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Constellation Nuclear

Calvert Cliffs
Nuclear Power Plant

A Member of the Constellation Energy Group

July 24, 2000

U. S. Nuclear Regulatory Commission
Washington, DC 20555

ATTENTION: Document Control Desk

SUBJECT: Calvert Cliffs Nuclear Power Plant
Unit Nos. 1 & 2; Docket Nos. 50-317 & 50-318
Response to Request for Additional Information Concerning the Containment Tendon Long-Term Corrective Action Plan (TAC Nos. MA7782 and MA7783)

REFERENCES:

(a) Letter from Mr. C. H. Cruse (BGE) to NRC Document Control Desk, dated December 7, 1999, Revisions to the Containment Tendon Long-Term Corrective Action Plan

(b) Letter from Mr. A. W. Dromerick, Sr. (NRC) to Mr. C. H. Cruse (BGE), dated May 25, 2000, Calvert Cliffs Nuclear Power Plant, Unit Nos. 1 and 2 – Request for Additional Information RE: Containment Tendon Long-Term Corrective Action Plan (TAC Nos. MA7782 and MA7783)

In our letter dated December 7, 1999 (Reference a), we provided revisions to our long-term corrective action plan regarding the Calvert Cliffs Nuclear Power Plant Units 1 and 2 Containment tendon degradation. Attachment (1) to this letter provides the information requested by the NRC staff in your letter dated May 25, 2000 (Reference b).

Should you have questions regarding this matter, we will be pleased to discuss them with you.

Very truly yours,

CHC/DJM/dlm

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ATTACHMENT (1)

RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION CONCERNING THE CONTAINMENT TENDON LONG-TERM CORRECTIVE ACTION PLAN

NRC Request

Review of the information provided in Table 1, "Results of 1999 Tendon Inspection," listed under the second item of Reference 1, clearly indicates a steady and continuous trend of additional wire breakage and tendon degradation when compared to the results of the 1997 inspection. Yet, in Reference 1, you are proposing to (1) postpone the replacement to possibly as late as December 31, 2002, and (2) replace the specific tendon replacement commitments defined in Reference 2 with a generally undefined tendon replacement program. Additionally, the engineering analysis to be used in defining the scope of the proposed replacement program is also undefined. We request that you address the following questions in your response to this request for additional information:

1. *The third item of your Containment Tendon Long-Term Corrective Action Plan provided in Reference 2 states, in part that by December 31, 2000, BGE* [Baltimore Gas and Electric Company, name change effective July 1, 2000, Calvert Cliffs Nuclear Power Plant, Inc.] *will replace all severely corroded vertical containment tendons, (i.e., 63 of 202 vertical tendons in Unit 1 and 64 of 204 vertical tendons in Unit 2) with new tendons. However, in your revised Containment Tendon Long-Term Corrective Action Plan (Reference 1) you stated, in part that after reviewing the final report for the 1997 inspections, it was determined that 123 of 202 vertical tendons from Unit 1 and 130 of 204 vertical tendons from Unit 2, did not have indications of corrosion. This statement seems to imply that, based on your more recent review of the 1997 final inspection report, there are 79 (202-123=79) and 74 (204-130=74) severely corroded tendons for Units 1 and 2, respectively. Please explain the above numerical discrepancies with respect to the numbers of so-called "severely corroded tendons" identified during the two different reviews performed on the 1997 tendon inspection data.*

   CCNPP Response

   The initial Containment Tendon Long-Term Corrective Action Plan, dated May 14, 1998, was submitted prior to the final disposition of the nonconformance reports from the 1997 inspection. In our initial plan, we stated that the estimated number of severely corroded tendons was 63 for Unit 1 and 64 for Unit 2. This estimate was based on verbal day-to-day communication with the vendor during the 1997 inspection. Subsequent to the May 14, 1998 submittal, we received the Final Report for the 1997 Containment Post-Tensioning System Inspection from our vendor. During the preparation of the Final Report and review of the documentation for the 1997 inspection, we determined that the final number of severely corroded tendons for Unit 1 was 79 and for Unit 2 was 74. The initial Containment Tendon Long-Term Corrective Action Plan was submitted prior to the final review of the data being complete based on deadlines of the NRC letter dated January 23, 1998 (Reference 3). The differences in the numbers between the May 14, 1998 letter and the December 7, 1999 letter are due to the review of the 1997 inspection data report.

NRC Request

2. *Assuming that you have adopted a more or less consistent criteria in judging the severity of tendon corrosion during the two different review occasions, does the above noted discrepancies (i.e., from 63 to 79 and 64 to 74 tendons for Units 1 and 2, respectively) suggest a rather rapidly progressing degradation rate for Units 1 and 2 tendons? What is the engineering basis for your proposed relaxation with respect to the contents of the Calvert Cliffs Containment Tendon Long-Term Corrective Action Plan? Please address this issue from the standpoint of both the relaxation in criteria for tendon replacement and the proposed postponement in tendon replacement schedule, and potential effects on Calvert Cliffs' containment integrity.*

CCNPP Response

As described in the above response, the differences in the number of severely corroded tendons between the May 14, 1998 letter and the December 7, 1999 letter do not signify a change in degradation rate. The visual inspection performed in 1999 did not show any indications that our degradation rate was more severe than previously predicted. The engineering basis for our proposed action plan continues to be derived from our engineering evaluation report provided to the NRC in the October 28, 1997 submittal (Reference 4). The engineering evaluation of the degraded containment prestressing systems is based on the lift-off values measured during the 1997 inspection for the vertical tendons. The engineering evaluation determined that the wire failures were caused by corrosion that had been occurring for many years, perhaps since plant construction. The 1999 inspection supports our conclusion that the failures were caused by long-term corrosion. We believe the short-term corrective actions taken during the 1997 inspection have slowed this corrosion. Containment integrity is based on the lift-off values measured during the 1997 inspection for the vertical tendons. The 1997 inspections show that the vertical tendons are capable of providing the required force to the containment such that the containment can perform its safety function.

Our May 14, 1998 response was based on the inspections completed in 1997. Because we only had one data point, we adopted a conservative approach to ensure integrity of the containments. On further review and using additional inspection results gathered in 1999, we have additional evidence to conclude that the degradation of the tendon wires is a long-term process. Therefore, the actions previously planned were no longer necessary in a short time period. We revised our corrective actions to allow additional data collection and analyses to determine which, if any, vertical tendons need to be replaced. Our revised corrective action plan provides a more cost-beneficial and deliberate resolution, but it always ensures we meet or exceed our design requirements.

NRC Request

3. *Under the first paragraph of Justification for the Containment Tendon Long-Term Corrective Action Plan of Reference 2, you stated that "Our long-term plan does not rely on the statistical prediction of wire breakage." Yet, the last part of your second item of Reference 1 indicates that you still intend to use a questionable statistical distribution (Weibull distribution) and a set of generally unsupportable assumptions to make an engineering predication. The above-noted statements seem to present an inconsistent BGE position. BGE is, therefore, requested to use a deterministic based engineering analysis or a statistical approach supported by adequate and credible inspection data to draw its safety conclusion regarding the adequacy of its degraded containment prestressing systems.*

CCNPP Response

Calvert Cliffs Nuclear Power Plant, Inc. is not relying solely on a statistical model to ensure containment integrity. We will perform additional visual inspections of tendon anchorages to confirm the rate of wire failures.

In order to ensure that the containment structures continue to perform their intended safety function while corrective actions are being planned, scheduled, and conducted, we attempted to quantify an appropriate degradation rate to use in the deterministic analyses. We considered a number of options for determining an appropriate degradation rate including:

1. Crediting regreasing so that the future degradation rate would be zero;

2. Linearizing past failure observations so that the rate would be 231 wires divided by 24 years divided by 2 containments for a rate of approximately 5 wires per year, per containment; and

3. Modeling the corrosion mechanism in a statistical failure model.

While options 1) and 2) are deterministic methods, we determined that they were neither accurate, nor conservative. Instead, we applied what we believe is the standard and appropriate method to most accurately evaluate corrosion degradation of components. The statistical distribution used in our model (the Weibull distribution) is not a questionable distribution. Instead, it is the leading method for fitting life data, and is applied over a vast variety of engineering failure prediction situations (References 5, 6, 7, 8). Because we have data from two inspections, we have been able to develop a Weibull model based solely on tendon degradation data (including the Weibull slope).

To reiterate, we do not rely solely on a statistical model to determine the adequacy of the containment tendon prestressing system, or for corrective action planning. Nevertheless, the statistical model is a widely-accepted technique used to characterize the degradation rates for input into deterministic analyses. The statistical approach is supported by adequate, credible inspection data.

NRC Request

4. *Given the continuing tendon degradation noted above, please provide your assessment that this continuing degradation of the containment prestressing systems with its consequential reduction in design margins originally established per the applicable FSAR criteria for both Units 1 and 2 would not constitute an unreviewed safety question pursuant to 10 CFR 50.59.*

CCNPP Response

Our assessment of the adequacy of containment tendon design margin is the subject of the correspondence cited in this letter. The information provided establishes the basis for the plant's safety during our corrective action period.

As discussed above, our final corrective actions are still under development. The end state will not be determined until after evaluation of the data from inspections later this summer. We expect to complete that evaluation by October. If, as a result of that evaluation (or any subsequent development), we decide to accept "as-is" an end state different than that described in our Updated Final Safety Analysis Report, we will evaluate that condition in accordance with 10 CFR 50.59.

Calvert Cliffs Nuclear Power Plant, Inc. is addressing the issue of containment tendon corrosion as a degraded condition subject to our 10 CFR Part 50 Appendix B Corrective Action Program. Our correspondence regarding the corrective action plan associated with this condition has been provided to facilitate NRC staff's understanding of the adequacy of our corrective actions and the technical basis for our plan. This process approach is consistent with the guidance provided in NRC Generic Letter 91-18 Revision 1, which notes that 10 CFR 50.59 is applicable to this scenario only:

- If the condition is accepted "as-is" resulting in something different than described in the SAR; or
- If an interim compensatory action is taken to address the condition and involves a procedure change or temporary modification.

We do not intend to invoke any temporary procedure changes or plant modifications; therefore, we believe applying the criteria of 10 CFR Part 50, Appendix B, Criterion 16 for timely correction of the conditions commensurate with their safety significance is the applicable regulatory process, not 10 CFR 50.59.

