANALYSIS

1.1. Excessive Vertical and Hoop Stress

1.1.1. Description

Post-tensioned concrete structures use tension cables or tendons to introduce large compressive stresses in the concrete material. In the case of a nuclear plant, the reactor and the steam generators are contained in a large strong containment structure designed to contain possible radioactive material release under various postulated design loading combinations. The two typical approaches are to use reinforced concrete or to use post-tensioned concrete. PCCVs use tendons to carry a significant portion of the hoop stresses while reinforced concrete containments use primarily rebar.

1.1.2. Discussion

Vertical and hoop stresses are typically designed such that any tensile stresses will not exceed the capacity of the concrete [4]. Retensioning or detensioning strands incorrectly will cause structural damage but is typically averted with correct planning and engineering. Compressive-tensile interaction can be predicted during engineering design, and detrimental compressive-tensile interactions can be avoided by proper strand tensioning/detensioning.

Excessive vertical and hoop tensioning can exaggerate the radial tension between the plane of the hoop tendons and outer surface, which is of special concern for PCCV designs without radial tiebars. Figure 2 demonstrates the tensile stress that develops from hoop tensioning. Depending on the magnitude, this could initiate delamination-type cracking in the wall of the containment. Over time and in combination with other operation conditions, such as ambient thermal cycling, this cracking could degrade the ultimate capacity to withstand pressurization and also render the PCCV more vulnerable to issues with structural modifications. Excessive vertical and hoop tensioning can also induce additional compressive creep strains (over that assumed in design). Under constant load, this additional compressive creep strain is generally not a problem and tends to relax the stress, but could contribute to structural issues if there is a change in loading, for example, de-tensioning for structural modifications. Upon load removal from de-tensioning, these compressive creep strains start to slowly dissipate (viscoelastic behavior), but as they dissipate, they act similar to compressive thermal strains; that is, they can contribute to cracking if there is sufficient restraint. Excessive tensioning also means higher stress in tendons and, along with compressive creep in the concrete, will lead to a more rapid decay in the design prestress conditions. This can usually be corrected for PCCV designs with un-grouted tendons through scheduled inspection and re-tensioning. However, repeated cycles of this can again increase the risk for delamination cracking and generate additional compressive creep strains. It is also noted that the creep rate in concrete is generally sensitive to change in loading, that is, if the change is significant enough, the higher primary creep rate (consistent with the age of the concrete) can initiate. Repeated cycles of over tensioning would incrementally increase the age integrated total creep strains with corresponding changes in the rate of creep beyond that accounted for in the design leading to additional risks in detensioning.

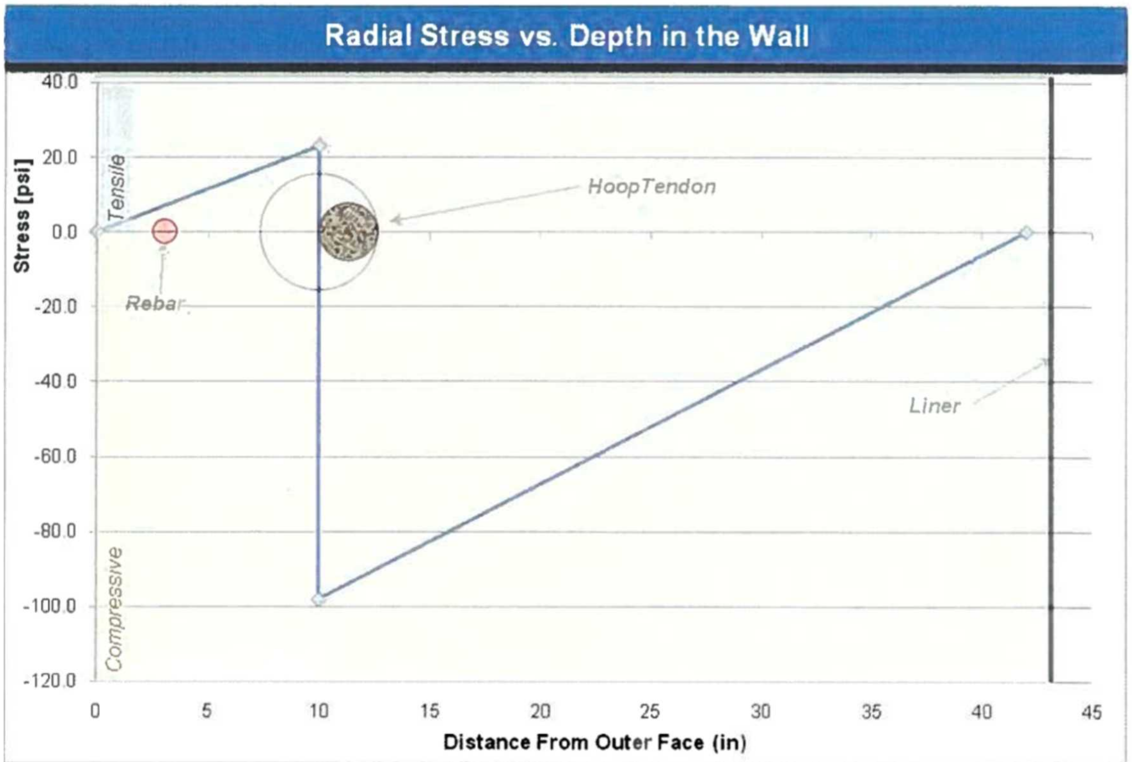

Figure 2. Tensile and compressive stresses in concrete wall cross-section due to horizontal tendons. [1]

1.2. Excessive Radial Stresses / No Radial Reinforcement Through the Containment Wall

1.2.1. Description

Post-tensioned systems using curved tendons are known to exert radial (through-thickness) compression on the inner region of the containment structure as shown in Figure 2; corresponding radial tension occurs on the outer region as the outer section of wall thickness resists the inward deformation of the post-tensioning. The common theoretical approach to calculating containment wall forces and stresses is a shell analysis which does not give detailed radial stress information. It is noted that it is not common to use radial strengthening in the containment walls, such as radial reinforcing steel and/or radial stirrups; see Figure 3. Only a few NPPs have radial reinforcements in the containment cylinder, namely Farley, Vogtle, Summer, South Texas, Calvert Cliffs, Wolf Creek, and San Onofre. It is very common to have radial reinforcements in containment domes because:

1. Tendons are located closer to the inner radius;
2. There are often three sets of intersecting tendons;
3. The dome is thinner than the cylinder.
4. Radial stresses caused by prestress are even higher in domes than in cylinders.

During plant operation, the radial tensile stresses present in this area of the containment wall originate from:

1. Compressive force due to the hoop tendons induces radial tension in the outer region of the containment structure (as the outer material resists the inward motion of the wall);
2. Stress concentration factors lead to localized tensile stresses;
3. Thermally-induced tensile stresses due to temperature differentials and solar effect on the concrete wall;

It should be noted that vertical compression from the vertical tendons (and the hoop compression from hoop tendons) leads to an increase in radial strain by Poisson's effect.

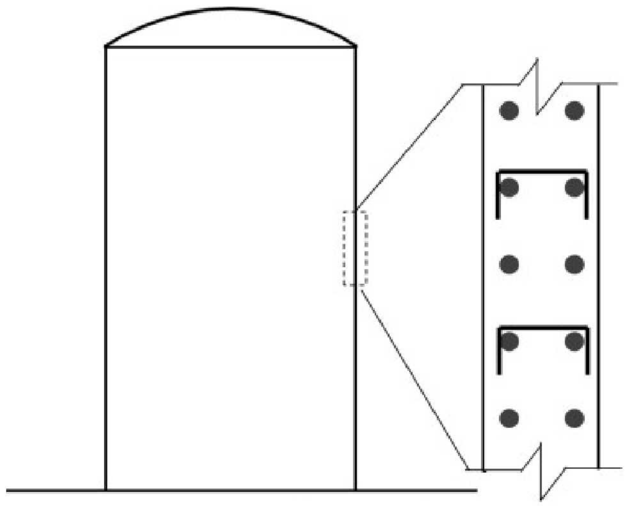

Figure 3. PCCV structure (left) with a schematic of horizontal tendons and radial reinforcement (right). [5]

1.2.2. Discussion

The ASME Boiler Pressure Vessel Code (BPVC) requires radial reinforcement in concrete structures under double curvature (such as the PCCV dome) but not necessarily under single curvature (such as the PCCV wall) [4]. Radial stresses are typically designed such that the tensile stress of the concrete is not exceeded. Excessive radial stresses could develop during improper tendon tensioning. It seems likely that the initiation of cracking due to incorrect design or incorrect installation generating excessive radial tensile stress may not be of sufficient magnitude to fail the containment in such a way that would be discovered early in life – but the cracking could contribute to aging problems later in life. Delaminations or concrete cracking may occur around the hoop tendons, and damage can be determined using nondestructive evaluation (NDE) techniques or coring.

In general, the lack of radial reinforcement could contribute to aging related failures for any condition that induces radial tension in this area, such as the excessive vertical and/or hoop tensioning discussed above or excessive ambient thermal cycles. In particular, the lack of radial reinforcement could contribute to failure of the wall if alkali-aggregate reaction (AAR) develops late in life. Without some radial restraint, the swelling induced by AAR could cause delamination of the wall outward of the hoop tendons. These may not occur or be discovered early in life and functional failure could be result of an accumulative effect over many years.

1.3. Excessive Tensioning Hoop Tendons

1.3.1. Description

As an example, the Crystal River Unit 3 (CR3) design calls for tensioning the hoop tendons to 1,635 kips with a design minimum of 1,252 kips. When considering the number of hoop tendons and the height of the containment building, we can calculate the number of hoop tendons per unit height and the hoop tendon force per unit height. The design minimum number of 770 kips/ft can be compared to typical industry standard for this type of containment. Additionally, occasional excessive tensioning, as allowed by normal operation, can damage the concrete by generating localized micro-cracks and/or enhanced creep.

1.3.2. Discussion

Damage caused by excessive tensioning of the hoop tendons may manifest as unnoticeable microcracks each time the tendons are retensioned, which can accumulate over time. High pre-stress levels lead to higher creep for a given concrete material, see FM 1.1. Creep strain and its effect on stresses is not fully understood in PCCVs, notably the combination of radial tension from hoop stresses with Poisson tension from vertical tendons. Diligent monitoring should be in effect in the plane of the hoop tendons to monitor for delamination.

Long-term or repeated excessive hoop tendon tensioning could contribute to functional aging issues in combination with other mechanism, such as excessive ambient conditions or AAR or increased vulnerability to seismic loading, since it induces additional radial tension in the outer part of wall.

1.4. Excessive Tensioning of Vertical Tendons

1.4.1. Description

As an example, the CR3 design calls for tensioning the vertical tendons to 1,635 kips with an upper limit at 1,878 kips during tensioning (80% of guaranteed ultimate tensile strength (GUTS)) and 1,721 kips afterwards [1]. When considering the number of vertical tendons and the diameter of the containment building, we can calculate the number of vertical tendons per unit circumference and the vertical tendon force per unit circumference. Additional, occasional excessive tensioning, as allowed by normal operation, can damage the concrete by generating localized micro-cracks and/or enhanced creep.

1.4.2. Discussion

See the application to aging PCCVs of FM 1.1 and 1.3.

In addition to the discussions in FM 1.1 and 1.3, excessive tensioning of tendons could also accelerate the aging degradation of the tendon itself since tendon failure is generally associated with stress corrosion cracking of the strands. This failure mode is mainly associated with vertical tendons and occurs most often at the lower anchorages where moisture can more easily accumulate. However, unless there is a chronic problem affecting many tendons, this failure mode can be repaired and with continued monitoring and maintenance should not affect the overall aging or ability of PCCV to maintain its function for extended operations.

1.5. Foundation Settling

1.5.1. Description

Uneven foundation settling can cause added asymmetrical stress in certain area in the containment and create localized stresses not accounted for in the design. Because the basemat is typically very thick, minor settlement can be "spanned" by the basemat, leaving the containment cylinder largely unaffected.

1.5.2. Discussion

Foundation settlement is always an issue during the lifetime of a PCCV. Regular monitoring of the structure is required to check for foundation settling. Monitoring typically includes visual inspection and position measurements of specified points on the structure (to detect vertical or lateral movements). Engineers should pay close attention to exacerbation of stresses near the tendon gallery.

PCCVs are founded on very thick, heavily reinforced basemats that span the entire nuclear island. Thus, the risk of aging related functional failure of PCCV due to uneven foundation settlement is negligible. However, settlement beyond that anticipated in the design could indicate physical changes in the foundation that could increase the risk of functional failure due to other potential failure mechanisms, such as slippage during earthquake or ingress of contaminants. If foundation settlement is detected, additional testing should be initiated to determine if the changing foundation properties will be within the design basis for the period of extended operations.

1.6. Inadequate Design Against Ground Movement

1.6.1. Description

Ground movement, improper geo-strength selection, elastic deformation of the foundation base rock, dissolution of the ground limestone, etc. can distort the containment structure resulting in localized, added stress in certain areas of the containment. The stress could result in crack initiation.

1.6.2. Discussion

Inadequate design against ground movement can cause added asymmetrical stress in certain areas in the containment. Regular monitoring of the structure is required to check for any ground movement. The cautions stated for FM 1.5 also apply here.

1.7. Containment Long-Term, Low-Lovel Vibrations

1.7.1. Description

During operation, the containment is subjected to long-term low-level vibrations due to the large rotating equipment located within or near it, and due to the wind. Rotating equipment generates 'humming' vibrations that are typically low-level amplitude but are present constantly over the years. In addition, the outside wind blowing on the containment also generates low level continuous vibrations. This failure mode investigates the long-term low-level amplitude vibrations induced by large rotating equipment and vortex shedding from the cross winds and whether they could have imparted a meaningful contribution or driver to long-term fatigue induced micro-cracking leading to the observed delamination in the CR3 plant. It was found that the first 11 natural frequency modes of the containment building are lower than 19.7 Hz (the operational frequency of the reactor coolant pump). The turbine operates at an even higher frequency of 30 Hz. The vortex wind frequency was calculated to be 0.2 Hz which was significantly lower than the first fundamental frequency of 4.3 Hz. Significant contribution to damage or distress from this failure mode is extremely unlikely.

