5E.2 LONG-TERM CORRECTIVE ACTIONS FOR VERTICAL TENDON CORROSION

5E.2.1 DISCOVERY OF CORROSION

During performance of the 20-year (1997) Technical Specification and American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (Reference 1) tendon surveillance on Unit 1, conditions that did not meet the acceptance standards were found on the Containment Structure. Conditions that did not meet the acceptance standards were found in all three containment tendon populations, i.e., hoop, dome, and vertical tendons. The abnormal conditions found on the hoop and dome tendons were considered minor enough that the acceptability of the concrete containment was not affected. The unacceptable conditions were found in the vertical tendon population. Several of the vertical tendons selected for surveillance were found to contain broken and corroded wires at their top ends, below the stressing washer. The discovery of broken wires in these tendons initiated an expansion of the Unit 1 vertical tendon inspection scope to perform visual inspections and lift-off testing on all Unit 1 vertical tendons. Subsequently, broken and corroded wires were found throughout the Unit 1 vertical tendon population at the top ends of the tendons. Following completion of the Unit 1 surveillance, the 20-year surveillance of the Unit 2 tendons was conducted. Although Unit 2 was only required to perform visual inspections, it was decided to also perform lift-off testing of all the vertical tendons in order to facilitate inspection of the tendon wires in the region of concern below the upper (top) stressing washer. Abnormal conditions very similar to Unit 1 were found on the Unit 2 vertical tendons. Precision Surveillance Corporation (PSC), performed all the inspection work. Precision Surveillance Corporation wrote a non-conformance report for every abnormally degraded condition that did not meet the acceptance standards of IWL-3220 and Reference 2. The original tendon post-tensioning system is described in Sections 5.1.2 and 5.1.4.

5E.2.2 CAUSE OF VERTICAL TENDON CORROSION

During the 20-year tendon surveillance on the Unit 1 and Unit 2 Containments, corrosion and broken wires were discovered on some vertical tendons. Reference 3 and Reference 4 evaluated the findings and determined the cause of the corrosion and wire breaks. The evaluation concluded that the tendon wire failures and corrosion problems resulted from a combination of water and moist air intrusion into the vertical tendon end caps (grease cans), and inadequate initial grease coverage of wires in the area just under the top stressing washer. To address issues identified in the evaluation, short-term corrective actions were taken. These actions included spraying hot grease under the top stressing washer, reorienting the stressing shims to leave a gap between the shims to allow a vent path to help eliminate voids, re-greasing non-corroded vertical tendons, and resealing around the original tendon can all-thread penetrations with caulking. Additional inspections were performed in 1999 and 2000 to verify the assumptions that were considered in evaluation and to provide additional data to help develop a long-term corrective action plan.

5E.2.3 LONG-TERM CORRECTIVE ACTIONS

The goal of the long-term corrective action plan is to ensure that the Containments meet their design basis requirements until plant end-of-life. As one part of the long-term corrective action plan, all the vertical tendons have been re-greased with new corrosion inhibiting grease (Visconorust 2090-P4). The non-corroded vertical tendons were re-greased in 2000, and the tendons with less severe corrosion were re-greased during 2001. The remaining vertical tendon population was replaced in 2001 and 2002, and had new grease put in place at that time. In addition, all of the vertical tendons had a redesigned pressure-tight, grease-filled cap installed at the upper-bearing plate to prevent water intrusion. The bottom grease cap for every vertical tendon was also replaced with a new redesigned pressure-tight grease cap. The redesigned grease cap has a flange that is attached by studs and nuts to the tendon bearing plates utilizing existing taps in the plates.

As mentioned in the above paragraph, another part of the long-term corrective action plan involved the replacement of a portion of the corroded vertical tendon population. Preliminary evaluations using a wire breakage predicting model had shown that without vertical tendon replacement, neither Containment would meet its design basis at plant end-of-life due to prestress loss from predicted future wire breakage. To determine which vertical tendons were to be replaced, a final vertical tendon future wire breakage prediction model and selection criteria were developed. The wire breakage prediction model is described below first, followed by the vertical tendon replacement selection criteria.

5E.2.3.1 Future Wire Breakage Prediction Model (a.k.a. Weibull Model)

As discussed previously, corrosion (abnormal degradation) at some of the top ends of the Units 1 and 2 containment vertical tendons was found during the 20-year 1997 tendon surveillance. To determine the acceptability of the Containments without repairing the vertical tendon wires, a model was developed to predict how the degradation of the tendon wires would affect the wires over the plant life. Wire degradation is predicted to lead to additional future wire breakage, as was found during the 1997 inspections.