NRC Request

5. *During a telephone conference held between the staff and BGE representatives on May 8, 2000, BGE indicated that some 102 Unit 2 vertical tendon top anchors, which were previously determined as not severely degraded during the 1997 inspection, were reinspected in 1999. BGE stated that the reinspection was intended for gathering additional data to support a general conclusion that no significant incremental degradation of both Units 1 and 2 vertical tendons has been experienced since the 1997 inspection. BGE is requested to provide a summary of the inspection procedure including sampling methods, evaluation criteria and findings of the 1999 inspection.*

CCNPP Response

Sampling Procedure

The Unit 2 inspection scope in 1999 was expanded to included the 74 tendons previously identified as severely degraded (original scope) and 28 additional tendons that were not considered to be degraded, for a total of 102 tendons inspected. The Unit 2 inspection scope was expanded to include more tendons without broken wires to provide additional data for the model. The random sample of 40 was chosen after the 74 tendons had already been examined. A random sample of 40 tendons was chosen from a group of tendons consisting of all tendons with no previous broken wires (but including tendons with severe corrosion and no broken wires). There was some overlap between the two groups, resulting in 28 additional tendons being inspected, for a total of 102. The population size from which the sample of 40 was selected was 177 tendons. The sample size of 40 was the minimum size that would give us 95% confidence that no more than 5% of the total vertical tendon population had broken wires.

Tendons on Unit 1 were also reinspected. The 1999 Unit 1 inspection scope consisted of re-inspection of the 79 tendons that had been determined to be severely corroded during the 1997 inspection. The 1999 Unit 1 inspection was completed as scoped. It should be noted that of the 79 tendons inspected, 19 had previously been identified as containing broken wires, while the remaining 60 did not have broken wires observed during the 1997 inspection.

Inspection Method

The inspection method consisted of removing the tendon top anchorage grease cap to allow visual examination of the tendon wire buttonheads at the tendon top anchorage. Broken wires are identified by the protrusion of the buttonheads.

Inspection Results

One additional broken wire was discovered in Unit 1, in a tendon previously identified as having broken wires. Eight additional broken wires were found in Unit 2. Seven of these wires were in tendons already identified as having broken wires and one wire was found in a tendon with no previous broken wires. The results of the 1999 inspection were summarized in Reference 1, Table 1.

Philosophy of Sampling

For modeling purposes, tendon inspection provides two types of useful information: 1) the number of tendons with broken wires; and 2) the average number of broken wires per affected tendon. Inspection of tendons not previously identified as having broken wires provides the best information about increases in the number of affected tendons. Inspection of tendons previously identified as having broken wires provides the best information about the average number of wires broken per affected tendon. During the 1999 inspection of Unit 1, we re-inspected only tendons previously identified as being severely corroded. The population of tendons that were severely corroded included tendons that had broken wires and tendons that did not have broken wires. Therefore, the Unit 1 inspection provided additional information for both modeling purposes.

Estimation of the number of affected tendons is accomplished by inspecting a different set of tendons than those used to estimate the average number of broken wires per affected tendon. To determine the distribution of affected tendons (again, where "affected" means having at least one broken wire), it is necessary to inspect tendons previously known to not have broken wires. When fewer than 100% of the unaffected tendons are inspected, the estimate of affected tendons is less certain and it is necessary to make confidence estimates. During the re-inspection of the Unit 2 tendons in 1999, Calvert Cliffs increased the sample size for non-affected tendons to permit determination of 95% confidence estimates.

Estimation of the average number of wires per affected tendon (where "affected" means having one or more broken wire) may be conservatively accomplished by inspecting only tendons previously identified as having at least one broken wire. This sample size is conservative because it excludes from consideration tendons that are not inspected, but that have recently experienced an initial wire failure. Such tendons typically have a low number of broken wires so that their exclusion from the estimate tends to make the estimate higher than it actually should be. For this reason, the sampling in both Unit 1 and Unit 2 was appropriate and conservative for determining the average number of wires per affected tendon.

BASIS FOR USING UNIT 2 TO REPRESENT BOTH UNITS

The random sample from Unit 2 was used to construct a tendon degradation model for both units. The 1997 inspection results were very similar for the Units 1 and 2 vertical tendons. Unit 1 had 19 tendons with broken wires and 117 total broken wires, while Unit 2 had 27 tendons with broken wires and 102 total broken wires. The results of the root cause analysis indicated that both containments had tendon wires degrading due to the same mechanism. The root cause analysis is provided in Reference 4. In fact, both containments are similar to the degree that a single model developed for Unit 1 performed well for Unit 2 in 1997. During the 1999 inspection, a statistical model based on the common mechanism was developed using the inspection data from both units. We believe this model is equally applicable to both Units. In this combined model, estimates of the average number of broken wires per affected tendon are based on relatively complete data sets from both Units during both inspections.

The estimates of the number of affected tendons in the combined model is based on the 100% inspection in 1997 and the sampling of 40 unaffected tendons on Unit 2 in 1999. The size of the data set was chosen to permit determination of 95% confidence bands. Since the design and degradation mechanism for both containments is similar, and since the model is composed of data from both Units, we consider the model to be a reliable predictor of future degradation rates for either Unit. The selection of a sample of 40 tendons from Unit 2 alone, instead of a sample from

each Unit, for example, was mostly a function of when the decision was made to expand the sampling. The decision was made after the inspection equipment had been removed from Unit 1 and placed on Unit 2. Since the planned 2000 inspection scope included a much larger sample of tendons that had not been previously observed to have broken wires, confidence in the prediction of the fraction of affected tendons would be improved at that time. Since the model predicted a slow increase in the number of broken wires, we concluded the planned 2000 inspections would provide timely verification of the model predictions.

In summary, we completed the 1999 Unit 1 inspection scope. Calvert Cliffs Nuclear Power Plant, Inc. decided to expand the 1999 Unit 2 inspection scope to include more tendons without broken wires. The results of the inspection verified the model prediction that degradation would progress slowly. Calvert Cliffs Nuclear Power Plant, Inc. used the inspection results to develop an improved model. The improved model continues to predict slow progression of degradation. Calvert Cliffs Nuclear Power Plant, Inc. concluded that it was appropriate to wait for the planned larger inspection scope in 2000 to further improve the confidence statistics in the predictive model.

NRC Request

6. *Provide a copy of the BGE engineering report mentioned during the above noted telephone conference which addresses BGE's development of its containment tendon Weibull models and, as appropriate, discuss in detail how uncertainties related to the models were adequately dealt with (e.g., performance of sensitivity analysis).*

CCNPP Response

The detailed report on the statistical tendon degradation model is contained in Enclosure 1.

Description of Model and Assumptions

A statistical model was constructed using two inspection data points. The model is a two-tiered model, using a Weibull distribution for the number of tendons with broken wires, and a gamma distribution for the distribution of broken wires among the affected tendons.

Weibull Model

The 1997 Unit 2 inspection results were used as the first data point. In 1997, 27 tendons in Unit 2 had broken wires out of the 204 total vertical tendons. This was a 100% inspection, so there was no uncertainty in the results. The second data point was the 1999 random sample results. One additional tendon with broken wires was found in the random sample of 40 tendons.

When one tendon with broken wires was found in the random sample, a sensitivity study was made to evaluate the effect of expanding the sample to achieve 95% confidence that no more than 5% of the sample population had broken wires. The sample would have had to be expanded to 76 with no additional failures to have 95% confidence that no more than 5% of the tendons had broken wires. The end-of-life prediction for the fraction of tendons degraded was found to be relatively insensitive to whether we had 1 tendon out of 40 or 1 tendon out of 76 with broken wires. We therefore chose not to expand the random sample.

A 95% confidence interval was constructed around this inspection result. The 95% confidence upper bound was 9% of the population or 16 additional tendons with broken wires. The data point used was, therefore, 16 tendons plus the 27 previous tendons with broken wires, for a total of

43 tendons. A Weibull slope was determined from the two data points. The second data point used to determine this slope took into account statistical uncertainty. The basic Weibull equation is of the form:

$F(t) = 1 - \exp[-(t/\theta)^b]$
Where:
$F(t)$ = fraction of population failed
t= time
θ = Characteristic time
b = slope

The parameters, θ and b determined from the plot of the two data points are $\theta = 32$ years and $b = 7.5$. The b value is relatively high. Note that the average b for stress corrosion cracking phenomena is around 5.5, and the average b for stress corrosion cracking of prestressing wire is 3.7. The reason for the high b value determined from the two data points is the use of a confidence interval upper bound for the second data point. The upper bound value was chosen to conservatively bound the statistical uncertainty introduced by using a random sample to draw conclusions about a larger population. If the best estimate (50% confidence) slope has been used, the b value would a 2.6.

Gamma Distribution

The second part of the statistical model is a gamma distribution for the distribution of broken wires among the affected tendons. The gamma distribution probability density function is given by:

$$F(x') = \frac{\beta^{-a} x'^{-a=1} e^{-x'/\beta}}{\Gamma(\alpha)}$$

Where $\Gamma(\alpha)$ is the standard gamma function, and α and β, are estimated from the actual inspection data by the following equations:

$\beta = V/m$
$\alpha = m/\beta$
where m is the mean and V is the variance of the actual data.

See Enclosure 1 for the definition of the terms.

Uncertainty Issues

There is uncertainty in both parts of the statistical model. The first part of the model is the Weibull model for number of tendons affected. The parameters b and θ were determined from the plot of the two inspection data points (Figure IV-2 in Enclosure 1). Since the 1999 inspection data point was determined from a sample, there is uncertainty in the actual number of additional tendons affected by broken wires in 1999. This uncertainty was accounted for by constructing a 95% confidence interval for the number of tendons affected in the entire tendon population. The 95% confidence upper bound for number of tendons affected was used to plot the slope labeled 95% confidence in the figure. For comparison a 90% confidence interval and 50% confidence interval were also constructed. One can see that from the 50% slope to the 90% slope there is a large change. However, the change from the 90% slope to the 95% slope is much smaller, indicating diminishing returns as one goes to higher confidence levels. Therefore, the uncertainties in the determination of b and θ from the actual inspection data have been conservatively accounted for.