1.7.2. Discussion

Continuous monitoring of the PCCV and NPP should provide warning against natural frequency vibrations from equipment or wind, primarily from excess noise in any area detrimentally affected by vibrations. Care should be taken over the life of the structure to carefully assess any structural modifications that could affect the natural frequencies of either the structure or the vibrations transmitted from equipment mounted within the structure so that the design basis is maintained. If modifications are to be implemented that cause a deviation from the design basis, long-term aging effects must be further considered in the assessment and design of the modifications. Any such modifications during the design life should be addressed in assessing adequacy for extended operations.

1.8. Tendon Ducts Not in the Same Plane

1.8.1. Description

Design calculations assumes that the hoop and vertical tendons are located in the same radial plane. In practice, that is not possible because of geometry placement as shown in Figure 4. This potential misalignment leads to changed stress conditions from those assumed in the design that could result in damage to the concrete and/or contribute to delamination initiation. Another factor to consider is the possibility that the ducts move during concrete setting due to hoop forces applied on them from the buttresses. This is a common concern in all post-tensioned concrete construction, not just containments. Ducts can move during concrete pouring in the radial direction outward from the center of containment or within the plane of the ducts. The installed ducts' ability to expand freely upon concrete pouring depends on the method used to attach the duct sections together and the duct ends inside the buttresses. Fixed ends can lead to bending of the ducts and high stresses in the concrete, especially if causing sharp bends or kinks.

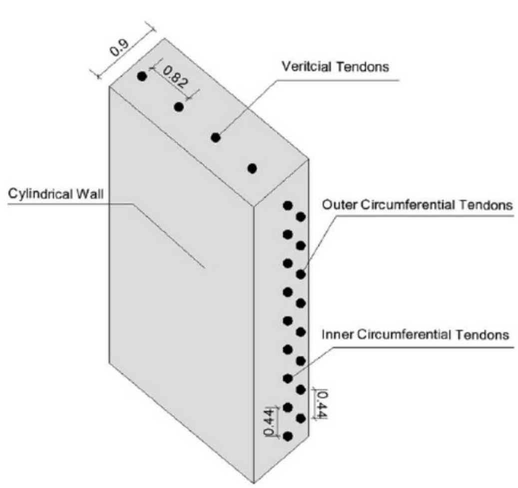

Figure 4. Schematic of a PCCV wall with circumferential and vertical tendons as-built. While tendons are not in the same plane as-built, design calculations often assume that they are. [6]

1.8.2. Discussion

Tendon ducts that are misaligned during concrete placement will cause unintended stress states during tendon tensioning. Hoop tendons exactly in the same plane can encourage crack propagation between the tendon ducts because this minimizes the distance between the stress concentrations caused by the tendon duct holes. Some variation in the location of tendon ducts would tend to breakup this weak plane in the wall section and minimize the potential for cracking that "connects-the-dots", see Figure 5. The stress variation associated with the tolerance for misaligned tendons is very small compared to design margins.

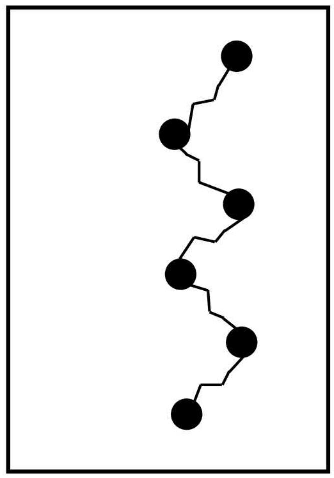

Figure 5. "Connect-the-dots" cracking traversing from tendon duct to tendon duct.

1.9. Tendon Spacing / Tendons Bending Around Penetrations

1.9.1. Description

Inadequate tendon spacing can potentially result in undesirable, uneven stress distribution or concentrations that can contribute to crack initiation or delamination propagation. Additionally, at penetrations, there are significant variations in tendon spacing where the tendons curve around the penetrations. In general, near penetrations the density of ducts, tendons, and prestressing force can be as much as 3-times that of the global wall away from penetrations. For example, this is observed around the equipment hatch for the vertical and hoop tendons. In particular, the forces radial to the axis of opening are significant as the post-tensioning will tend to crush the opening. Each penetration must therefore be built strong enough to handle these additional forces. Additional loads in the equipment hatch area are mitigated by a much thicker concrete section and high amounts of reinforcements. Note that tendons installed at wrong positions and/or moving during concrete pouring are addressed in FM 2.8 and local stress concentration around the hoop ducts is addressed in FM 1.15.

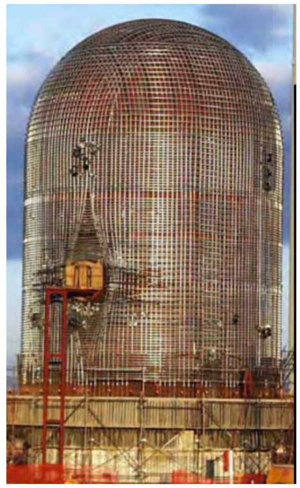

Figure 6. Tendons bending around an equipment hatch penetration in a 1:4-scale PCCV. [7]

1.9.2. Discussion

The effects of this FM may include:

- Uneven prestress loss in tendons around the containment due to stress concentrations and extra creep in those areas;
- Concrete cracking in areas with high stress concentrations due to tensile failure;
- Microcrack development under repeated tensioning during inspections or tendon retensioning.
- Microcracking around penetrations due to ovalizing effect from tendon tensioning

The stress variation associated with the tolerance for tendon spacing is typically small compared to design margins, so the effects of tendon spacing would not be of concern for aging issues. Design modifications affecting penetrations, including loads on the piping or other penetration components, should be carefully evaluated and designed so that the stresses in the concrete and sleeve around the penetration are kept within the design basis. Otherwise some aging issues for long-term performance could develop related to leakage around the penetration, for example, if elevated stresses or vibrations are introduced by the design modification. If such modifications have been made during the design life, the effects of same should be assessed in considering long-term performance for extended operations.

1.10. Added Stress from Voids Around Tendon Ducts

This FM is included in FM 2.7: Inadequate Vibration during Pour

1.11. Design for Excessive Microcracking

1.11.1. Description

Very fine cracks, commonly called microcracks, exist at the interface between coarse aggregate and cement paste even prior to application of load on the concrete. These cracks remain stable up to stresses of about 30% or more of the ultimate strength and then begin to increase in length, width, and number as the stress increases. New microcracks form in concrete as stress reaches 40-60% of ultimate strength. When stresses reach 70-90% of ultimate strength, the cracks start bridging across the mortar, creating a continuous crack pattern. As the stress approaches ultimate strength, the cracks grow until failure occurs1. [8]. The existence of microcracks explains how two materials (aggregates and cement paste) with nearly linear stress-strain behavior produce concrete that switches from linear stress-strain behavior at low stresses to non-linear behavior leading to ultimate failure. Microcracks existence and development also help explain the mechanism of fatigue where concrete cycled at stresses lower than the ultimate strength undergoes progressive degradation, leading to eventual failure without exceeding ultimate stress.

1.11.2. Discussion

Microcracks in the concrete do not heal in concretes typically used in PCCVs. Microcracks remain throughout the life of the PCCV and accumulate with varying stress states, environmental factors such as humidity and sulfate attack, and environmental loads such as wind and snow. Petrographic analysis can be used on core samples to determine the pH of the cement and thereby estimate the level of microcracking. If delamination cracking is suspected, then core sampling may be necessary to investigate.

Microcracking is a common condition in concrete structures and considered as part of the design basis. As such it is generally not a cause for concern for aging effects. However, excessive internal microcracking in combination with significant surface cracking can allow easier ingress of foreign agents such as sulfides and chlorides that do contribute to aging issues.

1.12. Added Stress from Inadequate Size of Tendon Ducts

Included in FM 1.13: Size of Tendon Ducts / Inadequate Net Loading Area

1.13. Size of Tendon Ducts / Inadequate Net Loading Area

1.13.1. Description

The tendons used in the post-tension design are located within ducts that are installed when the concrete forms are installed and are subsequently used as ducts. This FM addresses the size of the ducts in terms of:

- Duct size in relation to the area needed to contain the tendons;
- Ducts act as a hole in the concrete and locally reduce the effective area (area where concrete is actually present over total area, also called gross area).

All hoops tendons are close to the same radial plane from the center of the containment. This leads to a radial plane with reduced effective concrete area. This does not hold true around the equipment hatch where pairs of hoop tendons are located at the same elevation. All the vertical tendons also are close to the same radial plane from the center of containment. This generates a plane with reduced effective concrete area, creating a weak section in the concrete. It is common to reduce net available concrete loading area by 27-35% in the plane of either the hoop tendons or vertical tendons; however, design analysis suggests that the loss of gross section resulting from the presence of tendon duct does not yield unacceptable stress levels.

[1] As concrete cracks develop in reinforced concrete, the load is taken by reinforcement and failure does not occur.

1.13.2. Discussion

For inadequate net loading area in concrete, issues might be noticed during tensioning of tendons (deformation vs tendon force does not match design calculations) and/or first inspection of tendon forces shows more reduction than design calculations due to more creep because of higher concrete stress. Assuming a containment is operating that has net loading area smaller than predicted in design, the net effect is same as FM 1.1 through 1.4 (excessive concrete stresses) and concerns are the same for aging related issues.

1.14. Presence of Equipment Hatch

1.14.1. Description

The presence of an equipment hatch represents a major structural difference between its bay and the other bays in the PCCV. The issues potentially associated with the location of the equipment hatch are as follows:

- Added stress due to the weight of the concrete forming the hatch. In particular, it is possible to create a large vertical bending moment in the wall above the equipment hatch or horizontal moment along the edges left or right of the hatch.
- The containment wall in the area of the equipment hatch is twice the normal thickness and so is resistant to bending. That effectively shortens the bending length of the remainder of the wall. This could increase the bending stresses in the wall for a given forced displacement.
- Hoop tendons are bent to go around the equipment hatch. This redistributes the forces in the concrete, potentially creating high localized stresses relative to those in the surrounding areas. In particular, the hoop tendons just above and below the hatch are so close together that they run two in the same horizontal plane.
- Vertical tendons going around the equipment hatch also redistribute the forces and stresses in the area. In particular, the vertical tendons are now creating hoop forces.
- The added weight from the thickened containment wall also changes the resonant frequency. This bay does not behave like the others in terms of vibration.
- Problems associated with the special construction of the equipment hatch as an insert in the wall.
- Stress concentrations. Extra Reinforcement is added in this bay to compensate for 1) the opening, and 2) the increased local stresses associated with the tendons spaced close together. Away from the hatch, these added reinforcement mats end, and end abruptly. At high levels of pressure load and containment hoop stress, abrupt ends to added reinforcement become stress concentrations in the containment wall. The ends of concrete thickening also form similar stress concentration.

1.14.2. Discussion

The strength of the bay and the PCCV are typically successfully designed to eliminate structural failures. The added weight and stress due to multiple tendons going around the equipment hatch may cause excess creep which has not been studied in great detail. All PCCVs have equipment hatches and the operating experience is that there is no particular aging issue associated with PCCVs because of the presence of the equipment hatch. However, if modifications have been made to the equipment hatch or to the containment wall in the vicinity of the equipment hatch, for example cutting a hole for steam generator replacement, then indeed this condition should be assessed for implications on long-term performance and extended licenses. This type modification requires assessment to insure PCCV is brought back to design basis because of changes in stress distributions, changes in creep history, and discontinuity in concrete material.

1.15. Inadequate Design Analysis Methods for Local Stress Concentrations

1.15.1. Description

Hoop post-tensioned systems are known to induce tensile stresses in concrete perpendicular to the axes of the pre-stressing tendons (Figure 2). The common theoretical approach to calculating forces and stresses is a shell analysis which does not give detailed through-thickness stress information. Standard industry analysis of this type has led to the mindset that large margins exist and a delamination as observed at CR3 would not have been predicted using industry standard calculation tools. Analyses computed before 1980 utilized hand calculations to estimate requirements for steel reinforcement bars. These calculations relied upon estimations of forces and moments at various critical locations in the concrete containment structure. Any computer model associated with this work idealized the containment walls as 'thin shells' or plates. As such, high local stress concentrations in the concrete around the discontinuity created by the tendon duct were not included. The compressive stress produces secondary tension effects in regions of discontinuity such as holes in the concrete created by tendon ducts occurs in the general area of each tendon duct that contain the post-tensioning tendons. In essence, they behave like built-in 'holes' in the structure. These higher tensile stresses resulting from high stress can create small, non-active cracks. Standard industry analysis of this type has consistently shown that large margins exist in post-tensioned systems, and a delamination as observed at CR3 would not have been predicted using industry standard calculation tools.

1.15.2. Discussion

Tensioning the tendons will result in the formation of microcracks at areas of high tensile stress concentration, e.g. around each tendon duct and especially around where hoop and vertical tendon ducts cross each other. Successive detensioning and retensioning could result in more extensive cracking.

This issue is similar to FM 1.1 through 1.4 in that actual stresses are higher than assumed in design basis so that cracking and the tensile field between hoop tendons and exterior surface are likely more extensive than considered in design basis. This becomes more troublesome in combination with other mechanisms, such as extreme thermal cycles or presence of AAR, and in particular in assessing the aging effect on the true margin in pressure or seismic capacity for PCCVs without radial tiebars.