Reference 5 was used to determine the acceptability of the Containments without repairing or replacing the degraded vertical tendons. The objective of the report was to develop models for the future failures of tendon wires. The models could then be used to assess how long the vertical tendons would continue to meet structural integrity requirements, with the assumption that the short-term corrective actions and long-term corrective actions were not fully effective in stopping further corrosion degradation. The models were developed using a Unit 2 timeline. The Unit 1 tendons have been tensioned longer than those of Unit 2. However, the inspections of 1997, 1999, and 2000 indicated that the conditions of the tendons for the two units were comparable at the time. Therefore, the models are applicable and conservative for either unit on a calendar time basis, without adjustment for the longer service time under tension of the Unit 1 tendons. The models described in the report use the additional data derived from the 1999 and 2000 inspections to extend the postulated period of validity to the plant end-of-life. The model for ductile/general corrosion wire failures also uses the observed wire failures during lift-off tests to develop an additional data point for failures from that degradation mode. The report presents separate models for the two mechanisms of degradation: (1) hydrogen-induced cracking; and (2) ductile/general corrosion failures. The predictions for the two degradation mechanisms are then combined to obtain the total predicted wire failures.

Because of the conservative assumptions used to develop the combined model, it is anticipated that the model predictions will be bounding for observed behavior for the remaining extended operating license of the Units. Although the model developed in the report is expected to be a conservative upper-bound estimate of what will actually occur, it is based on minimal data and plausible assumptions. The conservatism of the model will be validated by future enhanced tendon inspections. The report shows that, conservatively, 2,714 wires could break on each Unit due to abnormal wire degradation by the end of the plant operating licenses. The report shows the spread of the number of future wire breaks in individual tendons throughout the tendon population. This range is from a predicted maximum of 86 wire breaks in one tendon, to a minimum of 1 wire break in 48 different tendons.

In order to apply the statistical model predictions to all of the original vertical tendons for each Unit, all of the vertical tendons were first grouped by as-found corrosion level in 1997. The various corrosion levels were determined during the visual examination performed on the tendon wire surfaces behind the shim stacks at the top of each vertical tendon in 1997 and 1998. This is the area defined by References 3 and 4 as the area susceptible to wire breakage. Once the individual vertical tendons were ranked by corrosion level, a list of tendons by corrosion level group was generated ranging from "extreme corrosion" to "no corrosion." An average predicted number of wire failures was then calculated for each corrosion level group. This average number was then assigned to each tendon in a particular corrosion level group to represent future wire breaks. This approach of assigning an average number of future wire breaks to a corrosion level group was conservative in that, as vertical tendons were selected for replacement, less future wire breaks would be removed from the predicted total. By taking this approach, more corroded tendons would be required to be replaced to achieve acceptability of the Containments.

5E.2.3.2 Selection Criteria for Corroded Tendons to be Replaced

To determine which vertical tendons would be replaced, a selection criterion was developed, as described below:

1. Replace all tendons that had two or more broken wires. Most of the additional broken wires discovered in 1999 were in tendons with two or more previous broken wires from 1997. Therefore, these tendons appeared to be the most likely to have future broken wires. Note: There was one exception to this criterion. Four buttonheads were found missing on the bottom of Unit 2 tendon 61V27 in 2001, and were not in the scope of Reference 4. Therefore, this tendon was not replaced.
2. Replace corroded tendons demonstrating lower lift-off forces. This applies to all tendons that were classified as having extreme or heavy corrosion and had a lift-off force of less than 649 kips in 1997. The small additional strain imparted by lift-off testing has the potential to cause additional wire breaks, as occurred in 1997. Corroded tendons with lower than predicted lift-off forces will be replaced to eliminate the possibility of premature wire breakage during future lift-off testing. Furthermore, replacing severely corroded tendons with low lift-off forces would prevent potential prestress losses associated with wire breakage from the restressing of these tendons. Restressing tendons increases the strain more than lift-off testing, and could potentially result in an even greater number of wire breaks.
3. Replace corroded tendons to ensure uniform distribution of prestress. The third criteria was specific to Unit 1 since it has two tendons that were not originally installed and, therefore, has two areas with low prestress force distribution. Calvert Cliffs replaced all the tendons that had extreme or heavy corrosion near the two empty tendon sheaths.
4. Replace corroded tendons to ensure uniform prestress force distribution after accounting for prestress losses from statistical Weibull model. This criteria ensures the loss of prestress that would result from the conservative prediction of wire breakage, would not violate design criteria described in Sections 5E.1.2 and 5E.1.3 at plant end-of-life. Calvert Cliffs applied the statistical model wire breaking predictions to all of the remaining original tendons that were not replaced under the first three criteria. This last criteria identified the areas around the Containments that, if the predicted wire breaks occurred, had the potential of driving the

distribution of vertical prestress force below the minimum design requirements. Once those areas were identified, appropriate corroded tendons were selected for replacement until the distribution of vertical prestress force exceeded the minimum design requirements at plant end-of-life.