However, if a 99% confidence interval had been used instead of a 95% confidence interval, the 1999 inspection data point would become 51 affected tendons. The resulting Weibull parameters for the 99% confidence slope are θ = 30 years and b = 9.5. Figure 1 is a plot of the Weibull function using both the 95% parameters (θ = 32, b = 7.5) and the 99% parameters (θ = 30, b = 9.5). The figure shows the fraction of affected tendons reaches almost 100% relatively quickly. For the 99% parameters, the 100% affected level is reached in about 2008 versus 2014 for the 95% parameters. In the short term, the number of affected tendons is slightly higher. However, the ultimate number of broken wires at the end of plant life is insensitive to the choice of the 95% or 99% confidence Weibull parameters.

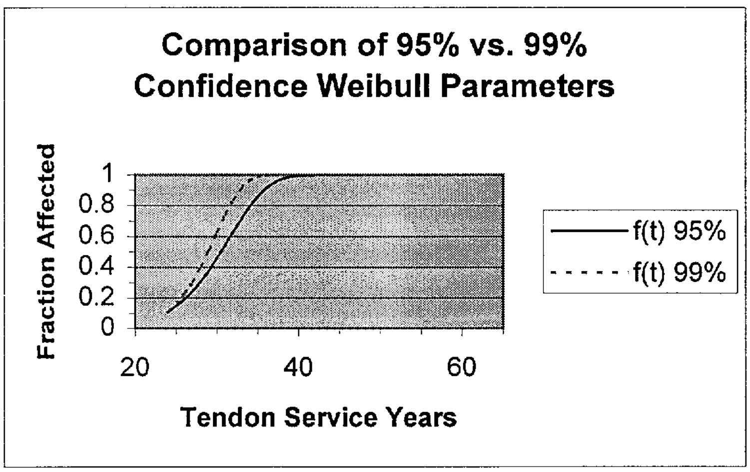

Figure 1

For the gamma distribution of broken wires among the affected tendons, the mean m and variance V of the actual inspection data are sources of uncertainty. To determine m, the actual number of known broken wires was divided by the actual number of known affected tendons for both 1997 and 1999. This was done for Unit 1 and Unit 2 combined. For 1999, only known affected tendons and broken wires were used, not the 95% upper bound on number of affected tendons. The mean m was observed to increase from 4.72 to 4.81, and the variance from 32.2 to 33.4. Three different assumptions could be made about the change of the mean and variance with time:

- The mean and variance do not change.
- The mean and variance increase linearly.
- The mean and variance increase exponentially.

The first assumption is not supported by the data. Either of the second two assumptions could be made. The model used the following equation to determine the mean number of broken wires as a function of the amount of time the tendons have been in service (note that at the end of plant life, the tendons will have approximately 64 years of service because they were tensioned several years prior to plant startup).

$$m(t) = 4.81+(t-26.5)*0.0521$$

where m is the mean number of wires and t is service time for the tendons.

An exponential rate of increase of m could also be calculated using

$$r = (m_1/m_0)^{1/b\Delta t}$$

where m_1 and m_0 are the means at two different tendon service times in years t_1 and t_0, $\Delta t = t_1 - t_0$, and b is a constant.

The choice of b is arbitrary and can be set to 1 since we have two known points to use for m_1 and m_0.

$$t_1 = 26.5,\ t_0 = 24.7;$$

Plugging in $\Delta t = 1.75$ years, and $m_0 = 4.72$, $m_1 = 4.81$, $b = 1$

Yields r = 1.0109

The value of m for any time can than be calculated using

$$m = m_1 * r^{(t-26.5)}$$

The mean for any year can be calculated using

$$m = 4.81*(1.0109)^{(t-26.5)}$$

where t is the time in years the tendons have been in service, and $m_1 = 4.81$

Figure 2 shows a plot of m calculated using both the linear and exponential methods. The difference in the predicted mean number of wires broken using both methods is minor. In the short-term, both methods predict a virtually identical number of broken wires, while at the end of plant life, the exponential method predicts a slightly greater number of wires broken. Table 2 compares the values obtained at several different points in time using both methods. The ultimate number of wires predicted to be broken at the end of plant life using the exponential method is 1471, compared to 1380 for the linear method that was actually used.

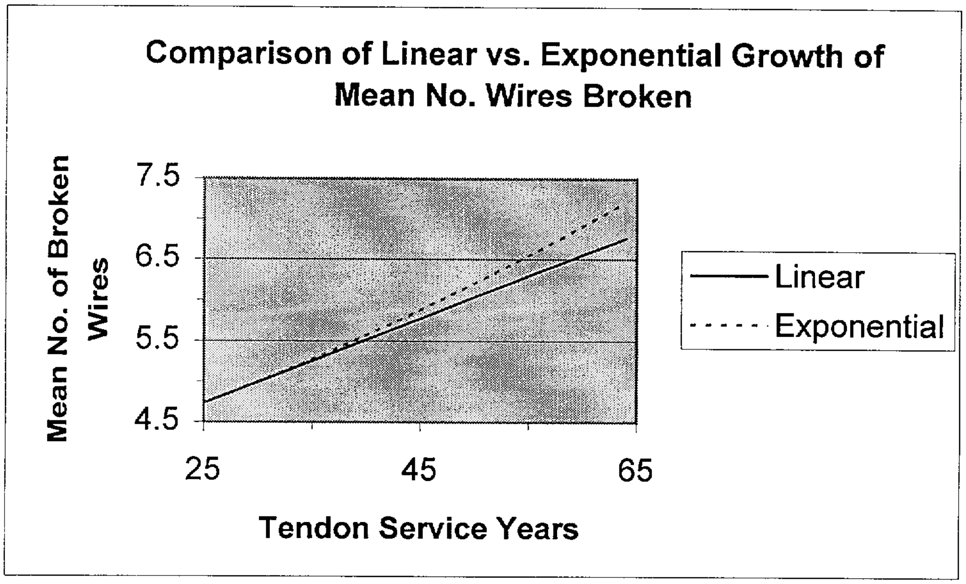

Figure 2

Table 2
Mean Number of Wires Broken per Affected Tendon,
Comparison of Linear and Exponential Predictions

Year	Tendon Service Years	Linear	Exponential
2001	28	4.89	4.89
2002	29	4.94	4.94
2003	30	4.99	5.00
2004	31	5.04	5.05
2005	32	5.10	5.10
2006	33	5.15	5.16
2011	38	5.41	5.45
2021	48	5.93	6.07
2031	58	6.45	6.76
2036	64	6.76	7.21

The growth in the variance over time was also calculated using a linear equation. Using the observed rate of increase in the variance from the 1997 to 1999 inspections, the variance increased from 32.2 to 33.4 in 1.75 years. The resulting equation is

$$V(t) = 33.4 + (t-26.5)*0.7$$

An exponential rate of increase could also be calculated using:

$$r = (V_1/V_0)^{1/b(\Delta t)}$$

where r is the rate, V_1 is the variance at time t_1, V_0 is the variance at time t_0, $\Delta t = t_2 - t_1$ where t_1 and t_0 are two different tendon service times in years.

Taking $V_1 = 33.4$, $V_0 = 32.2$ and b=1, and $t_1 = 26.5$ years, $t_0 = 24.7$ years, $\Delta t = 1.75$ years, yields $r = 1.0211$

The variance at any time t can therefore be calculated using

$$V = V_1 * r^{(t-26.5)}$$

$$V = 33.4*(1.0211)^{(t-26.5)}$$

Where t is the tendon service time.

Figure 3 shows plots of V as a function of time calculated using both the linear and exponential methods. Table 3 provides variance values for several different points in time calculated using both methods. There is very little difference in the short term (through 2005) using either method.

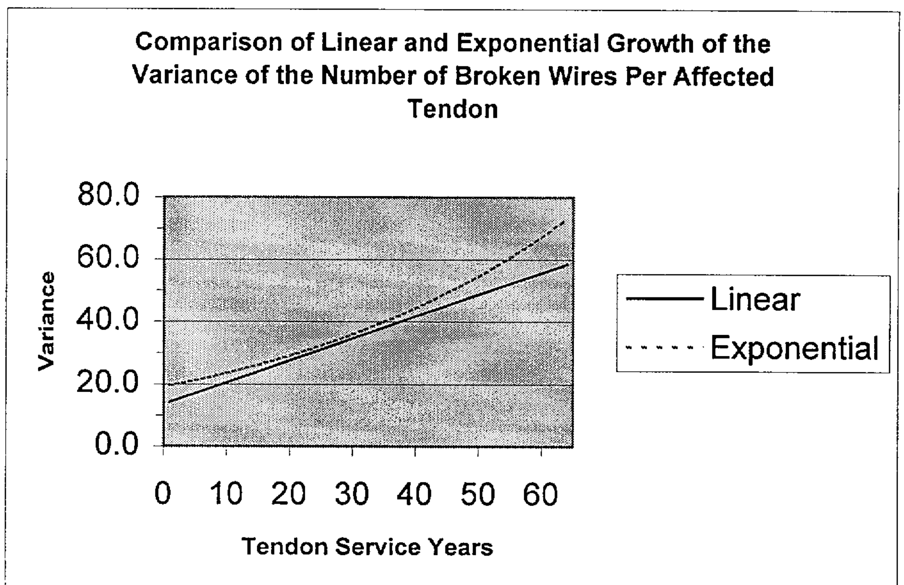

Figure 3

Table 3
Comparison of Linear and Exponential Methods of Calculating the Variance

Year	Tendon Service Years	Linear	Exponential
2001	28	33.3	34.5
2002	29	34.0	35.2
2003	30	34.7	35.9
2004	31	35.4	36.7
2005	32	36.1	37.5
2006	33	36.8	38.3
2011	38	40.3	42.5
2021	48	47.3	52.4
2031	58	54.3	64.5
2036	64	58.6	73.2

Uncertainty in the rate of increase in m and V results from the fact that the m and V for 1999 were not based on a 100% inspection. If a 100% inspection had been performed and several additional tendons had been found with broken wires, it is likely these tendons would have relatively few broken wires per tendon, causing the mean and variance to change less. For example, if 10 additional tendons in each unit were affected with one broken wire each, the mean number of broken wires would decrease to 3.67. Therefore, using the observed rate of increase in the mean and variance from 1997 to 1999 provides an upper bound for the mean and variance of the broken wire distribution in the future.