2. CONCRETE CONSTRUCTION

2.1. Inadequate Concrete Curing

2.1.1. Description

Curing is the maintaining of an adequate moisture content and temperature in concrete at early age so that it can develop its design properties without cracking. Excessive early drying will result in drying shrinkage before the concrete gains sufficient strength to resist cracking stresses. It may also deprive the concrete of moisture needed for the chemical reactions through which it achieves the desired strength and durability. In cold climate, it is also necessary to maintain the concrete at a temperature that allows adequate strength development through chemical reactions. Curing is achieved through the physical protection of the concrete from the environment, and by maintaining its surface moisture for a recommended period (seven or more days). Protection can be provided by leaving the forms for the desired period or by protecting the concrete with impervious membranes (plastic sheets or applied curing compounds). Moisture may be applied to the surface with water spray, soaked fabric, etc.

2.1.2. Discussion

Inadequate concrete curing is generally a short-term issue, that is, concrete will harden over time and strengthen through continued hydration so that the concrete properties (even at the start of operations) are generally well above the values assumed in design. The only loading conditions where this could be a problem are thermal induced loads and seismic loads where the demand can be a function of the stiffness. For these 2 conditions, concrete cracking usually develops which then reduces the stiffness, and this range of stiffness for assessing the demands is covered in the design basis. As long as the PCCV was not subjected to any significant loadings before reaching the design strength, this should not have any long-term performance or aging issues.

2.2. Inadequate Placement

2.2.1. Description

Concrete placement is the process of transporting the fresh concrete into the forms in a way that will result in uniform distribution and properties throughout the element with minimal separation of coarse aggregate. The two most common methods are pumping and transport by buckets. Pumping has the advantage of providing easy reach into spaces with limited accessibility whereas buckets allow placement of less workable concrete. The disadvantage of pumping is the need for more workable concrete, usually with higher cement and water contents, and the need to 'lubricate' the pipes with grout. Moreover, pumping equipment requires considerable additional cleaning and maintenance for efficient operation. Buckets, although simpler to operate, have limited reach and may not allow the same flexibility in concrete spreading as can be achieved with pumps. Note that this FM addresses the 'transport' and 'deposit' parts only. Other placement issues, such as grout, joint treatment, and vibration, are discussed in other FMs.

2.2.2. Discussion

If placed improperly, concrete 'weak zones' have a chance to align with areas of high stress. This may result in extensive internal cracking or premature failure. It is believed that Quality Control procedures would identify and correct inadequate delivery and placement of concrete, so any resulting weak zones would be a localized condition at best. For PCCVs, the compressive prestress also helps mitigate the potential for slippage or cracking at these local weak zones. Hence, this effect is considered minor and not a concern for aging related degradation leading to functional failure in PCCVs. If weak zones are present, cracking could be a concern during detensioning.

2.3. Inadequate Slump (Includes FM 3.6)

2.3.1. Description

Slump is a standard measure property used to define workability and the ease of flow of concrete into various forms of confined areas (such as in the rebar cage, between ducts and rebars, etc.). Historically (during the construction of most NPPs in the US), slump was normally specified as a maximum, not to exceed, value that is used in field testing to verify compliance with approved mix design and detect variations in the uniformity of a mix. Lower slump makes placing and consolidation more difficult, which in turn can result in the formation of voids. Higher slump makes concrete more workable, but may be an indication of excess water and a higher w/c ratio than desired. Excess water can lead to segregation, impact the concrete strength properties, lead to increased shrinkage, and increase creep in the long term. It is important to remember that slump alone does not define workability. It is possible to make low slump concrete that is workable when the right materials and tools are used.

2.3.2. Discussion

Inadequate slump can lead to voids and 'weak zones' in the concrete. Voids in hardened concrete can be detected using NDE techniques or taking core samples. It is believed that Quality Control procedures would identify and correct inadequate slump, so any resulting voids or weak zones would be a localized condition. Hence this effect is considered minor and not a concern for aging related degradation leading to functional failure in PCCVs. See FM 2.7 for more discussions on effects of voids in general.

2.4. Inadequate Control of Early Age Cracking

2.4.1. Description

Early age cracking can occur when concrete is exposed to stresses exceeding its tensile capacity before it matured and gained strength. These cracks are usually the result of early, excessive drying shrinkage. They may also occur when forms and supports are removed too early and excessive loads are imposed on the structure before the concrete reached its design strength. These cracks can extend the full depth of the element and lead to early failure from strength loss and/or durability related distress.

2.4.2. Discussion

This type of deficiency during construction should be caught and resolved from the Quality Control procedures imposed during construction. If for some reason, cracking develops during the construction and it is passed by QA, then there can be some effects on aging and long-term performance. In particular, the cracking will likely allow more rapid ingress of contaminants that can degrade the concrete and steel affecting structural performance.

2.5. Inadequate Temperature Control during Placement

2.5.1. Description

Concrete hardens through chemical reactions that generate heat. Maintaining low temperatures in fresh concrete will minimize stress levels in the hardened concrete due to volume change caused by subsequent temperature drop. Excessive higher temperature can cause rapid set, reduced workability, and loss of control over placing and finishing operations. Excessive lower temperatures can delay set, damage concrete through early-age freezing, and lead to damage from pre-mature form removal.

2.5.2. Discussion

There are design requirements to keep internal concrete temperatures at acceptable levels and for protecting exposed surfaces from extreme temperatures during curing while the concrete reaches the design strength. A generally accepted practice is to keep the peak temperature within a concrete placement below 160°F so as to prevent delayed ettrigite formation (DEF) which affects the long-term durability of the concrete. The Quality Control procedures should prevent any extreme or extended time variances from the design requirements. Generally, if a temperature related anomaly is detected, construction is halted until it is resolved, so that any effect of inadequate temperature control should be a localized condition.

2.6. Inadequate Mix Design

2.6.1. Description

Concrete mix design is a process of determining the right combination of cement, aggregates, water, and admixtures for making concrete that will have specified properties. Part of the process includes a trial mix and physical testing intended to prove compliance and to fine-tune the proportions. Once a mix design is approved, it should not be modified without evaluation of property changes and without approval from the responsible engineer. Inadequate mix design can result in deficiencies in the fresh concrete's properties, such as workability, creep and shrinkage characteristics and in deficient hardened concrete physical properties, i.e. air entrainment, strength, and modulus of elasticity. These deficiencies could contribute to distress from physical attack and to stress-induced cracking. This FM addresses the mix design process only. Material choices and concrete properties are discussed in FM 2.12 and FM 3.1 to 3.7.

2.6.2. Discussion

The mixture design could give valuable insight into material degradation modes that may take years to manifest. A mixture design with low slump (workability) could result in voids or honeycombing; a mixture design with high slump (flowability) could result in aggregate/paste segregation; a mixture design with low air content could result in freeze-thaw susceptibility; a mixture design with high paste content could result in excess creep or stress relaxation. Any change in mixture design must be approved by at least the project engineer, and modifications must be tested to ensure that requirements are met.

Concrete mix designs will generally always provide concrete that meets the specified compressive strength (and thus stiffness and tensile strength). Any flowability and workability issues should be worked out during construction. For aging related issues, the important concrete properties are durability for resisting surface attack and providing creep and shrinkage characteristics consistent with the design assumptions. Inadequate durability can be identified from visual inspection. Creep properties are best established through testing of samples during mix design and during construction. If this was not performed, then testing on core samples is required to estimate creep properties for comparison with design basis. The other very important aspect of concrete mix design for aging issues is the testing or procedures used to minimize the risk of AAR. Because of the potentially long gestation periods for AAR to manifest itself, some of the older testing procedures developed for screening against AAR in concrete mixes have proven to be unreliable and inadequate, as evidenced by the current situation at Seabrook.

2.7. Inadequate Vibration during Concrete Pour (Includes FM 1.10)

2.7.1. Description

Concrete, especially low slump concrete, requires mechanical vibration to achieve optimal consolidation levels. Vibration helps remove excess entrapped air, resulting in denser concrete. However, excessive vibration could result in segregation of concrete constituents, while too little vibration could result in voids and aggregate pockets even when the concrete slump is within specifications. The containment structure is pre-stressed with minimal reinforcement above ground and away from openings. The tendons and rebars are spaced in a way that allows unimpeded access for the workmen to place and consolidate concrete. Voids around tendon ducts (originally FM 1.10) and other inserts are also minimized by effective consolidation.

2.7.2. Discussion

Voids around tendon ducts due to insufficient vibration are generally hard to detect during construction. The stress disruptions associated with smaller voids are considered similar to those associated with tendon ducts and would be within the design margins and not a cause for concern for aging issues. Larger voids creating bigger disruptions in the stress distributions could be of concern. If there are anomalies with the tendon tensioning, for example one or a few hoop tendons in an area having larger pull displacements for a given force than the average or a hoop tendon requiring abnormal force to tension (more friction) or perhaps liner distress from vertical tensioning, this might be associated with larger voids around tendon ducts (or near the liner). It is hypothesized and hoped that the Quality Control for design specifications on slump and time of vibration would minimize voids and limit the size such that any generated voids would not contribute to aging related degradation. If there are no serious issues attributed to concrete voids during the initial operating license, then it is likely none will develop during an extended operation period, unless there is also evidence of concrete distress in the area where voids are suspected.

2.8. Inadequate Support of Tendon Ducts during Pouring

2.8.1. Description

If the tendon ducts (ducts) are not supported well, they may move during concrete pouring. Such movements have the potential to result in localized friction between the tendon and its duct or non-uniform stress in the concrete over the length of the tendon, or both.

2.8.2. Discussion

NDE techniques can be used to accurately determine the location of the ducts in the hardened concrete. See FM 1.8.

2.9. Inadequate Concrete Forms

2.9.1. Description

Forms constructed improperly with gaps between sections or with inadequate strength will likely result in concrete seepage between sections and/or in form deformation. Seepage could result in voids, aggregate pockets, and non-uniform surface finish. Form deformation could result in excessive fins and/or an uneven outer surface. Often, inadequate concrete formwork can be detected upon form removal and the concrete can be repaired as needed.

2.9.2. Discussion

This only affects the quality of the surface and is considered a minor and localized effect that would not contribute to aging, unless surface cracking is significant enough to allow ingress of contaminants.

2.10. Concrete Deformation from Tensioning Too Early

2.10.1. Description

Applying full design preload to the installed post-tension tendons before the concrete achieves sufficient maturity can result in excessive creep and deformation.

2.10.2. Discussion

This is typically not an issue in PCCVs. Construction schedules typically allow sufficient time for the concrete to properly mature before tensioning. Concrete is expected to gain ~85% of its final strength by 90 days.

The most likely possibility for this FM is the least mature concrete the final lifts forming the top of the dome. Tendon tensioning on concrete earlier than specified in design would mean that the accumulated creep strain is higher than accounted for in design due to initially higher creep rates. If cutting a hole in the dome will be part of the extended operations and there were deformation anomalies during the prestressing of the dome, then some assessment of in situ conditions and effects on planned structural modifications should be considered.

2.11. Inadequate Horizontal Cold Joints

2.11.1. Description

Special procedures are specified when fresh concrete is to be placed over hardened concrete in a ‘cold joint’. The old concrete surface has to be thoroughly cleaned, roughened, and brought to a saturated-surface-dry condition. These steps are required to ensure good bond between the hardened concrete and the newly placed concrete. Excessive stresses, debonding, and/or cracking are possible if a cold joint has physical properties that are not compatible with the rest of the concrete.

2.11.2. Discussion

A cold joint between two exceptionally different concrete mixtures (e.g. one properly mixed batch and another batch with flaws) could initiate a slip plane due to two mixtures with differing strengths, especially over long periods of time and stress cycles such as seasonal thermal changes. In PCCVs, these horizontal cold joints should be kept in compression from the vertical prestressing, which would minimize cracking at the joint. Cold joints will have continuous rebar and/or tendons across the joints which, along with the compressive stress, help maintain shear capacity. This is generally not of concern unless there is evidence of cracking or spalling at the joint indicating more than one aging mechanism may be at work. If inadequate cold joints are present, cracking could be a concern during detensioning.

2.12. Concrete Mechanical Properties

2.12.1. Description

The main concrete strength properties used in design are compressive strength (f'_c) and tensile strength (f_t). Of those, those most commonly used is f'_c which is easy to measure and can be related to all other properties through empirical expressions. Direct tensile strength is difficult to measure accurately and is normally replaced with splitting tensile strength (f_{tsp}) that is measured with the 'Brazilian' test. Concrete strength properties are influenced by multiple parameters, the most important of which include the water to cement (w/c) ratio, aggregate properties, and total voids. These parameters are analyzed separately in other FMs. When evaluating strength properties for failure analysis, it is advantageous to analyze the strength at three distinct time frames (if data is available): the strength at twenty-eight (28) days compared to the specifications and design parameters; strength development during the early period (up to 90 days) to evaluate potential variations in material properties and curing conditions; and strength of the current structure's concrete to evaluate potential degradation caused by chemical or physical interactions.

2.12.2. Discussion

Inadequate concrete strength can result in unexpected failures in future repairs or modifications. In the CR3 delamination, the tensile strength of the concrete in the bay that failed proved to be ~10% lower than the adjacent bays. The original project specifications for CR3 did not require testing for tensile strength—splitting, direct, or flexural. Prior to any major modifications, core samples could be taken to ensure concrete strengths.

3. USE OF CONCRETE MATERIALS

3.1. Inadequate Air Content

3.1.1. Description

The amount, size, and distribution of air voids inside concrete have significant influence on its physical properties and durability. For strength considerations, air voids have the same effect as other voids by creating initiation points for cracking and by reducing the net concrete section. For durability, small, well distributed voids help protect the concrete against damage from freezing and thawing cycles. The 'beneficial' voids are formed by specialized, air-entraining admixture that is added to the fresh concrete during batching. The other type of air voids are those entrapped through the process of mixing and placing the fresh concrete. The entrapped air is composed of larger, non-uniform voids that are randomly distributed in the concrete. Concrete specifications provide requirements for total air content.