Once a vertical tendon was replaced, the future number of broken wires in the new tendon is assumed to be zero. The number of future wire breaks in non-replaced tendons is the average wire breaks for that corrosion level group. After tendon replacement on each Unit, the conservative predicted number of wire breaks at plant end-of-life drops to 1,195 for Unit 1 and 1,228 for Unit 2.

It was determined that 47 tendons on Unit 1 and 46 tendons on Unit 2 were the most cost-effective number of tendons to replace on each Unit that would provide the most uniform circumferential vertical prestress at plant end-of-life. It was also determined to restress 20 original vertical tendons on Unit 1, and 30 original vertical tendons on Unit 2, that had exhibited low lift-offs in 1997.

5E.2.3.3 Stressing Sequence of Tendons Replaced and Restressed

The process of replacing and restressing vertical tendons on each Containment was done at full power. Therefore, to avoid operability issues during the work process, the number of tendons destressed at any one time, and the sequence in which tendons were destressed for removal, was critical to keeping the Containments within their design basis. Figures 5E-1 and 5E-2 show the final stressing sequence and individual vertical tendons replaced or restressed in 2001 and 2002 for Unit 1 and 2, respectively.

5E.2.3.4 Tendon Bearing Plate Concrete Void Repairs

While performing lift-off testing on all the vertical tendons, two Unit 1 bearing plates depressed during the testing. The concrete under these bearing plates had been previously repaired as part of the tendon bearing plate study discussed in Appendix 5D. However, the repairs made to these bearing plates were not adequate to prevent bearing plate flexure. It was decided to remove these bearing plates and perform additional concrete void repairs with grout. The vertical bearing plates that received grout repairs in 2001, type of grout used, and repair method are shown on Figure 5E-1 for Unit 1.

5E.2.4 ACCEPTABILITY OF CONCRETE CONTAINMENTS

Table 5E-2 provides a summary of vertical prestress conditions for both Units in 2002 for the original design and with corrective actions. Table 5E-2 also provides the predicted vertical prestress conditions in 2034 for Unit 1, and 2036 for Unit 2. The table is intended to provide a comparison of required and predicted vertical gross prestress, and a comparison of required and predicted mean average force per tendon sheath distribution.

Since not all the vertical tendons on each Unit exhibiting corrosion have been replaced, it should be noted that any corrosion on the original .25-inch diameter tendon wires could potentially reduce the effective cross-sectional area of the wire. A reduced effective cross-sectional area at the point of corrosion will cause the unit stress in the wire to increase. During initial stressing of the original tendons, the wires were left at a seating stress between 0.7 $f_s{}'$ (168 ksi) and 0.73 $f_s{}'$ (175.2 ksi) (Section 5.1.4.2). Over time, the original tendon wires have relaxed, reducing the stress in the wires as a percentage of $f_s{}'$. Therefore, the wire stress in the corroded areas should still be below the wire material minimum yield point of

0.8 f_s' (192 ksi). For the wires with severe corrosion that do become stressed beyond the wire material yield point and ultimately break, the total number has already been enveloped in the Containment acceptability evaluation.

5E.2.5 ENHANCED VERTICAL TENDON INSPECTIONS

The future inspection of the vertical tendons is a two-tiered approach. First, ASME Section XI code inspections will be performed as required by the NRC-mandated ASME Boiler and Pressure Vessel Code (Reference 1). Lift-off testing will be conducted on the replacement tendons as required by the ASME Code. Second, enhanced inspections will be performed to examine the tendons for potential wire breaks. To monitor future changes in the conditions of all tendons, a database has been created to catalog the complete scope of all tendon inspection and repair activities.

The goal of enhanced inspections is to ensure that the Weibull Model bounds existing field conditions. To accomplish the enhanced inspections, the anchorhead/buttonhead region is required to be examined to determine if any wire breaks have occurred in the area under the vertical tendon top-stressing washers.

By the end of 2005 and 2007, Calvert Cliffs Nuclear Power Plant (CCNPP) will perform an inspection for wire breakage on 100% of the original vertical tendons. Unit 1 has 155 remaining original vertical tendons. Unit 2 has 158 remaining original vertical tendons. The purpose of these inspections will be to determine the number of failed (i.e., protruding) buttonheads at the top end of the vertical tendons. The resulting total number of protruding buttonheads will be compared to the number of predicted wire breaks for future specific years. If the total number of actual wire breaks is less than the number predicted for that unit in that year, and no tendon has more than the average number of failed wires in their corrosion group, then the actual condition of the containment vertical tendons are within the bounding conditions predicted by the statistical Weibull Model (Reference 5). If the number of failed wires in a tendon exceeds the average for that corrosion level group, the number will be compared to the average for that group at plant end-of-life. If a tendon's actual number of wire breaks exceeds the plant end-of-life predicted failure numbers, then an engineering evaluation will be performed.