Summary/Conclusions

Uncertainty has been accounted for in the Weibull portion of the statistical model through the use of a confidence interval upper bound for the number of affected tendons in 1999. This results in a very conservative (steep) Weibull slope. The ultimate number of affected tendons has been shown to be insensitive to the use of an even more conservative (99%) confidence interval upper bound on the 1999 inspection results. In the gamma distribution portion of the statistical model, conservatism has been introduced through the use of data from tendons known to have broken wires. This should result in a conservatively high mean. The reason for this is that presumed newly affected tendons among the tendons that were not inspected in 1999 are likely to have only one or two broken wires each. This would reduce the mean. If exponential growth of the mean and variance are assumed, the mean number of wires broken is slightly higher at the end of plant life, resulting in about 100 additional broken wires for each unit.

REFERENCES

(1) Letter from Mr. C. H. Cruse (BGE) to NRC Document Control Desk, dated December 7, 1999, Revisions to the Containment Tendon Long-Term Corrective Action Plan

(2) Letter from Mr. C. H. Cruse (BGE) to NRC Document Control Desk, dated May 14, 1998, Containment Tendon Long-Term Corrective Action Plan

(3) Letter from Mr. A. W. Dromerick (NRC) to Mr. C. H. Cruse (BGE), dated January 23, 1998, Review of Containment Tendon Evaluation Report – Calvert Cliffs Nuclear Power Plant, Unit Nos. 1 and 2 (TAC Nos. M99880 and M99881)

(4) Letter from Mr. C. H. Cruse (BGE) to NRC Document Control Desk, dated October 28, 1997, Containment Tendon Engineering Evaluation Report

(5) The New Weibull Handbook, 2nd Edition, Robert B. Abernathy, Gulf Publishing Company, 1996

(6) NUREG/CR-5788, A Comparison of Weibull and B(IC) Analysis of Transition Range Fracture Toughness Data, January 1992

(7) NUREG/CR-5378, Aging Data Analysis and Risk Assessment Development and Demonstration Study, August 1992

(8) NUREG/CR-4214 R2 PT1, Health Effects Model for Nuclear Power Plant Accident Consequence Analysis, October 1993

Enclosure 1

Extended Model for Containment Building Vertical Tendon

Degradation for Calvert Cliffs 1 and 2,

R-3645-02-02, Revision 1, June 2000

Calvert Cliffs Nuclear Power Plant, Inc.
July 24, 2000

DOMINION ENGINEERING, INC.

Extended Model for Containment Building Vertical Tendon Degradation for Calvert Cliffs 1 and 2

R-3645-02-02

Revision 1

June 2000

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Record of Revisions

Rev.	Description	Prepared by Date	Checked by Date	Reviewed by Date
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The last revision number to reflect any changes for each section of the report is shown in the Table of Contents. The last revision numbers to reflect any changes for tables and figures are shown in the List of Tables and the List of Figures. Changes made in the latest revision, except for Rev. 0 and revisions, which change the report in its entirety, are indicated by a double line in the right hand margin as shown here.

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I. SUMMARY

In this report a model is developed for the future failures of vertical tendon wires in the Calvert Cliffs Unit 1 and Unit 2 containment buildings. The model is based on the results of inspections of tendons performed in 1997 and 1999. The model assumes that the additional failed tendon wires found by the 1999 inspections represent continuing corrosion degradation that has not been arrested by remedial actions taken following the 1997 inspections (re-application of grease and resealing of tendon top closures). It is further assumed that the failures observed to date are the leading edge of a Weibull distribution of failure times. This implies that the rate at which additional tendons become affected will increase rapidly as the peak of the distribution is approached. These are considered to be pessimistic assumptions because it is probable that the broken wires found in 1999 were severely degraded and close to failure in 1997 such that the remedial measures were applied too late to prevent their failure. If that is the case, observed rates of failure could decrease in the future as the population of severely degraded wires decreases.

The model consists of two parts. The first part utilizes Weibull statistical methods, similar to those used to model numbers of steam generator tubes experiencing corrosion, to estimate the number of tendons that will be affected (i.e., have one or more broken wires) during the remaining years of operation. The second part of the model estimates the numbers of broken wires per affected tendon. The second part assumes that the distribution of the number of wires failed per affected tendon can be represented by a gamma distribution, similar to a method used for modeling circumferential crack sizes in steam generator tubes. The results of the 1999 inspections indicate that the mean and variance (width) of the gamma distribution that describes the number of broken wires per affected tendon are increasing slowly with time. The degradation model assumes that slow growth in the mean number of broken wires per affected tendon will continue for the remainder of the extended lives of the units and that the distributions will continue to broaden. The impact of the continued broadening of the distribution is that the numbers of broken wires in the most severely affected tendons increases more rapidly than the mean number of broken wires.

As discussed in Section IV of this report, this model for vertical tendon wire degradation is developed to be an upper bound for the future tendon degradation at both Units 1 and 2. The results of the model are shown in Table I-1 and Figures I-1 and I-2. As shown in Figure I-1, the predicted number of tendons affected (tendons with at least one

Table I-1

Tendon Degradation Model Predictions

Calendar Year	Service Years	Affected Tendons[1]	Total Broken Wires[3]	Average Broken Wires per Affected Tendon	Maximum Broken Wires in any Tendon[2]
1997	25	27	127	4.70	23
1999	26	43	205	4.77	26
2004	31	119	608	5.11	35
2009	36	189	1017	5.38	40
2014	41	204	1147	5.62	43
2019	46	204	1200	5.88	44
2024	51	204	1253	6.14	46
2029	56	204	1305	6.40	47
2034	61	204	1359	6.66	48
2036	63	204	1380	6.76	49

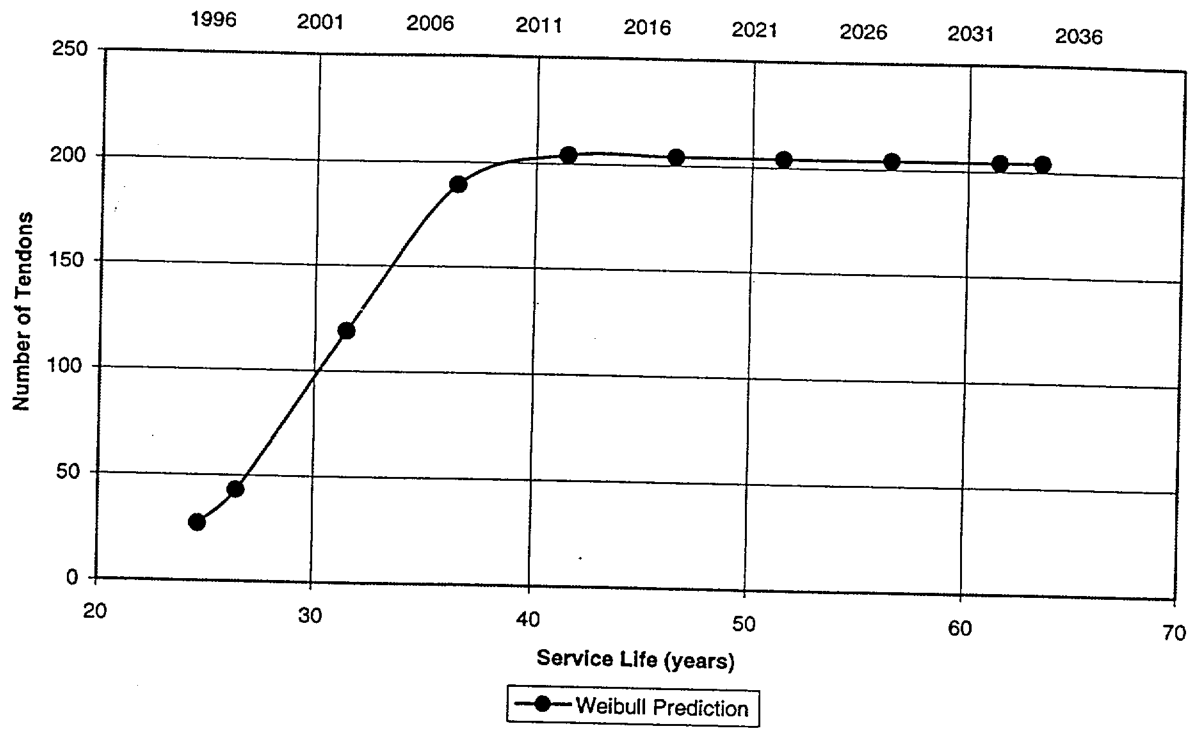
Notes

1. For Unit 1 there are only 202 tendons in service. Two tendons were abandoned and not tensioned during original construction. Model predictions are considered to be upper bound for both units.
2. These numbers correspond to the 99.75% =203.5/204 cumulative failure level of the distribution.
3. Predicted total broken wires for 1997 is greater than actual for either unit.

broken wire) increases rapidly until all tendons are affected in approximately 2014 (15 additional years of service, 41 years of service total). Figure I-2 shows that the predicted total number of broken wires initially rises rapidly because of the increasing number of affected tendons, but continues to rise after all tendons are affected because the mean number of broken wires per tendon increases continuously for the remainder of extended plant life.

As shown in Table I-1, The total predicted number of broken wires in all tendons at end of extended life in 2036 is 1380. With 90 wires per tendon, this corresponds to less than 16 total tendons lost by the end of extended life. The maximum number of broken wires in any tendon at end of extended life is predicted to be 49 (54% of the 90 wires in the tendon). Because of statistical uncertainties, the worst tendon at end of life might have considerably more than 49 failed wires, but there is a very low probability that there will be more than one tendon with as many as 49 failed wires. The model predicts that all tendons will have at least