3.1.2. Discussion

Entrapped air causes voids in the concrete that act as weak spots and initiation points for flaws. More importantly, for aging PCCVs, insufficient entrained air can lead to freeze-thaw damage in the appropriate climate. Freeze-thaw damage can require years to become noticeable, and is therefore directly related to aging PCCVs. If there is evidence of freeze thaw or other environmental damage to exposed surfaces indicated by surface spalling or cracking, then long-term effects on performance should be considered for extended operations. Part of this assessment would be inspection for extent of internal voids or cracking damage, extent of rebar and tendon deterioration, and testing for verification of in-situ material properties.

Another issue to consider related to excessive air voids is pressure due to steam generation in concrete at elevated temperatures, for example in the concrete backing the liner during accident conditions. The voids will contain free water that can turn to steam if temperatures exceed 100°C causing internal pressure within the concrete. This internal pressure can cause cracking damage in the concrete affecting the liner anchorages and can apply a backpressure on the liner. Generally, for an accident condition causing excessive temperatures inside containment, there is also elevated pressures that counter acts the liner backpressure and keeps the liner in contact with the concrete wall. The danger comes when containment spray is initiated that suddenly cools and drops the pressure inside containment. Since it takes some time for the lower temperatures to penetrate into the wall, a net differential backpressure could develop resulting in possibility of liner bulging or tearing. If there is evidence of inadequate air content or excessive air voids, such as distress on the outer surface, then NDE testing to assess the extent of voids on the inner concrete next to the liner may need consideration as basis for assessing possible capacity reduction in extended operations.

3.2. Inadequate Grouting Materials

3.2.1. Description

Mortar and/or grout are occasionally used in mortar beds between pours (to minimize the effects of cold joints) and in repairs of defects (voids & aggregate pockets) in the concrete. Grout is also occasionally used to prepare the pump and its pipes for the relatively dry concrete by smoothing the surface with a layer of wet mortar.

3.2.2. Discussion

If grouting materials are inadequate, then the weakened grout can act as initiation points for further damage. For repair of voids, even a weakened grout should be better than the empty void and thus is considered a lower concern than the existence of voids discussed in FM 2.7 and 2.9. Weakened grout at cold joints would seem to be somewhat better than actual cold joints, and this effect should be minimized by presence of compressive prestressing across joint.

3.3. Inadequate Cement Materials

3.3.1. Description

Cement properties can have considerable impact on the physical properties and durability of the concrete when the cement fails to meet specifications and industry standards. The standards (ACT and ASTM) referenced by the original specifications create the basis for testing and acceptance program of cement. Some of the main potential problems with cement include:

- Slow reacting cement can slow strength gain;
- Fast reacting cement can cause rapid loss of workability and early set;
- High C3A cement can support failure when exposed to sulphates (as well as accelerate reactions);
- High alkali cement may cause problems when reactive aggregates are used.

Problems may also be caused by imbalance between the cement's main compounds, particle size that is too large (slow, incomplete reactions) or too fine, or the inclusion of containments that affect the cement's performance. ASTM C150 covers the production and use of cement and is normally used to determine compliance and suitability of the cement for the intended application.

3.3.2. Discussion

Inadequate cement is a serious concern for aging related degradation of functional performance. Concrete susceptible to chemical attack or degradation over time can directly affect functional performance over time. Inadequate cement materials could expose the concrete to sulphate attack, delayed ettringite formation, or alkali-silica reaction. Any evidence of structural distress should trigger testing and assessment for root cause and long-term performance for extended operations.

3.4. Inadequate Aggregate

3.4.1. Description

Aggregates occupy 60-75% of concrete volume and therefore have large influence on the mix design, physical, chemical, and thermal properties. The aggregate's gradation, strength, porosity, mineral composition, hardness, and chemical stability are evaluated through a set of ASTM standards that determine its suitability for use in concrete. Aggregate with deficiency in any of these properties may still make good concrete when combined with proper ingredients in a proper mix design. Therefore, failure in any of these tests does not automatically disqualify the aggregate for use in concrete. It is common practice to accept aggregates based on their proven ability to produce concrete with the specified strength through long-term local experience.

3.4.2. Discussion

Aggregate properties are extremely important in concrete at all maturities, from fresh mixing to decades old. Inadequate aggregates can severely limit the capacity of the final concrete in one or several ways. Inadequate aggregates can easily reduce strength or stiffness, or they can lead to premature cracking. Aggregate gradations significantly affects workability. Coarse aggregate size influences strength and freeze-thaw durability with larger aggregates creating poorer concrete [8]. Most applicable to aging PCCVs are deleterious chemical reactions with either cement or intruding chemical from the environment such as alkali-silica reaction. If there are any anomalies between construction test records and mix design specifications or test data, then testing for in-situ concrete properties, including creep, is advised, especially if major modifications to containment are planned as part of extended operations.

3.5. Inadequate Admixtures

3.5.1. Description

Admixtures are materials, other than cement, water, aggregates, and reinforcement, used as ingredient of concrete and added to the batch immediately before or during mixing. Common chemical admixtures used are water reducing admixtures, air-entraining admixtures, and retarder or accelerator admixtures. Air entrainment is normally added to concrete exposed to potentially destructive exposure such as freezing thawing cycles. It may also provide a limited benefit in workability improvement. Water reducer/retarder improves workability of low slump concrete while allowing more time for placing in high temperature conditions. Admixture use must be carefully controlled since excessive amounts of air can result in strength deficiencies, whereas excessive amounts of retarders can lead to delays in setting and low early strength gain.

3.5.2. Discussion

Inadequate or improper admixtures typically cause flaws in the concrete that can be detected during analysis of the fresh properties. Too much or too little water-reducing admixture will change the slump. Too much or too little air-entraining admixture will be detected when determining air content of the fresh paste. Inadequate admixtures will lead to other FMs. This FM is of no serious concern for aging issues unless there is evidence of surface cracking or spalling.

3.6. Inadequate Slump (included in FM 2.3)

This FM is included in FM 2.3.

3.7. Inadequate Concrete Testing

3.7.1. Description

Construction projects require a quality assurance (QA) program that, among other things, involves the selection of test methods, establishing test criteria, testing the fresh concrete, testing the hardened concrete, statistical analysis of test results, and follow-up procedures. Fresh concrete is tested for its workability (slump test), temperature, and air content. Hardened concrete is tested for its strength under compressive loading. The purposes of strength tests of concrete are to determine compliance with a strength specification and to measure the variability of concrete (ACI 214 provides a discussion of methods and analysis for strength tests of concrete). It is necessary to establish the quality of the test program in order to be able to evaluate its results and conclusions.

3.7.2. Discussion

If concrete testing was performed inadequately at time of placement, then many assumptions (strength, air content, stiffness, etc.) made of the concrete may be false. If the concrete testing was inadequate at time of placement, core samples must be taken and used in combination with other testing (e.g. petrographic) to determine actual material properties. In order to assess the long-term performance for extended operations, there should be adequate documented test data for the concrete properties. Test results from the mix design should include data for assessing concrete strength and modulus over time, creep performance at least to 180 days for various ages of loading (loading at 3 days, 7-days, 28-days, and 90-days), adiabatic temperature rise tests for heat of hydration, autogenous shrinkage, as well as slump and air content. Testing results for presence of conditions that may lead to AAR should also be available even though it is now known that some earlier testing methods were not necessarily accurate over the long term. Then there should be adequate testing during construction to verify that the as delivered and placed concrete meets the specifications of the mix design. If this data is not available or is inadequate, then material testing is required in order to assess the long-term performance taking into account the environmental and operational history over the design life. Assessing current, in-situ concrete properties is also very important for assessing and establishing a program for major structural modifications, which may be needed for extended operations. It is noted that even if AAR susceptibility test data is available, it should be questioned for adequacy, and if necessary, core samples examined for presence of AAR if there are any suspicions or related history.

4. CONCRETE SHRINKAGE, CREEP, AND FATIGUE

4.1. Excessive Plastic Shrinkage

4.1.1. Description

Plastic shrinkage cracks occur when fresh concrete is allowed to dry before setting is complete. These cracks are usually parallel, shallow, and do not extend through joints. In general, plastic cracking is not considered a cause for strength deficiency or durability problems. Plastic cracks can be a problem when they serve as initiation for later cracking due to stresses through the life of the structure.

4.1.2. Discussion

Excessive plastic shrinkage should be easily noticed and monitored early in the life of PCCVs. Drying shrinkage is a surface effect and can be controlled with surface protection during construction. Even if not properly controlled, the results are generally hairline surface cracking. The only concern on aging would be a reduced durability where this condition early in life (during construction) could allow a more rapid deterioration due to long-term environmental effects such a freeze thaw of exposed surfaces and ingress of contaminants on buried surfaces.

4.2. Excessive Shrinkage (includes FMs 4.3 and 4.4)

4.2.1. Description

Concrete will shrink when it dries. In fresh concrete, the volume of water mixed with the cement and aggregates can be significant. As concrete dries, the excess water is removed, causing shrinkage in the hardened cement paste and leaving behind voids of various sizes. Cracks may result if the concrete is restrained. The extent of shrinkage depends on a combination of factors including the volume of water in the fresh concrete, the aggregate/cement paste ratio, the water to cement ratio and the concrete's strength and rigidity at the time of moisture loss. Coarse aggregate properties, especially its modulus of elasticity and moisture content, are also important factors in concrete shrinkage. Therefore, to minimize drying shrinkage, concrete should be batched with the smallest volume of water needed for workability and the largest aggregate fraction practical. It should also be kept moist (wet cured) until it gains enough strength and rigidity to withstand the stresses of drying shrinkage When these preventive steps are deficient, the concrete may crack and/or develop micro-cracks where cracks initiate due to stresses later in its life. Concrete shrinkage may also be the result of autogenous process where water is consumed in the hydration process without external loss (formerly FM 4.3). Another shrinkage cause is carbonation shrinkage, which is a byproduct of the carbonation process (formerly FM 4.4). These secondary processes result in limited shrinkage whose effect cannot be separated from drying shrinkage.

4.2.2. Discussion

The effects of plastic and autogenous shrinkage should manifest in the initial license of the NPP. However, due to concrete being porous, drying shrinkage should be monitored throughout the life of the NPP. Carbonation shrinkage requires time to manifest and will continue to develop as more cracks are exposed to the environment (e.g. more cracks from severe weather). Another effect of drying shrinkage that is pertinent to aging PCCVs is the phenomenon known as drying creep (discussed in FM 4.6).

Autogenous shrinkage is generally a short-term issue that saturates well before the initial design life. During concrete mix design, testing is performed to characterize the shrinkage properties of the mix to be used in construction. The construction is then designed to limit cracking issues associated with autogenous shrinkage, that is, lift heights and placement timing and sequences are configured to minimize potential for shrinkage related cracking during construction. Once the concrete has cured sufficiently, the shrinkage will have saturated, and there should be no additional long-term or aging related issues.

4.3. Excessive Autogenous Shrinkage

This FM is included in FM 4.2.

4.4. Excessive Carbonation Shrinkage

This FM is included in FM 4.2.

4.5. Creep (Basic and Drying – Includes FM 4.6)

4.5.1. Description

Basic (or true) creep is the time-dependent increase in strain under sustained load of a concrete specimen in which moisture loss or gains are prevented (sealed specimen). Drying creep is a phenomenon wherein a concrete specimen under load and exposed to a dry environment accrues more strain than the combined strains of shrinkage and basic creep. In the case under consideration, it is not practical or necessary to separate the two and the following will address the total creep experienced by the structure. Creep is influenced by multiple variables including:

- Concrete properties: aggregate/paste volume, modulus of elasticity of the paste and aggregate;
- Environmental: temperature and humidity;
- Structural: restraint, size effect, stresses, and time.

Since creep happens in the hardened cement paste (HCP), the total quantity as well as quality of the HCP is a major consideration. The larger the HCP volume and the lower its modulus of elasticity (Ec) the larger the total creep. The aggregates can reduce creep by reducing the total HCP content and by providing restraint due to their stability and rigidity. In pre-stressed structures, concrete creep results in at least three issues:

- Time-dependent losses in the pre-stressing force that could result in pre-stress levels below design requirements;
- Large deformations of the containment structure;
- Residual stresses induced as the loading conditions change.

In #3, removal of the load results in instantaneous elastic recovery (not a full recovery), followed by creep recovery (also not a full recovery). This can cause localized increase in microcracks with corresponding reduction in strength properties. This creep spring-back can contribute to microcracking during detensioning. This FM combines basic creep (FM 4.5) and drying creep (FM 4.6).

4.5.2. Discussion

In large concrete structures where the surface area to volume ratio of the concrete is small (such as PCCVs), drying creep tends to be negligible. The surface area to volume ratio is further reduced in US PCCVs since one face is covered by a steel liner. Additionally, shrinkage is also governed by the surface area to volume ratio, and is expected to be very small for a large structure with little access to the surface to lose or gain moisture. The most convenient approach to working with creep in a tri-axial stress state as present in an NPP containment structure is to determine the specific creep of the material, or creep strain per unit load applied, typically given in micro-strains per psi. While creep in the structure can be approximated by measuring the creep coefficients in samples, continuous monitoring of the structure is necessary to ensure that adequate tendon prestress is maintained. If creep is left unchecked, prestressing tendons will lose tension, leading to increased probability of failure in the PCCV.

While creep strains under a constant load will saturate over time, the effects of creep can contribute to long-term performance issues because creep effects are sensitive to change in loading. In particular, PCCVs with concrete having excessive creep rates relative to the concrete mix properties assumed in design could be vulnerable to long-term performance issues, especially if major structural modifications are planned. Excessive creep could be associated with inadequate aggregate strength and this combination makes the PCCV more vulnerable to structural distress due to changes in loading, such as detensioning and retensioning of the tendons.

4.6. Excessive Drying Creep

This FM is included in FM 4.5.