In 2007, following the results of the ASME Code and enhanced inspections, CCNPP will assess the need to continue with enhanced inspections. This assessment will determine if the ASME Code inspections alone would provide adequate information to validate the statistical Weibull Model. If the model continues to bound field conditions, but more of a sample is required than that provided by the ASME Code surveillance population, the enhanced inspection frequency will be changed to a five-year span and then completed concurrently with the ASME Code inspections.

5E.2.6 CONTAINMENT PRESSURE TEST

Reference 1, Article IWL-5000, provides requirements for pressure-testing concrete containments following repair or replacement activities. The concrete repairs to the Unit 1 Containment associated with the discovery of corrosion on the containment vertical tendons in 1997 only involved the removal of vertical tendon top bearing plates and the filling of voids with grout. These repairs were outside the outermost layer of structural reinforcing steel in the ring girder. The repairs and replacements to the containment vertical tendon system involved the exchange of post-tensioning tendons, tendon anchorage hardware, shims, and corrosion protection medium for both Containments. In accordance with the ASME Code, by performing these types of repairs and replacements only, no additional containment pressure tests were required to demonstrate containment structural integrity upon completion. The conclusions of the containment structural tests to 115% of design pressure following original Units 1 and 2 construction remain valid as discussed in Section 5.5.1.2.

5E.2.7 REFERENCES

1. American Society of Mechanical Engineers Boiler and Pressure Vessel Code, 1992 Edition through the 1992 Addenda, Section XI, Subsection IWL, "Requirements for Class CC Concrete Components of Light-Water Cooled Power Plants"

2. NRC Regulatory Guide 1.35, Revision 2, "Inservice Inspection of Ungrouted Tendons in Prestressed Concrete Containment Structures"

3. Calvert Cliffs Unit 1 20-Year Containment Tendon Surveillance Engineering Evaluation, October 28, 1997

4. CCNPP Root Cause Analysis Report, RCAR-9808, Root Cause Investigation of Containment Tendon Wire Corrosion and Failure, March 26, 1998

5. Dominion Engineering, Inc. Report, R-3648-00-01, Updated Model for Containment Structure Vertical Tendon Degradation for Calvert Cliffs 1 and 2, December 14, 2000

TABLE 5E-2

PRESTRESS COMPARISON IN VERTICAL TENDON SYSTEM

(Tendon relaxation losses for new tendons installed in 2001 and 2002 based on actual wire test Reports)

(Values in kips)

		Unit 1[1]				**Unit 2**			
		Gross Prestress	Mean Average Force per Tendon Sheath	Gross Margin	Mean Average Force per Tendon Sheath Margin	Gross Prestress	Mean Average Force per Tendon Sheath	Gross Margin	Mean Average Force per Tendon Sheath Margin
1.	Design Basis	123,620	606	N/A	N/A	123,620	606	N/A	N/A
2.	Predicted Prestress in 2002. No replacements, no restressing, no wire breaks. Original tendon design.[2]	130,694	641	7,074	35	133,416	654	9,796	48
3.	Predicted Prestress after 2002 Corrective Actions. Includes replacements, includes restressing, no wire breaks.[3]	143,880	705	20,260	99	143,373	702	19,753	96
4.	Predicted Prestress at 2034 and 2036. No replacements, no restressing, no wire breaks. Original tendon design.[4]	129,280	634	5,660	28	132,192	648	8,572	42
5.	Predicted Prestress at 2034 and 2036. Includes replacements, includes restressing, includes wire breaks.[5]	132,334	648	8,714	42	131,353	643	7,733	37

TABLE 5E-2

PRESTRESS COMPARISON IN VERTICAL TENDON SYSTEM

Note: All values in Table 5E-2 have been conservatively rounded down except the line 2 Unit 1 Mean Average Force per Tendon Sheath value, which has been rounded up.

(1) Unit 1 has only 202 vertical tendons, but both Units have 204 sheath locations.

(2) The respective data considers the prestress losses associated with concrete creep/shrinkage and wire relaxation only, and does not consider potential wire breaks.

(3) Comparing Lines 2 and 3 show the predicted margin after the planned corrective actions.

(4) These values can be considered the “original design” margins expected at the end of the operating licenses in 2034 and 2036, if tendon corrosion and wire breakage had never occurred.

(5) Denotes the predicted prestress values following the 2001 and 2002 corrective actions of restressing and replacing tendons, while accounting for prestress losses associated with concrete creep/shrinkage and wire relaxation and a conservative amount of predicted wire breaks.