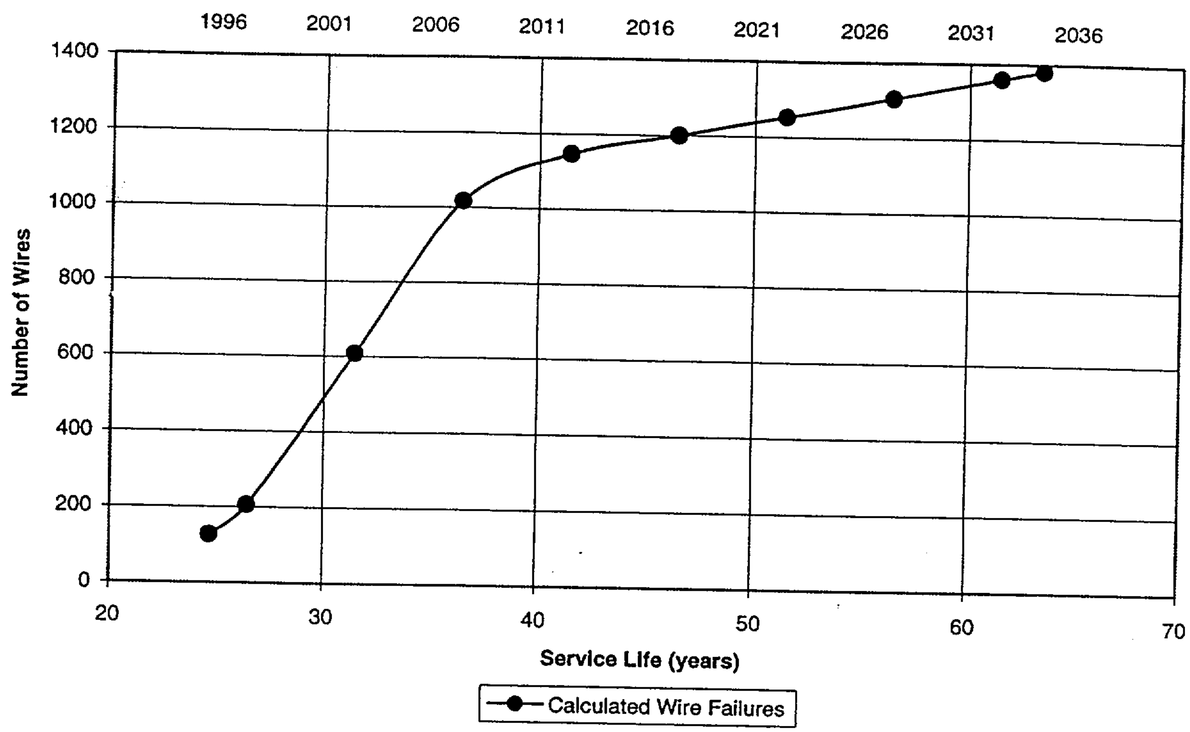
Figure I-1. Number of Tendons With Broken Wires



one broken wire by 2014 and 90% of the tendons will have 16 or fewer broken wires by 2036. These results imply that the broken wires are expected to be fairly uniformly distributed around the containments. Operability evaluations for the tendon systems prepared in 1997[1] concluded that 176 intact tendons are required to maintain the design prestress load for the containment. This corresponds to loss of 28 full tendons for Unit 2 or 26 full tendons for Unit 1. Loss of a small number of wires from each of the tendons is a less severe condition than loss of entire tendons. Therefore, failure of 1380 individual wires, uniformly distributed around the containment is within the acceptance criteria established in 1997. It should be noted that there is no need to detension tendons even when they have a large number of broken wires. Tensioning the tendons is a strain-controlled operation. As wires break, very little of the load they were carrying is transferred to the remaining wires. Thus, as wires break, the load in a tendon decreases in proportion to the number of broken wires, but the remaining intact wires cannot become over stressed.

A number of important assumptions were made in the predictive models. These assumptions were made in a way that is intended to assure that the predictions will be

Figure I-2. Total Broken Wires in Vertical Tendon System



conservative upper bounds for the actual tendon degradation that is experienced over the remainder of plant life. These assumptions include the following:

- The Weibull model used to predict the increase in the number of tendons with one or more broken wires is based on a data point for 1999 which uses the 95% confidence value for the result of the random sample inspection of Unit 2 tendons that had no broken wires in 1997. Forty tendons, selected at random from the set of corroded and non-degraded tendons, were inspected for broken wires in 1999. One tendon from this random sample was found to have one broken wire. This is a median (50% confidence) failure rate of 2.5%. However, the 95% confidence level failure rate is 9.1%. (The inspection result of one failure in a sample of 40 gives 95% confidence that the fraction of failed tendons in the entire population is less than 9.1%.) Using the 95% confidence value for the failure rate provides a high probability that the Weibull distribution model for the rate of increase in the number of affected tendons will be an upper bound for degradation for the remaining life of the plant.
- The model assumes that, in a statistical sense, degradation of the tendon system will behave in the same way it has in the past for the remainder of plant life. This

essentially assumes that the remedial actions taken following the 1997 inspections (re-application of grease and resealing of tendon top closures) have had no effect on the spread of degradation and will have no effect in the future. This is considered to be conservative because it is probable that most of the broken wires found in the 1999 inspections were severely degraded in 1997. The remedial measures may prevent degradation from spreading to tendons that have not yet been corroded and may be effective in preventing corrosion of additional wires in tendons that have experienced some degradation. Therefore, the assumption that all wires in all tendons are currently as susceptible to degradation as they were in the past is conservative.

- The model assumes that the rates of increase in the mean number of wires broken per affected tendon and the variance of the broken wire distribution observed between 1997 and 1999 will be the same for the remaining plant life. Because only one new tendon with broken wires was found in 1999, the observed changes in the distribution are characteristic of already affected tendons. If more newly affected tendons had been included in the 1999 population, it is expected that the mean and variance of the distribution would have changed less. Thus, using the observed rates of increase from 1997 to 1999 should give an upper bound to the mean and variance of the broken wire distribution function in the future.

Although the assumptions made in developing this model should be very conservative, the model is based on minimal data. Therefore, it is important that future inspections be performed to verify that the model remains an upper bound to actual experience. Because the model predicts the number of affected tendons to reach 100% in about 15 more years of operation, relatively small size sampling inspections will be sufficient to verify that the model for affected tendons remains bounding. The model predicts that within 15 years, any tendon chosen at random will have a high probability of having at least one broken wire. If small samples of previously unaffected tendons are inspected (e.g., for the Technical Specification required surveillance) and no broken wires are found, this provides high confidence that the model is bounding. Periodic inspections of the most severely degraded tendons coinciding with Tech Spec. surveillance should also be performed to assure that degradation is not spreading more rapidly through the wires of affected tendons than predicted. Because the most severely affected tendons are identified, inspection of a modest number of tendons should assure that the distribution function for broken wires per affected tendon remains conservatively bounding.

II. INTRODUCTION

Some tendon wire failures were noted during the 20 year inservice inspection (performed in 1997) of the Calvert Cliffs Unit 1 containment building vertical tendons.[2] The causes of the wire failures were investigated by BGE, and corrective action plans were developed. Short term corrective actions included 100 percent inspection of the Unit 1 and Unit 2 tendons to assess the overall condition of the tendon systems, re-application of grease, and re-sealing of tendon top closures to minimize degradation over the following few years while the need for longer term corrective actions could be evaluated.

The tendons at both units have been inspected again in 1999.[3] The scopes of the 1999 inspections included the following:

1. All tendons for both units that had been found to have broken wires in 1997.
2. All tendons for both units that had been categorized as corroded in 1997. The tendons categorized as corroded did not have broken wires in 1997.
3. A random sample of 40 Unit 2 tendons to assess the increase in the number of affected tendons.[4]

There was some overlap of the random sample and the "corroded" tendon sample. This was acceptable on a statistical basis because the purpose of the random sample was to determine if the number of tendons with broken wires was increasing. Inspections of the tendons that were identified in 1997 as either having broken wires or as being "corroded" was to assess the progression of degradation of the tendons known to be affected.

One tendon from the random sample was found to have a single broken wire. One additional wire in Unit 1 and 7 additional wires in Unit 2 were found broken in tendons that already had broken wires in 1997.

The objective of this report is to develop a model for the future failures of tendon wires that can be used to assess how long the vertical tendons will continue to meet structural integrity requirements under the pessimistic assumption that the short term corrective actions (re-application of grease and re-sealing of tendon top closures) will have no effect on the rate of wire failures. The model is to be a conservative upper bound for the rate of wire failures for the extended licensed lives of the units (2034 for Unit 1 and 2036 for Unit 2). The model is an extension of a previous model developed in 1997 using the then available data.[5] The 1997 model was considered to be valid for approximately four additional years of operation.

The model described in this report uses the additional data derived from the 1999 inspections to extend the postulated period of validity to the end of plant life.

III. BACKGROUND INFORMATION AND TENDONS AFFECTED AND WIRE FAILURE DATA

Each vertical tendon consists of an array of ninety (90) 1/4 inch diameter wires made of high strength 0.8% carbon steel to ASTM A421-65 Type BA.[6] The wires are loaded to a high stress, in the neighborhood of 160 ksi, which represents about 83% of their yield strength. After installation of the wires, the tendon conduits were filled with a paraffin type grease to minimize corrosion. The top anchorage of each tendon is enclosed in a sealed steel container that is intended to protect the tendon from the environment.

There were originally 204 vertical tendons in the containment building design. In Unit 1, two of these tendons were not used during original construction, leaving 202 tendons put into service.[7] All 204 tendons were placed in service in Unit 2. Small numbers (3 to 6 tendons per inspection) of tendons were inspected after 1, 3, 5, 10 and 15 years of operation. One Unit 1 tendon was found at the 5-year inspection to have two broken wires, but these were not considered to be service induced failures. Additional broken wires were found during the 20-year surveillance inspection in 1997. This resulted in expansion of the 1997 inspection scope to inspection and testing of 100% of the inservice Unit 1 and Unit 2 tendons.

The wires that were found to have failed in 1997 all failed a short distance below the top stressing washer, typically about six inches from the top button head. The failures are of two types. The first failure mechanism involves thinning due to general corrosion with ductile failure of the thinned core region. The second failure mechanism is brittle and intergranular in nature and is attributed by BGE to hydrogen induced cracking.

The typical location of the wire failures appears to be associated with the top of the protective grease. Visual inspections indicated that, in 1997, the grease level in essentially all tendons was a few inches below the bottom of the stressing washer, corresponding to the typical failure location of about six inches below the top button. Whether the grease was at that level from initial installation until 1997 or whether the grease level decreased over the years is not known. The root cause analysis by BGE. attributed both general corrosion and hydrogen induced cracking to poor grease coverage and water intrusion into the top anchorage area. As a part of the remedial actions applied in 1997, the tendons were regreased in the top anchorage area and the top housings were resealed.

The years given above for the times of the surveillance inspections are the nominal inservice inspection years since start of commercial operation. Because stress corrosion

could occur at any time after the wires are tensioned, years of service while tensioned is a better measure of time for this model than years of commercial operation. For both Unit 1 and Unit 2, the vertical tendons were tensioned several years before start of commercial operation, but were detensioned for short periods after initial tensioning in connection with concrete repairs. Based on information provided by BGE, it is understood that the Unit 1 vertical tendons were originally tensioned about November 1971 and were subsequently detensioned for about four months, and that Unit 2 vertical tendons were originally tensioned about May 1972, and were subsequently detensioned for about ten months.[8]

IV. TENDON WIRE DEGRADATION MODEL

Evaluation of 1999 Inspection Results

Results of the 1999 inspections are shown in Table IV-1.[9] One broken wire was found in a random sample inspection of 40 Unit 2 tendons that previously had no broken wires. Eight additional broken wires were found in tendons that had broken wires in 1997.