4.7. Excessive Stresses from Different Material Properties

4.7.1. Description

When concrete mixes of different physical properties are combined, they may perform differently under stress. These differences can cause stress concentrations at the interface, leading to bond failure and cracking. In concrete construction, it is possible to have concrete of different strengths placed adjacent to each other while expected to perform as a uniform material with the same properties.

4.7.2. Discussion

This FM will only be applicable if concrete mixes in direct contact with each other had significantly different strength or elastic stiffness properties. Warning signs of differing strength/elastic stiffness would most likely, but not 100% assuredly, have manifested in fresh concrete testing (significantly different slumps or air content). Different concrete batches should not be significantly different because of quality control procedures during construction. The stress differences of slightly different batches next to each other is considered within the design margins and is further mitigated by compressive prestressing in PCCVs. There is also some effect due to differences in coefficients of thermal expansion between concrete and steel. The larger this difference the more stress is generated at the rebar bond during thermal excursions, including heat up from the heat of hydration during construction. This can cause some microcracking at the rebar-concrete interface weakening the bond. It is not expected that this would contribute to early functional failure from aging related effects.

4.8. Cyclic Loading

4.8.1. Description

Concrete structures exposed to cyclic changes in stresses, humidity, or temperature can be damaged by fatigue even when the cyclic stresses are not large enough to cause failure in one application. Fatigue damage starts at the pre-existing microcracks at the aggregate interface, inserts interfaces, and voids. A large number of these cycles can lead to propagation and extension of the microcracks into larger, structurally significant cracks. These cracks can expose the concrete to environmental attacks and allow increased deflections. The structure will fail as a result of excessive cracking, excessive deflections, or brittle fracture. Normally, concrete structures are designed to codes that limit design stress levels to a point that fatigue is not an issue. However, localized fatigue damage may develop at locations exposed to excessive cyclic loading such as at machine connections.

4.8.2. Discussion

Damage to concrete from thermal cycles would be the result of tensile stresses that cause microcracks to grow and multiply. Theoretically, such damage might be detected through petrography and through comparative strength tests between damaged and undamaged areas. However, due to the normal scatter of strength tests, it is not possible to determine such damage to any significant certainty unless extreme damage has been sustained.

Non-vibration cyclic loading is more of a local damage issue rather than concern for functional failure of the PCCV. Given the margin on ultimate capacity of PCCV designs, the number of cycles needed would be well over 1M according to the above discussion. Potential thermal or other environmental loading, such as wind, significant enough for global cyclic loading would seem to be on the order of a few dozen a year or a few thousand over the life of the plant. It seems far more likely that extreme cycles in temperature would be a short-term storm issue that under repeated cycles might develop some local cracking damage due to wind driven water penetration and freezing.

5. CHEMICALLY OR ENVIRONMENTALLY INDUCED DISTRESS

5.1. Contamination During Construction

5.1.1. Description

During construction operations, it is possible for contaminants to be mixed with the fresh concrete. Some of these materials have the potential to weaken the concrete and/or affect its durability. Sources of contamination can be dirty aggregates that may include organic material or other reactive elements. Another source is construction related material such as grease/oil, nails/ties, tools and safety items, clothing, cigarettes, food, and other debris. Foreign material can impact the concrete by either replacing sound concrete with weak/incompatible filler, or by adding reactive elements that react inside the concrete. Contamination can be detected by inspections during construction, visual inspections for signs of distress such as spalls and cracks, and analysis of concrete removed from the structure (during demolition and coring). Precautions involve strict control of aggregate sources, good construction and safety practices, and effective Quality Control (QC) program that monitors potential for contaminations.

5.1.2. Discussion

Contaminants in concrete will decrease strength and elastic stiffness, primarily acting as voids (if the contaminant is soft) or stress concentration sites. Some organic contaminants such as wood can create further problems by absorbing moisture, swelling, and then shrinking as the absorbed moisture is released into the surrounding concrete. There is no way to check for contaminants other than continuous visual inspection of the structure or NDE techniques.

For concrete, the relative volume of such containments compared to volume of competent concrete will be very small, and thus only have a localized effect with concerns similar to voids. Based on operation experience, the bigger concern here would be for contaminants left next to the liner. Over time, these can contribute to premature corrosion of the liner or degraded support for the liner, which can result in a tear in the liner as a functional failure of the leak tightness of the containment.

5.2. Salt Water Related Distress

5.2.1. Description

Concrete exposed to salt water can, over time, lose its ability to protect the embedded iron from corrosion. This FM is a leading cause of failure in bridge decks or harbor structures that are frequently or constantly in contact with salt water. The pH inside concrete is >11, which causes a film to develop on reinforcing steel that protects the steel. Chloride ions in salt water penetrate this protective coating and cause the steel to rust. As the steel rusts, it expands in volume and causes cracking and spalling of the concrete. Concrete exposed to wetting/drying by salt water can suffer deterioration related to chemical reactions and cycles of shrinkage/expansion.

5.2.2. Discussion

This FM is only applicable in PCCVs that are in frequent contact with salts or salt water. If a PCCV is in frequent contact with salts or salt water, continuous inspection should be required to check for cracking and iron oxide leeching (signs of rust formation, expansion, and concrete cracking/spalling).

Deterioration of steels can also develop from contact with brackish water. Brackish water is usually in grown water affecting the foundation of the basemat, so risk of functional failure is low. PCCVs in high humidity or contact with water are also more susceptible to initiation of AAR if concrete mix is prone to this reaction. In general, the more a PCCV (or any structure) is exposed to water or moisture, the more susceptible the PCCV is to aging related issues. Thus, there could be some concern for PCCVs with more extensive exposure to salt water or other moisture unless they have good history of inspections without findings.

5.3. Chemicals Introduced during Routine Maintenance

5.3.1. Description

Routine maintenance of industrial structures can involve the application of deleterious materials, including solvents, cleaning agents, or aggressive water. ACI committee 515 compiled a list of potential deleterious materials, most of which are either harmless to good quality concrete, require high concentrations, will only attack porous concrete, and/or must be dissolved in water in order to penetrate the concrete. The issue of chemical attack is discussed in another FM.

5.3.2. Discussion

This FM is only applicable if routine maintenance constantly uses an aggressive chemical. There are no chemicals that are constantly used in concrete maintenance that can damage concrete. Any chemicals that can damage concrete that are used in maintenance around concrete (e.g. chemicals used in or to clean equipment) should be kept out of contact of the concrete. No concerns about chemicals used in routine maintenance causing aging related issues with PCCVs.

5.4. Concrete Form Release Agent

5.4.1. Description

Release agents are applied to the form contact surfaces to prevent bond and facilitate stripping. They may be applied to the form before each use, at which time care must be exercised to prevent coating adjacent construction joint surfaces or reinforcing steel. A good release agent should provide a clean and easy release without damage to either the concrete face or the form, while contributing to the production of blemish free surfaces. It should have no adverse effect upon either the form or the concrete surface. When applied improperly, form oil may prevent bond between the concrete and reinforcing bars or weaken joints by preventing bond of old to new concrete.

5.4.2. Discussion

Any surface defects during construction due to inadequate forms are easily detected and would be corrected during construction. Improper application of form release agents that affect rebar bonding would likely be a localized issue where improper procedure is corrected through quality control. Thus, if it exists, the stress variation should be localized and within design margin. No concerns for long-term aging effects on PCCVs.

5.5. Corrosion of Rebars, Tendons, and Inserts

5.5.1. Description

Corrosion of embedded metal is one of the main causes of failure of concrete structures. The critical elements needed for corrosion to occur are water, oxygen, and chloride ions, which in turn makes permeability the main concrete property that influences corrosion resistance. The high alkalinity (pH>11) of the concrete protects the thin iron-oxide film on the surface of the steel, thus making the steel passive to corrosion. The alkalinity can be reduced by carbonation or exposure to acidic solutions, allowing corrosion when oxygen and moisture are more available. In the presence of chloride ions, the pH threshold for corrosion initiation is considerably higher than when chlorides are not present. The initial stage of corrosion often produces cracking, spalling, and staining in the surrounding concrete. These can be detected by visual observations. Industry standards use water to cement (w/c) ratio as an indication of concrete's permeability. It has been established that concrete with w/c of 0.4 or lower has a voids system that is mostly made of disconnected discreet small voids, making it practically impermeable when undamaged. Another source of moisture and chloride ingress can be surface cracks.

5.5.2. Discussion

This is one of the primary FMs that will affect aging PCCVs. Corrosion of rebars, tendons, and inserts is consistently the most prevalent FM in reinforced concrete structures. Visual inspection of the structure should be rigorously maintained to check for cracking, spalling, and staining of concrete that will provide evidence of corrosion. This FM could manifest at any point in the history of the containment. Cracks could initiate in the structure due to multiple FMs and increase the permeability of concrete, increasing the probability of embedded steel corrosion.

Corrosion of embedded steel is a good sign that the structure is not aging well and thus sets a flag that assessments should be performed to determine the overall long-term health and fitness for extended operations. Testing and studies are needed to determine the root cause for correction and not just local repair of the symptom.

5.6. Inadequate Grease Protection Capability

5.6.1. Description

Grease is placed into the tendon ducts primarily to protect the tendons. Routine tendon surveillance provides opportunities to evaluate grease losses and examine the grease for deterioration, but also provide opportunities for grease contamination, all of which may result in tendon capability loss. In vertical tendons, grease settles over time, reducing the protective layer near the top of the tendons.

5.6.2. Discussion

Continuous monitoring of the tendons and grease is recommended during the operational lifetime of the PCCV. Inadequate grease protection of tendons can lead to tendon failure due to stress corrosion cracking. Because of requirements for routine inspections and maintenance, this is considered a local failure that can be repaired before functional failure. However, persistent maintenance issues with a few tendons could mean some influence of other issues, such as concrete voids causing inadequate tendon duct support that may need further investigation for extended operations.

5.7. Physical Attack

5.7.1. Description

Concrete is vulnerable to multiple mechanisms of physical attack that may lead to deterioration over time and potential failure. Physical processes include non-structural cracking, salt crystallization, freezing and thawing, abrasion and erosion, thermal exposure, irradiation, fatigue and vibration, and settlement. Shrinkage cracking, thermal exposure, fatigue, and settlement are discussed in FMs 1.5, 4.2, and 4.8. Salt crystallization is a process where dissolved salts move through the concrete by capillary action and crystallize on or under the surface as the water evaporates. The growing crystals can exert pressure on the 'skin' of the concrete, resulting in spalling of the concrete surface. This process can continue as long as there is a ready supply of moisture from the soil or atmosphere and the concrete experiences cycles of wetting and drying. Freezing and thawing is a process where water freezes inside the concrete, exerting pressure from the inside as it turns into ice of larger volume. Repeated cycles of freezing and thawing can cause spalling of the surface in concrete that is not adequately air-entrained. Abrasion and erosion are processes where surface material is removed from the concrete by either dry rubbing/grinding or impact of fluid carried particles. Irradiation by either neutrons or gamma rays can cause changes to concrete's physical properties and/or volume change of aggregates. They also affect steel properties, i.e., neutron embrittlement.

5.7.2. Discussion

Each of these modes of physical attack are directly applicable to PCCVs throughout the operational lifetime. Non-structural cracking increases permeability that increases carbonation, freeze-thaw damage, and susceptibility to water and chemical ingress. Salt crystallization can occur at any age of the PCCV and can increase cracking. Freeze-thaw damage is more likely to occur as the PCCV ages due to increasing concentrations of cracks in the structure (due to other FMs). Abrasion and erosion are only relevant where constant frictional forces are present; this is not a typical scenario in PCCVs (excluding local contact with equipment). Irradiation can be an issue if there is a leak in the radiation shielding, but is not expected to be an issue under normal operation—irradiation damage should be checked if any radiation leaks occur in the primary radiation shielding.

Recent studies are showing that even the concrete bioshield/pedestal supporting the NSSS inside containment next to the reactor vessel will not accumulate enough irradiation damage over extended operations to cause structural issues for these critical structures. This should rule out concerns of irradiation damage to PCCVs as potential mechanism leading to functional failure.

5.8. Chemical Attack

5.8.1. Description

Concrete is vulnerable to multiple mechanisms of chemical attack that may lead to deterioration over time and potential failure. In porous materials, water can be the source of chemical processes of degradation by transporting aggressive ions. Therefore, controlling permeability is the main method for limiting chemical related damage. The two other factors affecting durability are the availability of aggressive ions and the presence of concrete constituents that are vulnerable to these ions. Chemical attack may be prevented by reducing permeability, using non-reactive concrete components, and preventing aggressive ions from penetrating the concrete. Chemical attack may be the result of sulfate attack, acid and base attack, aggressive water attack, phosphate ion attack, alkali aggregate reactions (AAR), carbonation, efflorescence/leeching, and biological attack. A detailed discussion of these mechanisms is beyond the scope of this document and may be found in external sources (such as ACI 201). The effects of chemical attack vary, but generally include loss of concrete cover accompanied by staining, erosion, reduction of concrete constituents, cracking, and spalling. A visual survey is considered (ACI 349) to be an effective way of quantifying the effects of damage and identifying possible sources and composition of the aggressive chemicals.

5.8.2. Discussion

Each of the types of concrete chemical attack listed above are discussed herein. The types of chemical attacks are:

- Sulfate attack requires both high transport properties through concrete and the ingress of sulfate ions. This mode of chemical attack is not expected in PCCVs since the majority of the PCCV is not in contact with sulfate ions. The exception is the base of the PCCV which may be in contact with sulfate ions in the soil or groundwater, in which case the base of the PCCV should be inspected for excessive cracking.
- Acid attack of PCCVs may be an issue near the base of the PCCV or on surfaces exposed to rain. Acid attack at the base of PCCVs may occur if the soils are uncharacteristically acidic. PCCV surfaces exposed to rain are susceptible to acid rain, especially surfaces that pool rainwater. Acid attack can reduce the pH of the internal concrete, exposing the reinforcing steel to corrosion.
- Aggressive water attack is essentially water that contains harmful ions or chemicals (e.g. sulfate attack, acid attack, etc.).
- Phosphate ions that intrude into concrete can react with the calcium-saturated systems and decalcify the hydrated cement pastes via phosphoric acid.
- Alkali aggregate reactions can cause swelling of the aggregates that create tensile stresses inside the concrete and eventually crack and destroy the concrete.
- Carbonation can decrease the pH of concrete, exposing the embedded steel to corrosion.
- Efflorescence/leeching occurs when moisture exits the concrete, carrying with it concrete pore solution water and ions such as calcium hydroxide. Efflorescence/leeching is easily seen as a discoloration or buildup on the concrete surface.
- Biological attack can occur in moist environments over long periods of time. Micro-organisms can consume algae or other bacteria on the surface of the concrete and produce chemicals that can damage the surface of the concrete over time, exposing the concrete to even more modes of chemical attack.