Table IV-1

Results of 1999 Tendon Inspections

Unit	Tendon #	Number of New Broken Wires	Failure Mode	Previous Failure Modes	Number of Previous Broken Wires
1	56V29	1	HIC	HIC	6
2	12V9	1	HIC		0
2	61V17	1	I	GC(2), I(3)	5
2	56V22	2	HIC	HIC	9
2	56V13	2	HIC	HIC	12
2	56V24	1	HIC	HIC	8
2	56V27	1	HIC	HIC	9

HIC = hydrogen induced cracking
GC = general corrosion (ductile fracture)
I = indeterminate

The random sample inspection result of one new tendon with a broken wire from the 40 sample random inspection was evaluated to determine the 95% confidence level failure percentage for the entire corroded and non-degraded sample population of 177 tendons.[10] This evaluation is shown in Figure IV-1. The bottom table of Figure IV-1 shows that at the 95% confidence level, 1 failure in a sample of 40 corresponds to a failure rate of 9.1% (16 tendons) in the population of 177. Adding 16 tendons to the 27 tendons that had broken wires in 1997 gives a data point of 43 tendons with broken wires in 1999. This is an upper

Figure IV-1

Calvert Cliffs Unit 2 - Tendon Sample Plan - 95% Confidence

Results of 1997 Inspection

Total Tendons	204
Tendons with Broken Wires	27
Intact Tendons	177
Corroded Tendons	47
Non-degraded Tendons	130

1999 Inspection Plan Parameters

Sample Population (Intact Tendons)	177
Desired Confidence level	0.95
Confidence Coordinate for 95% Confidence, Zc	1.645

Of 204 total tendons, there are 27 which have one or more identified broken wires. Therefore, the "intact tendon" population remaining to be inspected is 177 tendons. Of these, 47 have been identified as "corroded" and 130 have experienced no identifiable degradation.

The calculations below determine the single sided 95% confidence limits for various sample sizes and inspection results. This means that there is 95% confidence that the the actual percentage of tendons with broken wires is less than the percentage given for the sample size and result.

Example:

An inspection sample of 40 with 0 tendons found with broken wires provides 95% confidence that the actual percentage of tendons with broken wires in the sample population of 177 tendons is less than 5%.

	Sample Size						
	11	22	40	48	59	76	107
Finite Population Factor	0.971	0.938	0.882	0.856	0.819	0.758	0.631
Adjusted Confidence Coordinate, z'	1.597	1.544	1.451	1.408	1.347	1.246	1.037

	Tendons with Broken Wires	Sample Size						
		11	22	40	48	59	76	107
Observed Success Rate (1-P)	0	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	1	0.909	0.955	0.975	0.979	0.983	0.987	0.991
	2	0.818	0.909	0.950	0.958	0.966	0.974	0.981
	3	0.727	0.864	0.925	0.938	0.949	0.961	0.972
	4	0.636	0.818	0.900	0.917	0.932	0.947	0.963

		11	22	40	48	59	76	107
Maximum True Failure Rate at 95% Confidence	0	18.83%	9.77%	5.00%	3.97%	2.98%	2.00%	1.00%
	1	31.46%	16.87%	9.10%	7.41%	5.79%	4.17%	2.50%
	2	41.95%	22.92%	12.62%	10.36%	8.20%	6.04%	3.78%
	3	51.35%	28.49%	15.89%	13.11%	10.45%	7.77%	4.99%
	4	59.96%	33.74%	19.00%	15.73%	12.60%	9.44%	6.15%

bound estimate of the current situation. This result with the 1997 inspection results gives two data points for cumulative tendon "failures" vs. time, one for 1997 (27 failures at 24.7 years of operation), and one for 1999 (43 failures at 26.5 years of operation), where failure is defined as having one or more broken wires. These two data points were used to develop a Weibull failure time distribution for the progression of tendons affected by broken wires as described below. Using a 50% confidence failure fraction from the 1999 inspection (1/40 = 2.5%) would predict the current number of Unit 2 tendons with broken wires to be between 31 and 32.

Prediction of Numbers of Affected Tendons

As described in many statistical texts and handbooks, failure data are typically best described using Weibull or log normal distributions.[11] [12] [13] [14] For example, the Weibull distribution has been widely and successfully used to describe the occurrence of tube failures in PWR steam generators (EPRI report NP-7493).[15] Because of its flexibility and wide use, the Weibull distribution was selected for this part of this model, i.e., to project the increasing number of affected tendons with increasing years of service.

The basic Weibull distribution function is given by the following equation:

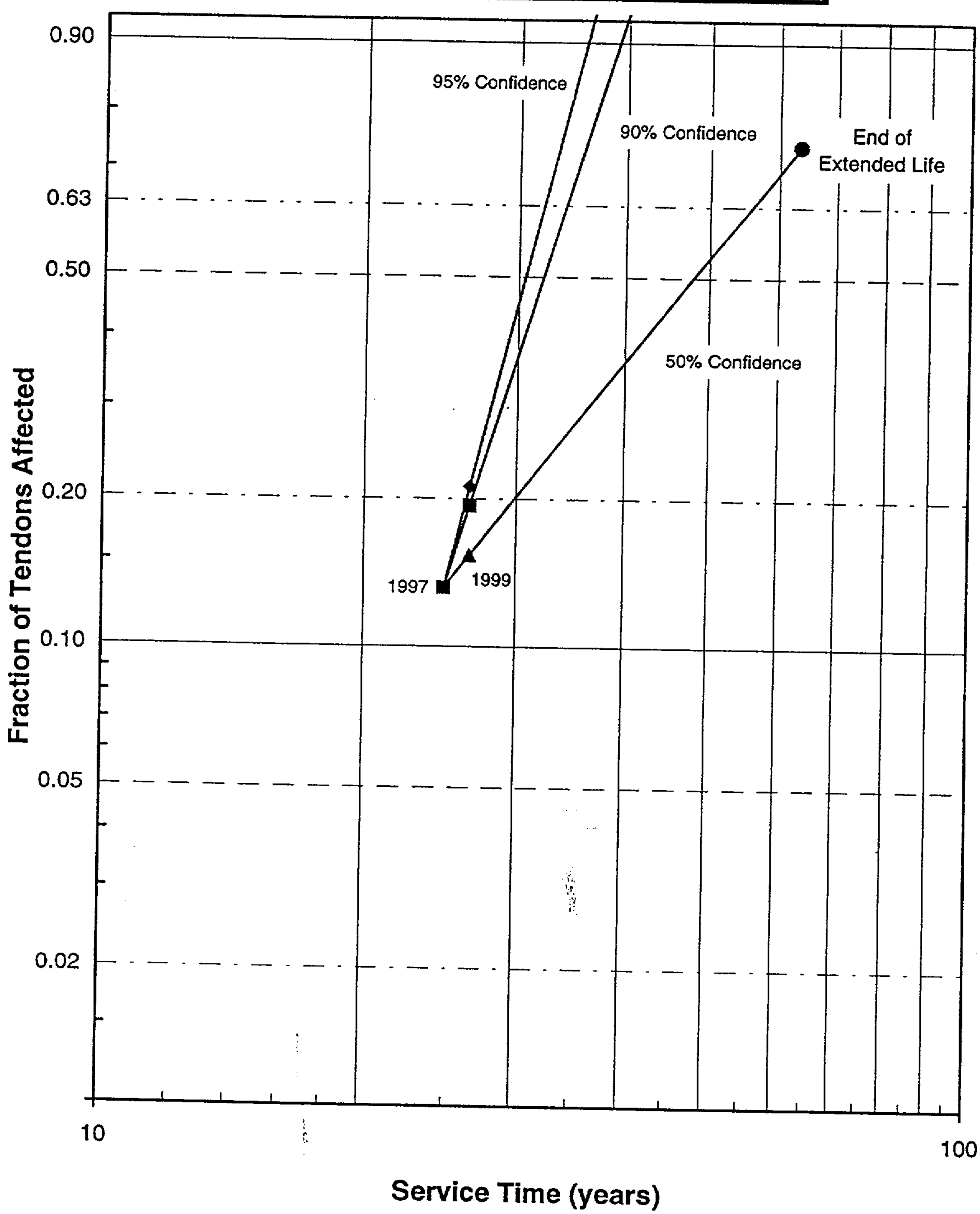
$$F = 1 - \exp\left(-\left(\frac{t}{\theta}\right)^{b}\right) \tag{1}$$

where

F	=	fraction of population failed (one of more broken wires)
t	=	service time while tensioned
b	=	Weibull slope, a fitted parameter determined by analysis of failure data
θ	=	Weibull characteristic time, a fitted parameter determined by analysis of failure data

Two data points are available to determine the two adjustable parameters (b and θ) of the Weibull distribution. The fit gives b = 7.5 and θ =32 years. The resulting Weibull prediction for tendons affected by broken wires is shown in Figure IV-2. Weibull lines for 90% and 50% confidence are also shown in Figure IV-2 for information purposes. The prediction using the 95% confidence value for the 1999 data point is that essentially all

Figure IV-2
Calvert Cliffs Tendon Degradation Model
Tendons With Broken Wires



tendons will have at least one broken wire after an additional 15 years of service life. If the 50% confidence value for the 1999 inspection result is used, it is predicted that 76% of the Unit 2 tendons will have at least one broken wire by the end of the extended license period in 2036.

Predictions of Numbers of Broken Wires Per Affected Tendon

(1) Gamma Distribution Function Fits to Observed Data

Distribution functions for the numbers of broken wires per tendon in 1997 and 1999 were developed using the entire set of affected tendons from Units 1 and 2 combined. Table IV-2 shows the numbers of tendons with given numbers of broken wires for 1997 and 1999. The mean numbers of broken wires per tendon and the variances of the observed distributions are shown at the bottom of Table IV-2.

In Report R-3632-01-02[16] it was shown that a gamma distribution provides a good description of the observed distribution of broken wires in the affected tendons. A gamma distribution has two adjustable parameters, α and β, which can be estimated from the mean (m) and variance (V) of the data as follows

$$\beta = \frac{V}{m} \qquad (2)$$

$$\alpha = \frac{m}{\beta} \qquad (3)$$

Using this method for setting the parameters of the distribution, the mean and variance of the data are preserved in the functional description.