Aging PCCVs require routine inspections to check for chemical attack. Visual inspections are the best check against chemical attack; efflorescence/leeching and excess cracking are the most common signs of chemical attack. Assessments should be performed to determine root cause and possible synergisms of different mechanisms if there is evidence of any distress as noted above. Assessments should be performed for subsequent long-term performance over extended operations and if necessary identify repairs or modifications needed to mitigate the root cause(s).

6. CONCRETE-TENDON-LINER INTERACTIONS (DURING OPERATION)

6.1. Uneven Force Distribution along Tendons

6.1.1. Description

This FM analyzes three separate but related issues.

- Effect of the non-uniform force along one tendon due to friction of the wires forming the tendon. The tendon force varies along the length of the tendon, with a maximum force at the jacking locations (except for the effects of anchor seating loss) and a decreasing force moving towards the center of the tendon. These variations lead to non-uniform pre-stress levels in the concrete material. The load *F(x)* at position *x* (in radians, $0<x<\frac{\alpha}{2}$) along the tendon is approximated by

$$F(x) = F(0)e^{-\mu x - Ks}$$

  Where *F(0)* is the load at the jacking point, μ is the angular friction coefficient (typically 0.16), α is the total angle change in radians, *K* is the wobble friction coefficient (typically 0.0003), and *s* is the length of tendon 'straight' portion (ft).
- Effect of the non-uniform force around penetrations due to curvature around the penetrations. Around penetrations, tendon curvatures are large; therefore, friction losses are larger than for typical horizontal tendons away from penetrations. The higher localized stresses can cause local micro-fracturing or local enhanced creep rates. Lower localized stresses can cause local variations in strength to resist internal pressure.
- Asymmetries in tendon lift-off force measurements. A large number of adjacent tendons with high asymmetry might be indicative of:
  - Differences in concrete condition along the tendon arc, such as a section of pre-existing cracked/delaminated concrete;
  - Differences in concrete condition along the tendon arc, such as a section with varying creep;
  - A bias in lift of measurement equipment utilization at one end of the tendon during surveillance.

6.1.2. Discussion

Most irregularities in force distribution in tendons are likely to manifest during the initial operating license. Asymmetric tendon forces should be found and corrected in tendon inspections. Tendon friction effects are most notable in PCCVs with few buttresses (4 or fewer); friction losses increase with increasing angle change in the tendons. If tendons are spaced such that a tendon that spans from buttress (n) to buttress (n+2) is between tendons that span from buttress (n+1) to (n+3) (and vice versa), the average frictional losses will be balanced at each buttress. Excess tendon curvature around penetrations can cause excess local stress gradients that are typically accounted for in design with extra steel reinforcement. Differences in concrete condition along the tendon arc can cause non-uniform creep, an effect that has not been diligently studied.

The distribution of prestress due to tendon friction is accounted for in design and some general variation is within the design margins. If there are anomalies in tendon jacking forces or deformations relative to design assumptions or localized issues with some tendons, then this might be indicative that other mechanisms, such as excessive voids, might be present.

6.2. Inadequate Tendon Wires

6.2.1. Description

The tendons in a concrete post-tensioned system are made of steel wires. The wires must have a very high tensile strength and must sustain high stress levels for long time-periods with minimal stress relaxation. Cold-drawn steel wires are typically used. The wire quality, strength, uniformity, and corrosion are tested during regular surveillances, as described in ASME Code Section XI, Subsection IWL. Relaxation of the tendon wires leads to reduced pre-stress levels in the concrete. Local strain variations and strain-hardening (work-hardening) along the tendon can lead to non-uniform pre-stress levels.

6.2.2. Discussion

Similar to FM 5.6, isolated incidents of breakage of strands in individual tendons can be detected and repaired so as to prevent PCCV functional failure due to long-term aging issues. However, persistent maintenance issues with a few tendons could mean some influence of other issues, such as concrete voids causing inadequate tendon duct support, which may need further investigation for extended operations.

6.3. Thermal Effects of Greasing

6.3.1. Description

The high-strength steel wires that make up the pre-stressing tendons are very sensitive to stress corrosion cracking while under tension. Corrosion protection was initially done by grouting the inside of the tendon ducts after tendon original stressing. However, NRC RegGuide 1.107 and NRC RegGuide 1.90 moved the industry towards non-grouted tendons in order to fulfill in-service periodic inspections. The procedure to grease the tendon during original installation is listed below:

1. Install the tendons inside the ducts (the ducts themselves were installed as part of the concrete form-work and they are embedded in the concrete);
2. Tension the tendons to lock-off force;
3. Grease the tendons by filling the ducts with grease (all around the tendons themselves).

At CR3, the grease is injected in the tendon ducts at a pressure up to 85 psi and a temperature up to 160°F. The pressure and temperature cause thermal expansion of the duct and of the concrete surrounding the duct. Differences in expansion and/or rate of expansion can induce thermal stresses and possibly cause cracking. Note that the stress difference comes from thermal conductivity, not thermal expansion coefficient. Ultimately concrete and steel expand by nearly the same amount. However, steel expands much faster and therefore transient stresses occur.

6.3.2. Discussion

Tensile stresses may develop in the concrete surrounding the duct ducts due to the quick expansion of the steel. Analysis in the CR3 special inspection report suggest that the additional stress due to thermal effects of greasing do not exceed a concrete tensile strength of 450 psi. Since the tendon-duct interface has already undergone some trauma due to the forces exerted during the post-tensioning operations, it doesn't seem likely that the thermal effect of applying grease would cause any significant additional damage to the interface. No impact on aging PCCVs is expected.

6.4. Stresses due to Rigid and Flexible Ducts

6.4.1. Description

In post-tensioned systems, ducts are installed at the same time as reinforcing bars to be used later for the post-tensioning tendons. Different types of tendon ducts are used in NPP containment structures. Rigid ducts are used in straight sections while flexible ducts must be used to go around containment penetrations.

6.4.2. Discussion

The ducts have a smooth exterior that does not form a strong bond with the surrounding concrete. The ducts are also too thin, even when classified as 'thick-walled ducts', to provide any structural significance. Rigid and flexible ducts ultimately add no structural support. In analysis, the ducts are treated as voids. The variation in stress due to rigid versus flexible sleeves is considered to be within the design margins and not expected to have an impact on aging PCCVs.

6.5. Inadequate Tendon Re-Tensioning in Surveillance Activities

6.5.1. Description

10CFR50.55a requires periodic inspections of the containment concrete and the posttensioning system following ASME Code Section XI, Subsection IWL. The NRC provided acceptable methodology in NRC Reg Guides 1.35 and 1.35.1. The predicted tendon force loss curves which establish acceptance criteria 'base' values are calculated for each tendon taking into account the causes of prestress losses. Typically, a tendon must be retensioned if it falls below 95% of base value—the 'base' value is the predicted liftoff force at the time of the tendon surveillance, not the original lock-off force when the tendon was first tensioned. The effect of retensioning tendons that fall below 95% back to base value is conservative and relatively minor as for as prestress levels in the containment even if several adjacent tendons are retensioned to base. In comparison, the effect on prestress level locally is greater than the above condition when one tendon is fully detensioned from each group during each surveillance because that detensioned tendon represents 800 kips or more depending on the tendon. Detensioning one tendon fully is considered acceptable even when the plant is online.

6.5.2. Discussion

Re-tensioning in surveillance activities should not affect aging PCCVs if completed properly. Incorrect tendon re-tensioning could result in complex stress fields that may cause cracking. Incorrect tendon re-tensioning is an FM that is equally applicable at any time during the operational lifetime of the PCCV, but aging (and FMs related to concrete deterioration) might exacerbate the potential for cracking damage during re-tensioning.

This FM seems more of an inspection/maintenance issue and unlikely that enough tendons to cause functional issues would be inadequately tensioned at any one time. It seems more likely that any locally inadequately tensioned tendons would be corrected during the next inspection and maintenance, so this would be considered a short-term excursion and not a contributor to aging degradation.

6.6. Inadequate Original Tensioning of Tendons

6.6.1. Description

Excessive original tensioning above the prestress levels accounted for in the design can damage the concrete by generating localized microcracks and/or by increasing the creep deformation due to the higher stresses. Also, unbalanced or incorrectly sequenced posttensioning can lead to high local stresses, microcracks, and/or delamination. Initial tensioning of tendons, among other factors, can lead to excessive stresses in the containment structure. This is of particular importance as the CR3 containment dome did delaminate upon original tendon tensioning in 1976 as well as another Florida containment dome that delaminated at Turkey Point upon original tendon tensioning. When tensioning, the tendons are initially stressed to 80% GUTS. Then shims are installed between the support plate and the back of the anchor head, and the load is reduced and the tendons are locked-off at 70% GUTS. Note that FM 1.1 deals with 'Inadequate prestress design'. This FM addresses the possibility that the tendons were tensioned other than as designed/required.

6.6.2. Discussion

CR3 and Turkey Point dome delaminations prove that even design tendon stresses can cause significant structural issues in a PCCV. In a worst-case scenario, inadequate original tensioning of tendons can cause immediate or delayed structural and material issues or failure that must be addressed. Also possible are high local stresses and microcracks that do not cause a failure, but the concrete would be damaged and more readily susceptible to future failure.

This FM is also covered by FM 1.1 – 1.4.

7. CONTAINMENT CUTTING

7.1. Accumulated Low Level Damage

7.1.1. Description

Concrete structures in service are exposed to multiple low level stresses on a regular basis. Normally these stresses can be safely ignored in distress analysis since they are too low to cause damage to the concrete. Theoretically, such low level stresses may include:

1. Thermal stresses, daily, seasonally, and during outages (see FM 4.8);
2. Shrinkage and expansion due to drying/wetting cycles (see FM 4.2);
3. Construction related vibrations or local stresses.

Each mechanism has the potential to degrade the material by introducing defects, such as localized cracks and/or microcracks. The accumulation of these low-level damages causes degradation of mechanical properties such as tensile strength and fracture energy.

7.1.2. Discussion

Some of the low-level stress mechanisms will actually cancel each other. For example, concrete that would expand when wet will shrink when the water cools it. In addition, concrete has the ability to 'heal' itself by hydrating cement exposed in cracks, effectively repairing the small tight cracks.2 This phenomenon is especially effective in cases of low-level damage that does not expand rapidly towards failure. The only practical way to determine if low-level degradation occurs over time is to compare current physical properties to original properties, taking into account normal time-related changes. Due to the large variation inherent in these tests and estimates, it will require a very large change in properties to conclude that a statistically significant degradation occurred.

7.2. Vibrations Induced by Hydro-Blasting

7.2.1. Description

During the steam generator replacement job at CR3, a large opening was created in the post-tensioned concrete containment. The method selected to remove the concrete was hydro-blasting. In hydro-blasting, high-pressure water jets impact the concrete to be removed. The pressure is obtained by means of plunger positive displacement pumps. The water nozzles rotate at 500 rpm. The water pressure that is used is nominally 20,000 psi. Damage to the concrete may occur if the jet pulsation frequency, or the nozzle rotation frequency, or the pumps vibration frequency equal one of the resonant frequencies of any part of the containment, panels, or ducts.

7.2.2. Discussion

This FM is only applicable to PCCVs if hydro-blasting is utilized at any point to cut through the structure. It was decided in the CR3 special inspection report that vibrations induced by the hydro-

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[2] This 'healing' cannot be predicted and cannot be counted on in design or in repairs. It is also highly dependent on concrete mixture properties: mixtures with low w/c ratios tend to have more of this type of 'healing' than mixtures with moderate or high w/c ratios.

blasting did not have enough energy to impact the structure or structural components even when applied frequencies aligned with natural frequency of the components. If a crack already exists, then hydro-blasting may expand the crack by adding high water pressure in to the existing crack.

Resonant vibrations by definition indicate the PCCV could be subjected to loading that is amplified and could initiate or extend cracking damage and thus could contribute to long-term aging issues. If the extended damage is localized to the area near the source of vibration, and that concrete is removed and repaired, then it would likely not contribute to aging issues. There is some concern and any planned structural modifications involving hydro blasting should be designed to minimize inducing vibrations that are resonant with a vibration mode of the PCCV. Any PCCV having undergone such loading should be assessed for likely extent of cracking remaining in PCCV after repair of opening before extended operations.

7.3. Inadequate Detensioning Scope and Sequence (Includes FM 7.4)

7.3.1. Description

This FM investigates the details of the tendon detensioning scope and sequence and the potential impact of the scope on building stresses. Hoop and vertical tendons in a PCCV are detensioned in a specific sequence and at specific load intervals. Detensioning a tendon creates a stress gradient in the structure. The stress gradient can be minimized when using a gradual uniform detensioning sequence of the posttensioned structure. This can sometimes be done, for example, by skipping one or more tendons in the detensioning sequence. In that manner, a more gradual and uniform release of post-tensioning forces and associated change in the concrete structure can be achieved.

7.3.2. Discussion

This FM is equally applicable to a PCCV at any age in its operational lifetime. Arguments can be made that 1) aged PCCVs are more susceptible to damage during detensioning due to accumulated damage accrual over time; or 2) aged PCCVs are not more susceptible to damage during detensioning due to concrete ‘self-healing’ (see FM 7.1) and concrete stress relaxation in local stress concentration zones. Clearly depending on the particular conditions, the more conservative set of assumptions should be followed.

Aged PCCVs are more susceptible to damage during detensioning not only because of accumulated damage over time, but because the accumulated creep is higher and the creep rate is lower and thus takes longer for the creep strains to dissipate for the structure to recover the creep induced deformations. These residual compressive creep strains will contribute to cracking if there is sufficient restraint, and chances are the activities for which the detensioning is performed will proceed while creep recovery is still active.

7.4. Inadequate De-tensioning Scope

Included in FM 7.3

7.5. Added Stress Due to Removing Tendons and Concrete at Opening

7.5.1. Description

The process for creating any new opening in a PCCV has two steps:

1. De-tension the tendons that would have to be removed;
2. Remove the concrete to make the opening.

This FM considers whether the concrete removal contributes to a PCCV failure (e.g. delamination).

7.5.2. Discussion

Research is inconclusive as to the effect of removing concrete (after properly preparing to remove the concrete) on the stress distribution in posttensioned concrete structures. There is some stress redistribution since the weight above must be redistributed around the hole – whether that contributes to any long-term aging issues is unclear. The larger issue for effects on subsequent aging may be the placement of new concrete in contact with the old. The newly placed concrete will have different aging and material properties which may cause stress concentrations.

7.6. Vibrations Due to Cutting Tendons under Tension

7.6.1. Description

At CR3, tendons were detensioned in preparation of cutting an opening in the sidewall of a PCCV. However, the tendons were not detensioned gradually: they were cut using a plasma torch. The procedure used at CR3 was as follows:

1. Degrease tendon ducts;
2. Cut tendons using a plasma torch;
3. Pull tendons using a coiler machine.

The tendon cutting was performed without releasing the tension. A plasma torch was slowly applied to the wire button-heads until the wire yielded and snapped in a tensile fracture. The sudden release of energy has a shockwave effect in the containment that can result in additional stresses and/or vibrations in the concrete.

7.6.2. Discussion

The consequence of cutting a wire is a shock vibration rather than a resonant vibration. Calculations performed for the CR3 special inspection report revealed that releasing one tendon generated only a small additional stress in the concrete structure. No major results are expected from a piano effect occurrence.

The vibration from shock was likely not a problem, but the forces transmitted into the concrete through friction as the tendon suddenly releases may have posed an issue. The duct protects the concrete from physical contact and whipping damage from the unleashed tendon. However, it would seem that the friction between the tendon and duct would be resolved into the concrete and be in a direction inducing tension in the concrete that could contribute to the delamination cracking.

7.7. Cracking Due to Pre-Existing Defects in the Local Area

7.7.1. Description

Nuclear prestressed concrete structures are subject to multiple sources of design, construction, and duty factors that can impact material properties and degradation:

- Design and construction material specifications, conformance with those design and construction specifications (see FM series 1 and 2);
- The concrete is subjected to large original prestresses when tensioning the hoop and vertical tendons;
- The tendon plane, particularly the hoop tendon plane, is the most vulnerable location for delamination potential from a stress standpoint, as the tendons are exerting maximum compressive stress on the inner concrete ring, and this results in a tensile stress on the outer concrete ring at this same interface plane. The large number of tendons also reduce the concrete load bearing area at this plane;
- The concrete is subjected to aging through thermal stresses, daily, seasonally, and during outages (see FM 4.8);
- The concrete is subjected to aging through long-term creep, time-dependent strain in the concrete under constant load (see FM 4.5);
- The concrete is subjected to aging through long-term vibrations (see FM 1.7).

Each of these factors provides potential for introducing defects that can take the form of localized cracks and/or distributed microcracks across the structure.

7.7.2. Discussion

The most effective means of detecting pre-existing defects in a PCCV is core sampling, though some NDE techniques could also detect defects of adequate size. One common approach to determine the age of a fracture surface is the carbonation analysis. This is based on the reaction between constituents in the concrete paste and the carbon dioxide in the air. Upon reaction, the pH of the concrete decreases and this can be observed using various pH tools. Typically, a delamination needs some event to form (e.g. initial tendon tensioning, tendon detensioning, severe weather event, seismic activity, etc.).

The presence of delamination cracking is a concern for PCCVs without radial tiebars. If pre-existing delamination is found in the area of hole cutting, it is likely that it also exists in other areas. Therefore, there is some concern that this PCCV could have degraded functional performance during extended operations.

7.8. Excessive Water Jet

7.8.1. Description

During hydro-blasting, a high-pressure water jet impacts the concrete to be removed. The water jet pressure that is used is nominally 20,000 psi although in practice it can vary by up to 4,000 psi. The pressure is obtained by means of a plunger positive displacement pump. The water nozzle rotates at 500 rpm. The jet flow rate per nozzle is around 50 gallons per minute. The intent of hydro-demolition as applied here is to damage and remove the concrete section of interest while not damaging the embedded steel components. This is indeed the point of using this technology in this particular application where concrete has to be removed. This FM looks at if and how the hydropressure might cause damage beyond the application area via force or pressure build-up. Damage to underlying or surrounding concrete (outside the targeted removal area) may occur if water jet pressure and flow is not maintained within a controllable range. From the CR3 special inspection report, calculations and American Hydro calculation confirm that the force from the water jet to the concrete is not sufficiently high to generate damage by itself. The principle of hydroblasting confirms that hydroblasting takes advantage of pre-exiting cracks (chapter 5 'Waterjets in Civil Engineering Applications from Professor David Summers). At the time of the CR3 special inspection report, American Hydro had performed eight hydroblasting openings in PCCVs; all were successful, demonstrating capability and process effectiveness for hydroblasting openings in PCCVs without unacceptable collateral damage to surrounding concrete or structures. In all literature, hydroblasting is the least damaging to the underlying structure, and no damage is expected to occur in surrounding concrete. Also, hydroblasting does not result in mechanical impact, but rather in rapid erosion/disintegration of the paste/aggregate sub-components.

7.8.2. Discussion

This FM is only applicable to PCCVs if hydrodemolition is used on the PCCV. Any cracks that are present in the concrete will be susceptible to damage from hydroblasting. Therefore, if microcracks are present from any other FM (such as over-tensioning tendons or thermal effects during curing), hydroblasting will degrade surrounding concrete. In short, hydroblasting will not create new major fracture planes, but it could propagate existing fractures. One solution to check for cracks before hydroblasting is to remove a core sample and check it for pre-existing cracks.

Excessive water jet pressure is considered a contributor to extending cracking, but should be fairly localized in the area of the hydro-demolition and repaired as part of returning the wall to fully functional condition. Thus, the effects should not contribute to further aging issues.

7.9. Inadequate Hydroblasting

7.9.1. Description

Detailed discussion of hydroblasting is in FM 7.8. This FM attempts to determine if and how the nozzle movement rate might cause damage beyond the application area via force or pressure build-up.

1. If the rate is too high (nozzles move fast over the concrete surface), the force may result in simply 'banging' on the concrete wall without any time for the hydroblasting process to really make a meaningful impact through the action of erosion and water pressurization within the pre-existing microcracks and pores in the structure;
2. If the rate is too low (nozzles move slowly over the concrete surface), the dwell time becomes higher and the depth removed per pass can become too high or the pressurized water can have time to go deeper into the structure, for example along tendon ducts;
3. This FM also considers the effect of the nozzles possibly being too close to the containment wall, leading to a higher impact pressure and a deeper concrete removal per each pass.

Note that issues associated with resonant frequency are analyzed separately in FM 7.2 and issues dealing directly with excessive impact force are analyzed separately in FM 7.8.

7.9.2. Discussion

This FM is only applicable to PCCVs if hydrodemolition is used on the PCCV. Inadequate hydro-blasting procedures is similar to FM 7.8 with the possibility of creating localized damage but part of concrete area removed and repaired. If the hole is repaired properly, the effects from inadequate hydro-blasting would not contribute to further aging issues.

7.10. Hydro-blasting Induced Cracking

7.10.1. Description

Detailed discussion of hydroblasting is in FM 7.8. The process of hydroblasting exploits the existence of microcracks, voids, capillaries, and cracks to enable concrete demolition using high pressure water jets. This raises the question of potential damage to the concrete in adjoining area through direct pressure, vibrations, or crack propagation. Note that issues of vibration induced by hydroblasting are covered in depth in FM 7.2, issues of excessive water pressure are covered in FM 7.8, and issues of nozzles rate are covered in FM 7.9. Published information about the principles of hydrodemolition describes the three modes through which it removes the concrete:

1. Water flow into cracks, creating stress at the tip of the crack;
2. Water flowing into capillaries, resulting in internal pressure amplification;
3. Water flowing through open pore system, creating friction forces to the material grains.

Hydrodemolition must be used with caution in structures with unbonded tendons for the following reasons:

1. Hydrodemolition is potentially dangerous because it can accidentally undercut embedded anchors and result in explosive release of prestressing forces;
2. If any part of the tendon is exposed to high water pressure, water may penetrate the tendon;
3. The water pressure used in hydroremoval equipment can force slurry into the tendon ducts.

Hydrodemolition is not sensitive to the strength of the aggregates because it exploits the existence of microcracks, voids, capillaries, and cracks to enable concrete demolition. If anything, weaker aggregates and/or defective aggregates could be removed more easily and therefore offer less resistance to the water jet and lead to less damage to the surrounding material.

7.10.2. Discussion

This FM is only applicable to PCCVs if hydrodemolition is used on the PCCV. This FM could become more significant at later ages if some form of concrete material internal degradation had taken place (such as alkali aggregate reaction or sulfate attack).

7.11. Added Stress from Pulling Tendons Out of Ducts and Grease after Cutting

7.11.1. Description

The procedure to remove the tendons from the ducts is as follows:

1. Degrease tendon ducts;
2. Detension tendons. This can be performed gradually or by cutting with a plasma torch;
3. Pull tendons using a coiler machine

The tendon coiler used is hydraulically driven. Its end attaches to one end of a tendon and it pulls and coils the tendon as it rotates. When used on the vertical tendons the coiler is positioned on the dome of containment. When used on hoop tendons, the coiler is located in a platform that comes down from the dome along the buttress. The platform motion is resisted by the containment wall and the buttress wall. The force required to pull the tendons out of the ducts can be high because:

1. The tendons and grease have been in place and pre-stressed for more than 30 years;
2. The grease has a high viscosity;
3. The degreasing operation is not thorough for the hoop tendons.

This can result in additional stresses in the concrete around the ducts during the removal operation.

7.11.2. Discussion

The forces at play in the posttensioned containment, seen by concrete in everyday operation, are much larger than the pulling capability of the tendon coiler. The forces exerted at the tendon duct and concrete interface during post-tensioning operations are significantly higher than forces transmitted from extraction of tendons. Thus, no significant new cracking damage should develop that would contribute to aging degradation.

8. OPERATIONAL EVENTS

8.1. Prior Spray Event Leading to Low Pressure inside Containment

8.1.1. Description

At CR3, a containment spray event in October 1992 resulted in an injection of ~9400 gallons of borated water into the reactor building atmosphere. The event resulted in a decrease in reactor building internal pressure.

8.1.2. Discussion

Historical records of the CR3 PCCV show that the event did not result in the containment pressure exceeding its negative design pressure of 2.5 psig below external pressure. If any such event occurs in an aging PCCV and the pressure becomes higher than design, testing should be performed to ensure no damage. Infrequent, low level variations in operating conditions should be covered in design margins and would not be expected contribute to aging degradation.

8.2. Thermal Stresses due to Containment Spray

8.2.1. Description

At CR3, a containment spray event in October 1992 resulted in an injection of ~9400 gallons of borated water into the reactor building atmosphere. The event resulted in a change to the average containment temperature.

8.2.2. Discussion

Historical records of the CR3 PCCV show that the event did not result in exceeding either a containment design or a technical specification temperature limit. If any such event occurs in an aging PCCV and the internal temperature suddenly changes beyond design or technical specification criteria, testing should be performed to ensure no damage. If the accident temperatures where high enough and the containment spray cooling and depressurization was fast enough, negative pressure on the liner could initiate bulging or tearing if aging degradation has affected liner or anchorage integrity.

8.3. Pressurization/Depressurization Rates during Last Integrated Leak Rate Test (ILRT)

8.3.1. Description

The procedure for conducting the containment integrated leak rate test (ILRT) (SP-178) allows a rate of change in internal pressure to 15 psi/hr.

8.3.2. Discussion

From a structural standpoint, depressurizing (or pressurizing) the reactor building at 15 psi/hr is not challenging, as accident conditions could be much more severe. Infrequent, low level variations in operating conditions should be covered in design margins and would not be expected to contribute to aging degradation.

8.4. Inadequate Concrete Structure Monitoring/Maintenance (IWL)

8.4.1. Description

Visual examinations contained within the ASME Section XI Subsection IWL are conducted to determine concrete deterioration and distress. These containment surface monitoring inspections sometimes result in identification of and subsequent repair to the containment concrete surface. While not a true failure mode, a deficient IWL program could miss identifying or properly evaluating indications that could lead to the identification and repair of a flaw. Note: The IWL program includes both concrete and tendon surveillances. FM 8.4 only addresses the concrete aspects of the program. The tendon aspects are discussed in the FM 6 series, which addresses concrete-tendon-liner interactions.

8.4.2. Discussion

Aging PCCVs are subject to more FMs than new PCCVs that require time to develop, e.g. alkali aggregate reactions, sulfate attack, thermal fatigue, etc. Many degradation modes can be detected via visual inspection if the degradation is progressing to a point where it needs repair. While an inadequate monitoring/maintenance system does not in itself indicate that a problem exists, an inadequate IWL could eventually lead to failures that may have been avoided.