The cumulative gamma distribution G(x), is defined for the range x greater than zero, and for the values of α and β appropriate for tendon wires the peak of the density distribution g(x) (mode of the distribution) is infinity at $x = 0$. Because the distribution function for failed wires is applied only to tendons with at least one failed wire, it is inconsistent to use a distribution function that peaks at $x = 0$. Also, the gamma distribution is a continuous distribution while the numbers of failed wires must be integers. To account for these characteristics of the distribution function two adjustments are made as follows:

1. A shifted independent variable for the gamma function, x', is defined as $x' = x - 0.5$. This is accomplished by defining an adjusted mean $m' = m - 0.5$ to be used in place of m in equations (2) and (3). The continuous distribution is discretized by assigning the

Table IV-2

Calvert Cliffs Units 1 and 2 Combined

Tendons with Broken Wires

Wires Failed per Tendon	1997		1999	
	No. Tendons	Total Wires Failed	No. Tendons	Total Wires Failed
1	19	19	20	20
2	6	12	6	12
3	3	9	3	9
4	2	8	2	8
5	3	15	2	10
6	2	12	2	12
7	1	7	2	14
8	1	8	0	0
9	2	18	1	9
10	1	10	2	20
11	1	11	2	22
12	2	24	1	12
13	1	13	1	13
14	0	0	1	14
15	0	0	0	0
16	0	0	0	0
17	0	0	0	0
18	0	0	0	0
19	0	0	0	0
20	0	0	0	0
21	0	0	0	0
22	0	0	0	0
23	0	0	0	0
24	0	0	0	0
25	1	25	1	25
26	1	26	1	26
Totals	**46**	**217**	**47**	**226**
	mean =	**4.72**	**mean =**	**4.81**
	variance =	**32.2**	**Variance =**	**33.4**

probability for the interval x - 0.5 to x + 0.5 to the center value x, where x is an integer. Thus, the probability of having n wires failed is the integral of the probability density over the interval $n-0.5 \le x \le n+0.5$. Because $x' = x-0.5$, this corresponds to integration over the interval $n-1 \le x' \le n$, and the cumulative probability that the number of broken wires is less than or equal to n is the value at the top of the interval G(n).

2. Because there are only 90 wires per tendon, the probability that the number of failed wires is less than or equal to 90 must be 1.0. This is accomplished by renormalizing the distribution by dividing the distribution function by G(90). This renormalization has no practical effect on the gamma distributions used for this analysis because the values of the distribution functions for $x > 90$ are negligible.

The probability density function $f(x')$ for the gamma distribution is given by

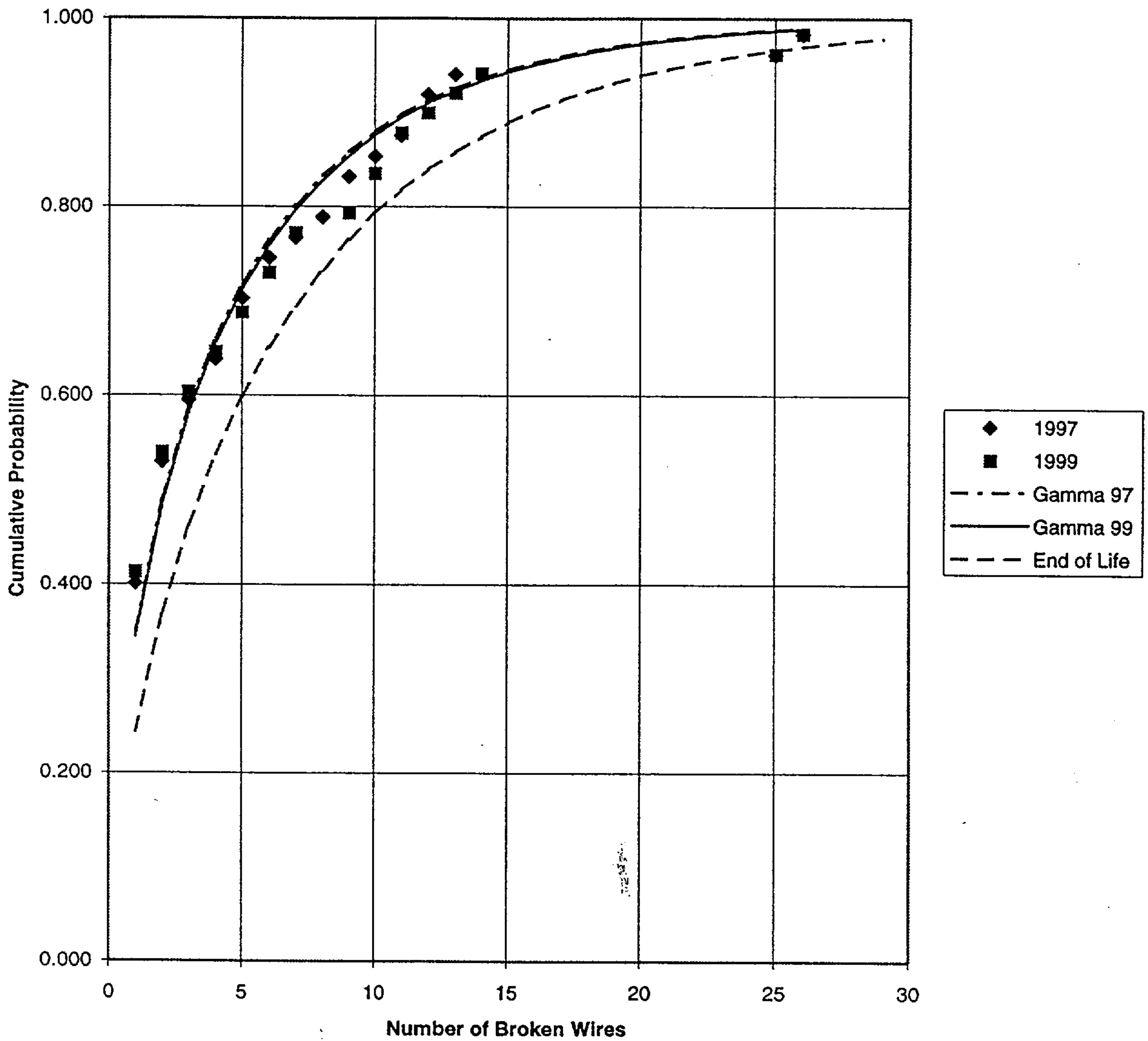
$$f(x') = \frac{\beta^{-\alpha} x'^{\alpha-1} e^{-x'/\beta}}{\Gamma(\alpha)} \quad \text{for } x' > 0 \qquad (4)$$

where $\Gamma(\alpha)$ is the standard gamma function, α and β are parameters of the distribution defined by equations (2) and (3) in terms of the mean and variance of the observed distribution, and x' is the argument variable, as discussed above. Gamma distribution fits to the tendon degradation data from 1997 and 1999 were defined using equations (2) and (3) with adjusted mean values m'. The data and distribution functions are compared in Figure IV-3 on a cumulative probability plot. It can be seen that the data are well described by the fitted distribution functions.

(2) Changes in the Distribution During Remaining Service Life

In the 1997 model (Report R-3632-01-02) it was postulated that the distribution function for numbers of wires failed in affected tendons would not change with time. It was assumed that the number of affected tendons would increase but the distribution function would not change because newly affected tendons would have few failed wires compensating for any increase in the number of wire failures for the previously affected population. Comparison of the 1999 results to the 1997 results shows that the assumption of a constant failed wire distribution is not precisely observed. Both the mean and variance of the distribution for failed wires increased from 1997 to 1999. The mean number of wires failed in affected tendons increased from 4.72 to 4.81 in approximately 1.75 years giving a rate of increase of 0.052 wires per year. The variance of the distribution changed from 32.2 to 33.4 giving a rate of increase of 0.703 per year. Given that only one newly affected tendon was

Figure IV-3
Calvert Cliffs Units 1 and 2 Combined
Gamma Distributions (Adjusted) for Number of Broken Wires Per Tendon



found while nine additional wire failures were observed, the increases in mean and variance of the distribution are to be expected.

As a conservative approach to modeling the distributions for numbers of failed wires per affected tendon in future years, it was assumed for this extended model that the mean and variance of the distribution will continue to increase at the same rate observed from 1997 to 1999. Making this assumption, the mean and variance of the distribution of failed wires per tendon can be computed for any time in the future. Equations (2) and (3) can then be used to determine the parameters of the gamma distribution from the mean and variance. Using 2036 as the end of life (Unit 2 end of extended license), the end of life gamma distribution shown in Figure IV-3 is obtained. This distribution has a higher mean value of broken wires per tendon and is broader than the 1997 and 1999 distributions.

<u>Composite Tendon Wire Failure Model.</u>

Using the two parts of the model described above, the predicted total number of failed wires and the distribution of these failures among tendons can be computed as a function of time. The procedure is as follows:

1. The Weibull distribution equation is used to calculate the fraction of the tendon population that will have one or more failed wires at any time of interest.
2. The observed growth rates for mean and variance for the failed wires per tendon distributions are used to calculate the fractions of the affected tendon population that will have a given number of failed wires.

Results for the predicted end of life failed wire distribution are given in Table IV-3. Results for total number of failed wires calculated at five-year intervals are given in Table I-1. The predicted total number of affected tendons (tendons with one or more broken wire) can be easily calculated using the Weibull distribution function (equation (1)) with b = 7.5 and θ = 32years.

$$M_A(t) = N_T\left(1-\exp\left(-\left(\frac{t}{\theta}\right)^b\right)\right) \qquad (5)$$

where N_T is the total number of tendons for the containment, t is total service time of the tendons while tensioned, and M_A is the number of affected tendons.

Table IV-3

Predicted Distribution of Broken Wires for End of Unit 2 Extended License in 2036

Wires Failed per Tendon	Cumulative Probability	Cumulative No. Tendons	No. Tendons	Failed Wires
1	24.4%	50	50	50
2	36.8%	75	25	50
3	46.2%	94	19	57
4	53.7%	110	16	64
5	59.9%	122	12	60
6	65.1%	133	11	66
7	69.5%	142	9	63
8	73.2%	149	7	56
9	76.5%	156	7	63
10	79.3%	162	6	60
11	81.8%	167	5	55
12	83.9%	171	4	48
13	85.8%	175	4	52
14	87.4%	178	3	42
15	88.9%	181	3	45
16	90.1%	184	3	48
17	91.2%	186	2	34
18	92.2%	188	2	36
19	93.1%	190	2	38
20	93.9%	191	1	20
21	94.5%	193	2	42
22	95.2%	194	1	22
23	95.7%	195	1	23
24	96.2%	196	1	24
25	96.6%	197	1	25
26	97.0%	198	1	26
28	97.6%	199	1	28
29	97.8%	200	1	29
32	98.5%	201	1	32
34	98.8%	202	1	34
39	99.3%	203	1	39
49	99.8%	204	1	49
			Total Broken Wires =	**1380**
			Mean Number Broken Wires =	**6.76**

The predicted total number of broken wires (N_T) can be calculated for any year from the number of affected tendons (M_A) and the mean number of wire failures per affected tendon (m). The mean number of broken wires per affected tendon as a function of time is given by

$$m(t) = 4.81 + (t - 26.5)*0.0521 \quad (6)$$

where t is total service time in years and m(t) is the mean number of broken wires at time t. The predicted total number of broken wires in the vertical tendon system as a function of time is then

$$N_T(t) = m(t)*M_A(t) \quad (7)$$

The predicted total numbers of broken wires in the tendon systems at the end of the extended license periods are structurally acceptable per the operability determinations written in 1997.[17] 1380 broken wires corresponds to less than 16 full tendons. The operability determinations indicate that the design prestress loads can be maintained with 176 vertical tendons. This allows the loss of 26 of the 202 vertical tendons in Unit 1 and 28 of the 204 vertical tendons in Unit 2. It should be noted that degraded tendons can still carry prestress loads proportional to the number of intact wires. There is no reason why tendons with many broken wires need to be detensioned. Tensioning the tendons is a strain-controlled operation. As wires fail, no significant load is transferred to the remaining wires. The total load in the tendon is simply decreased. Therefore, degraded tendons can still contribute to maintaining the prestress load on the concrete.

Estimation of Margins and Recommendations for Validation

Because of the conservative assumptions used to develop this model, it is anticipated that the model predictions will be bounding for observed behavior for the remaining lives of the units. The model development was done using parameter values for Unit 2, but the model should also be bounding for Unit 1. Unit 1 had less affected tendons than Unit 2 in 1997, and slightly more broken wires than Unit 2 in 1997 and only 6 more broken wires than Unit 2 in 1999.

An estimation of the probable margin in the model can be obtained by comparing the predictions for the increases in tendons affected and total wire failures using the 95% confidence and 50% confidence values for additional tendons affected from the results of the 1999 random sample inspection of 40 previously unaffected tendons. The 95% confidence value is 9.1% of the tendons that were unaffected in 1997 are affected in 1999. The 50% confidence is value is only 2.5%. The two different 1999 values were used in the Weibull

equation for rate of increase in the number of affected tendons. The Weibull equation lines are given in Figure IV-2. The results are also shown on a linear plot in Figure IV-4. These predicted numbers of affected tendons were used with the predicted mean numbers of broken wires per tendon to develop the predictions for total failed wires as functions of time shown in Figure IV-5. The same equations for the rate of increase of the mean numbers of failed wires per tendon were used for both curves in Figure IV-5. As can be seen from Figures IV-4 and IV-5, there is considerable margin in the predictions indicated by the differences between 50% confidence and 95% confidence approaches.

Although the model developed in this 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 should be validated by future tendon inspections. Because the model predicts a very rapid increase in the number of tendons affected by one or more broken wires, small random sample inspections, such as those required by Technical Specifications, will be sufficient to provide a high level of confidence that the true number of affected tendons is bounded by the model. If the model is not bounding, any tendon chosen at random after about 15 additional years of service should have broken wires. Approximately half of the tendons should have broken wires after five years, and more than 90% after ten years. Such high fractions can be validated with relatively small sample inspections. Furthermore, the end of life prediction, which is structurally acceptable, will not be exceeded before all tendons are affected by broken wires.

It is also necessary to verify that the numbers of broken wires per affected tendon are not increasing faster than predicted by the model. It is recommended that this be verified by inspecting a sample of the more severely affected tendons at the same times when the random surveillance inspections are performed. Because the most severely affected tendons were identified by the 1997 and 1999 inspections, a small sample set should be sufficient. Because the structural significance of tendon degradation is greatest when two degraded tendons are in close proximity, severely degraded tendons that are close to each other are good candidates for inspections performed to track rates of increase of the numbers of failed wires in affected tendons.

Figure IV-4. Number of Tendons With Broken Wires

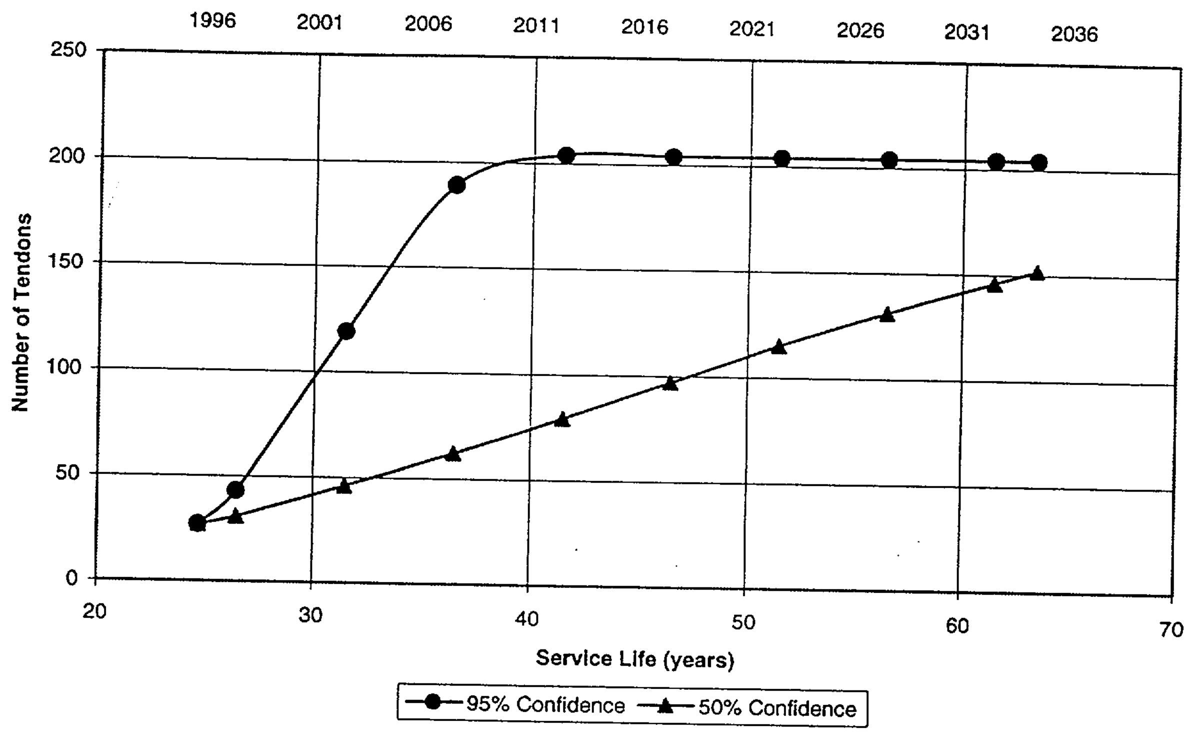
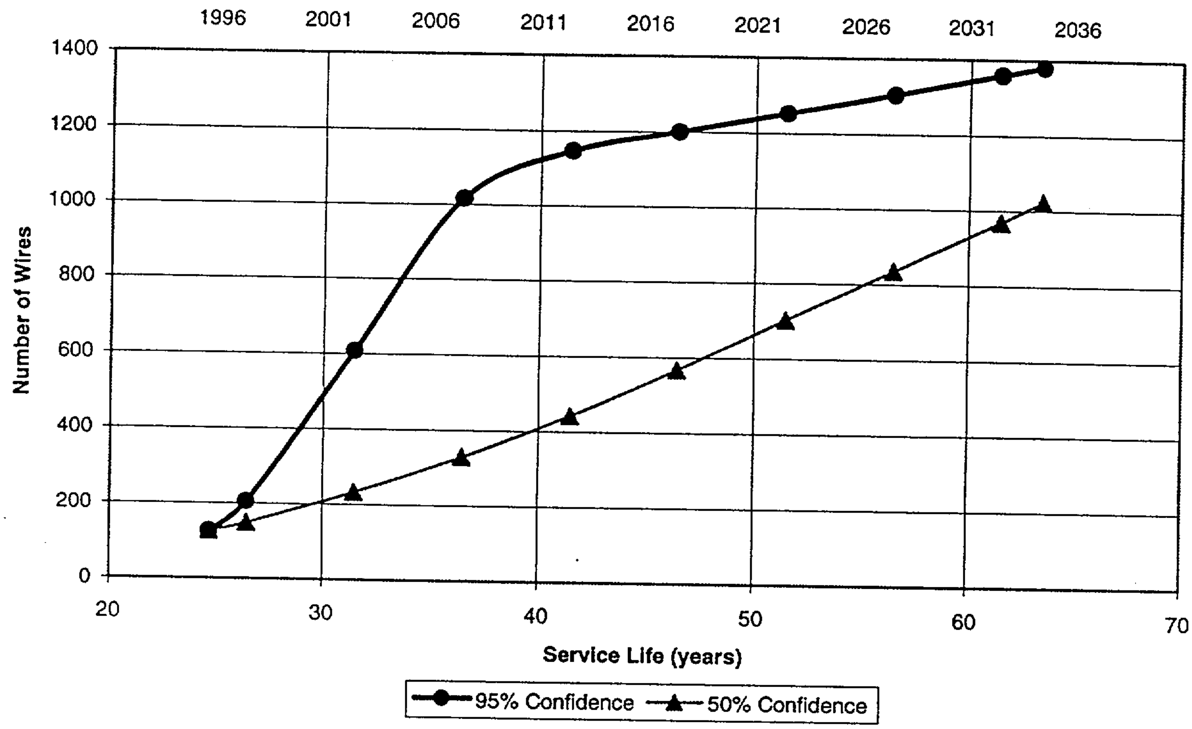


Figure IV-5. Total Broken Wires in Vertical Tendon System



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