8.5. Containment Depressurization Due to Inadequate Purging Operation

8.5.1. Description

In CR3, an event occurred in the late 1980s or early 1990s during which a purge exhaust fan was operating with the inlet valve closed. This resulted in a vacuum in the containment building.

8.5.2. Discussion

Subsequent calculations of a worst-case vacuum generated by the purge fan demonstrated that the maximum achievable vacuum is less than 1 psi, which is less than the design basis for containment. Infrequent, low level variations in operating conditions should be covered in design margins and would not be expected contribute to aging degradation. Infrequent, but significant operational events, might be cause for inspections to determine if aged PCCV performed as expected from design basis. If not, this could be an indication that some aging mechanism is present, and degradation has occurred.

9. EXTERNAL EVENTS

9.1. Hurricanes or Tornados

9.1.1. Description

External forces, with the potential to challenge the design bases of containment, can be applied to the containment structure if hurricanes or tornados occur at the NPP.

9.1.2. Discussion

Potential external forces applied to the PCCV could contribute to failure modes listed above or in outright structural failure. Hurricanes and tornados can cause extreme wind loads and pressure reversals. Infrequent but significant external events are cause for inspections to determine if aged PCCV performed as expected from a design basis. If the PCCV is not performing as expected, the weather event could have directly damaged the structure or exacerbated existing degradation issues that may have been heretofore undetected.

9.2. Seismic Events

9.2.1. Description

A seismic event of sufficient magnitude causing ground motion of sufficient intensity could exceed the design bases of the containment for such events.

9.2.2. Discussion

Any seismic event near or beyond design basis should be followed by an inspection to assess possible damages. The seismic event could directly damage the structure or exacerbate existing degradation issues that may have been heretofore undetected.

9.3. Ground Movements (Sink Holes or Geo-Sliding)

9.3.1. Description

Ground movement caused by sink holes and/or dissolution of the limestone under the containment can result in lack of foundation support.

9.3.2. Discussion

An indication of excessive ground movement should initiate an inspection to check for sinkholes and/or the dissolution of limestone under the containment. See discussion in FM 1.5 and FM 1.6. Excessive ground movement should also trigger an assessment for adequacy of long-term performance of the foundation and likelihood that foundation properties will remain within the design basis or adequate over the planned period of extended operations.

Table of Rankings for Importance by Failure Mechanism

1. Least important and minimal concern that this will contribute to long-term performance issues or jeopardize the ability of PCCV to perform for extended operations
2. Some concern that this mechanism might contribute to aging issues, perhaps in combination with other issues, and should be assessed when considering extended operations
3. Definite concern that this is important issue to be considered in assessing long-term performance of PCCV for extended operations

Failure Mode	Ranking	Comments
1. Containment Design and Analysis		
1.1. Excessive vertical and hoop stress	2-3	Depends on duration and/or frequency. Becomes a 3 if containment modifications are planned.
1.2. Excessive radial tensile stresses/no radial reinforcement through the containment wall	2-3	Becomes a 3 in presence of other aging effects for wall, such as AAR, or if containment modifications are planned.
1.3. Excessive tensioning of horizontal tendons	2-3	Depends on duration and/or frequency. Becomes a 3 if containment modifications are planned.
1.4. Excessive tensioning of vertical tendons	2-3	Depends on duration and/or frequency. Becomes a 3 if containment modifications are planned.
1.5. Foundation settling	3	Depends on history/magnitude, but should also trigger assessment of long-term adequacy of foundation support.
1.6. Inadequate design against ground movement	3	Depends on history/magnitude, but should also trigger assessment of long-term adequacy of foundation support.
1.7. Containment long-term, low-level vibrations	1-2	Becomes a 2 if structural modifications have been made that create vibration conditions outside original design basis.
1.8. Added stress from tendons not in the same plane	1	Considered minor effect and within design basis.
1.9. Added stress from variations in tendon spacing / Tendons bending around penetrations	1-2	Considered minor effect and within design basis, but becomes a 2 if structural modifications have been made to penetration components that create conditions outside original design basis.
1.10. Added stress from voids around tendon sleeves	1	See 2.7.
1.11. Effect of excessive micro cracks	1-2	Becomes a 2 in presence of surface cracking that can allow ingress of contaminants.
1.12. Added stress from inadequate size of tendon sleeves	1	Considered minor effect and within design basis.
1.13. Inadequate net loading area due to presence of horizontal tendon sleeves	2	The net effect is increased concrete stresses, so same issues/concerns as FM 1.1 through 1.4. Becomes a 1 if tendon forces have been adjusted so that concrete stresses comply with design basis.

1.14. Added stress from equipment hatch located underneath in same bay	1-3	Becomes a 3 if structural modifications have been made (or will be made) to hatch or wall near hatch.
1.15. Inadequate design analysis methods of radial tensile stresses	2-3	Net effect would be that in-situ stresses are higher than assumed in design so concern is same as FM 1.1 through 1.4. Becomes a 3 if containment modifications are planned.
2. Concrete Construction		
2.1. Inadequate concrete curing	1	Considered a small effect on long-term concrete properties.
2.2. Inadequate concrete pouring	1	Considered a small effect due to localized condition.
2.3. Inadequate slump (includes FM 3.6)	1	Considered a small effect due to localized condition.
2.4. Inadequate control of early age cracking	1-2-3	Becomes a 2 if cracking is significant enough to allow ingress of contaminants. Becomes a 3 if cracking is structural in nature.
2.5. Inadequate temperature control	1-2	1 if no evidence of surface cracking/distress. 2 if records indicate peak concrete temperatures exceeded 160°F during construction.
2.6. Inadequate mix design	1-2-3	Becomes a 2 if evidence of durability issues. Becomes a 3 if containment modifications are planned and test data, including creep properties, are not available.
2.7. Inadequate vibration during pour	1-2-3	Considered minor effect and within design basis. Becomes a 2 if there is history of tendon issues or anomalies in local tendon performance. Becomes a 3 if there are also signs of concrete distress in the area where voids are suspected.
2.8. Inadequate support of tendons during pouring	1	Considered minor effect and within design basis. Net result is similar to 1.8
2.9. Void or cracks due to inadequate forms (leaky, insecure, early stripping)	1-2	Considered minor effect on surface. Becomes a 2 if surface cracking is significant enough to allow ingress of contaminants.
2.10. Concrete deformation from tensioning too early	1	Considered too unlikely to be of concern for aging related issues.
2.11. Inadequate construction cold joint	1-2	Joint should be kept in compression due to vertical prestressing. Becomes a 2 if there is evidence of cracking or spalling at the joint or during detensioning.
2.12. Concrete mechanical properties	1-2	1 if construction records document that strength and creep are within design basis from batch testing. 2 if records do not exist or if major modifications are planned, then testing for in-situ concrete properties, including creep, is required.
3. Use of Concrete Materials		
3.1. Inadequate air content	1-2	2 if surface cracking is significant enough to allow

		ingress of contaminants. 2 if possibility that accident temperatures can exceed 100°C over a few days inside containment.
3.2. Inadequate grouting materials	1	Considered better than actual void or cold joint.
3.3. Inadequate cement materials	2-3	2 if construction records indicate anomalies between placed concrete and mix design specifications. 3 if evidence of structural distress.
3.4. Inadequate aggregates/weak aggregate	1-2	1 if construction records document that strength and creep is within design basis from batch testing. 2 if records do not exist or if major modifications are planned, then testing for in-situ concrete properties, including creep, is required.
3.5. Inadequate admixtures	1-2	2 if surface cracking or spalling is in evidence
3.6. Inadequate slump (included in FM 2.3)		See 2.3.
3.7. Inadequate concrete testing	2	If test results for concrete properties during the mix design and during construction are not available, testing to establish in-situ properties are required for assessing long-term performance.
4. Concrete Shrinkage, Creep, and Settlement		
4.1. Excessive plastic shrinkage	1	Minimal concern that excessive drying shrinkage would contribute to long-term aging issues.
4.2. Excessive shrinkage (includes FM 4.3 and 4.4)	1	Autogenous shrinkage is considered a short-term issue that saturates well before the initial design life.
4.3. Excessive autogenous shrinkage	--	Included in 4.2
4.4. Excessive carbonation shrinkage	--	Included in 4.2
4.5. Excessive creep	2-3	Creep can contribute to long-term performance issues when there are changes in the loading. Becomes a 3 if structural modifications are planned and creep data is not available or indicates concrete mix used had excessive creep relative to design.
4.6. Excessive drying creep		Included in 4.5.
4.7. Stresses due to differential material properties	1	Stress differences are within design margins.
4.8. Non-vibration induced fatigue cracking	1	Low probability that conditions with sufficient magnitude and frequency to affect functional performance will occur.
5. Chemically or Environmentally Induced Distress		
5.1. Foreign material intrusion/contaminants during construction	1-2	Most probable condition is contaminants in wall next to liner leading to aging distress in integrity of liner – but not easily identified. Becomes a 2 if operational history includes liner corrosion or distress.

5.2. Salt water intrusion	1	Assuming the more susceptible PCCVs with frequent or continuous exposure to salt or brackish water have good history of inspections without findings.
5.3. Chemicals introduced during routine maintenance	1	No long-term aging concerns.
5.4. Concrete form release	1	No long-term aging concerns.
5.5. Corrosion of rebars, ducts, and tendons	3	Existing corrosion of embedded steel is indicator that overall health and fitness should be assessed for extended operations.
5.6. Inadequacy of grease lubrication capability	1-2	Isolated incidents of corrosion/breakage of individual tendons can be detected and repaired to prevent PCCV functional failure due to long-term aging issues. Becomes a 2 if operational history has persistent or frequent tendon issues that could indicate other aging problems, such as concrete voids.
5.7. Physical attack	1-2	2 if evidence of concrete distress due to environmental conditions on exposed surfaces.
5.8. Chemical attack	1-2	2 if evidence of concrete distress due to environmental conditions on exposed surfaces.
6. Concrete-Tendon-Liner Interactions (During Operation)		
6.1. Uneven tension distribution along the tendon due to excessive local duct friction	1-2	Some variation in assumed stress distribution along tendons is within design basis. Becomes a 2 if there are anomalies in prestressing operations or persistent issue with tendons over operating life.
6.2. Inadequate tendon wires	1-2	Isolated incidents of corrosion/breakage of individual tendons can be detected and repaired to prevent PCCV functional failure due to long-term aging issues. Becomes a 2 if operational history has persistent or frequent tendon issues that could indicate other aging problems
6.3. Added stress from thermal effects of greasing	1	No impact on aging is expected.
6.4. Added stress from differences between rigid and flexible sleeves	1	No impact on aging is expected.
6.5. Inadequate tendon re-tensioning in surveillance activities	1	This is an inspection/maintenance issue that may result in some local and short-term deviations, but is not a mechanism for aging related failures.
6.6. Inadequate initial tensioning of tendons		See 1.1 through 1.4.
7. Containment Cutting	3	Any major modifications, especially cutting large holes, is cause for some concern of long-term performance and that assessments are needed to insure the PCCV is truly put back to a state compatible with the design basis.
7.1. Accumulated low level damage	1	No concern for low-level damage as aging

		mechanism leading to functional failure.
7.2. Shock or concrete separation due to resonant vibrations during hydro-blasting	2	Resonant vibrations could lead to damage affecting long-term functional performance and should be assessed.
7.3. Inadequate pattern/sequence of de-tensioning of tendons	2	Some concern that aged PCCVs may be susceptible to damage from inadequate care in detensioning.
7.4. Inadequate de-tensioning scope	2	Some concern that aged PCCVs may be susceptible to damage from inadequate care in detensioning.
7.5. Added stress due to removing tendons and concrete at opening	2	Some redistribution of stresses due to hole in containment, but concern is that repaired wall is indeed brought back within original design basis.
7.6. Vibrations due to cutting tendons under tension	2	Some concern that although shock propagation from snapped tendon is not aging issue, the forces transmitted to concrete can cause additional cracking and contribute to aging related issues.
7.7. Cracking due to pre-existing defects in this area	2	Pre-existing cracking found during structural modifications (or in-situ testing) means there is likelihood of pre-existing cracking in other areas and would cause some concern for contributing to aging, especially if PCCV does not have radial tiebars.
7.8. Excessive water jet pressure	1	Consider a localized effect and repaired as part of wall repair.
7.9. Inadequate hydro-blasting rate	1	Consider a localized effect and repaired as part of wall repair.
7.10. Formation of fine micro-cracks from hydro-lasing	1	Considered a localized effect and microcracking is accounted for in the design basis.
7.11. Added stress from pulling tendons out of sleeves and grease after cutting	1	No additional cracking damage significant enough to contribute to aging degradation is anticipated.
8. Operational Events		
8.1. Prior spray event leading to low pressure inside containment	1	Infrequent, low level variations in operating conditions should be covered in design margins and would not be expected contribute to aging degradation.
8.2. Thermal stresses due to containment spray	2	For more severe accidents, any resulting trauma on liner could be indication that liner/anchorage has aging degradation issues.
8.3. Effect of faster pressurization/depressurization rates during last integrated leak rate test (ILRT)	1	Infrequent, low level variations in operating conditions should be covered in design margins and would not be expected contribute to aging degradation.
8.4. Inadequate concrete structure monitoring/maintenance (as determined by subsection IWL of the ASME code)	3	Inadequate monitoring and maintenance can directly contribute to long-term functional failure by failing to identify aging related issues.

8.5. Containment depressurization due to inadequate purging operation	1	Infrequent, low level variations in operating conditions should be covered in design margins and would not be expected contribute to aging degradation.
9. External Events		
9.1. Hurricanes or tornados	1	Not considered an aging issue, but a trigger for inspection to look for any anomalies in performance of aged PCCVs that might indicate aging degradation is present.
9.2. Seismic events	1	Not considered an aging issue, but a trigger for inspection to look for any anomalies in performance of aged PCCVs that might indicate aging degradation is present.
9.3. Ground movements (sink holes or geo-sliding)		See FM 1.5 and 1.6.

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