DOMINION ENGINEERING, INC.

Updated Model for Containment Structure Vertical Tendon Degradation for Calvert Cliffs 1 and 2

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Record of Revisions

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1	Revised number of affected tendons for 2000 in Table I-1 and Figure I-1 from 36 (total Units 1 and 2) to 27 (Unit 2) to be consistent with Note 3 for Table I-1.	APL Turner 12/14/2000	JA Gorman 12/14/00	JA Gorman 12/14/00

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.

Table of Contents

List of Tables

List of Figures

I. SUMMARY

In this report models are developed for the future failures of vertical tendon wires in the Calvert Cliffs Unit 1 and Unit 2 containment structures from two degradation mechanisms: (1) general corrosion, and (2) hydrogen induced cracking. Separate models are used for the two mechanisms. The models are based on the results of inspections of tendons performed in 1997, 1999, and 2000. The model for general corrosion explicitly evaluates the results of tendon lift-off tests performed in 1997. In several tendons, wires that were intact when the tendon anchorage cover (grease cap) was removed failed when the tendons were stretched slightly to lift the stressing washer off the spacer shims. Wires failed during the lift-off tests in tendons that had broken wires in the as-found condition, and also in tendons that had no broken wires as-found. A lift-off test increases the stretch in the wires by only a small amount compared to the stretch imposed when the tendons were initially tensioned. Examination of the wires that failed during the lift off tests determined that the failure mechanism was ductile failure as the result of material loss from general corrosion. This experience indicates that the tendons identified by inspection as "corroded" contained a significant number of degraded wires that were near the failure limit at the time of the test and that there are probably a number of degraded wires still in service in tendons classified as severely corroded. There have been no additional wire failures classified as ductile/general corrosion identified in 1999 or 2000 inspections. The tendon inspections in 2000 were predominantly of tendons that had been classified as not degraded in earlier inspections, but 13 degraded tendons (11 from Unit 1 and 2 from Unit 2) were inspected in 2000. None of these 13 tendons had any new broken wires.

The model for general corrosion degradation assumes that the lack of additional wire failures since 1997 is because the lift-off tests accelerated failures of marginal wires that would have failed between 1997 and 2000. This is a conservative assumption because it implies that remedial measures implemented in 1997, particularly addition of grease to the top anchorage region of the tendons, have not stopped the corrosion, but rather that the acceleration of failures by the lift-off test has created a delay in observation of additional failures. For modeling purposes, it is assumed that all lift-off test wire failures would have occurred normally by the time of the 2000 inspections, that the delay period is over as of now and additional failures will occur. This is a conservative assumption, because the delay period for general corrosion may extend for several more years, or even longer, depending on the long-term efficacy of the remedial measures taken, starting in 1997. Because of the

uncertainties regarding general corrosion degradation introduced by the results of the lift-off tests, the model predicts much more rapid progression of degradation than is predicted for the hydrogen induced cracking degradation.

No hydrogen induced cracking (HIC) wire failures occurred during lift-off tests and 8 additional HIC wire failures were found in 1999 inspections. One wire failure was found in Unit 2 in the 2000 inspections, but the "pop-up" occurred at the lower anchorage and the degradation mechanism was not identified. This wire may have been damaged during construction. It is assumed that this wire failure is not of the same type as those observed near the top anchorage. It is assumed that the wire failures observed to date are the leading edge of Weibull distributions of failure times. This implies that the rate at which additional tendons become affected will increase as the peak of the distribution is approached. This is considered to be a bounding assumption because it is probable that the broken wires found in 1999 were already cracked and close to failure in 1997 such that the remedial measures were applied too late to prevent their failure. Recent inspection results indicate that rates of wire failure are decreasing rather than increasing as assumed in these models.

Each of the two models, one for general corrosion and the other for hydrogen induced cracking 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 lift-off tests and 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 distributions is that the numbers of broken wires in the most severely affected tendons increase more rapidly than the mean number of broken wires.

As discussed in Section IV of this report, these models for vertical tendon wire degradation are developed to be conservative upper bounds for the future tendon degradation at both Units 1 and 2. The results of the models are shown in Table I-1 and Figures I-1 and I-2. Additional results are given in tables in Appendix A. As shown in Figure I-1, the predicted number of tendons affected (tendons with at least one broken wire) increases rapidly until all tendons are affected in approximately 2026 (26 additional years of service, 53 years of service total). Figure I-2 shows that the predicted total number of broken wires initially rises at an accelerating rate as the number of affected tendons increases, and then continues to rise, but more slowly, when most 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 Unit 2 extended life in 2036 is 2714. With 90 wires per tendon, this corresponds to approximately 14.8% of the total tendon wires lost by the end of extended life. The models predict that the maximum number of wires to fail in one tendon by end of plant life will be 86. As many as 14 tendons are predicted to suffer failure of more than half the wires. The remaining broken wires are expected to be relatively uniformly distributed among the remaining tendons. 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 do not 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 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 for ductile/general corrosion degradation assumes that the delay period introduced by the lift-off tests performed in 1997 was over as of the time of the 2000 inspections so that ductile/general corrosion failures of wires in previously unaffected tendons will start to occur as of now. This is conservative because it is likely that the degradation is still in the delay period and that the delay will extend for an additional period before new failures are observed. This assumption leads to the conservative prediction that general corrosion degradation will spread rapidly through the population of tendons that currently have no broken wires.
- The Weibull model for HIC degradation is fit through three data points for 1997, 1999, and a best estimate that there were no additional HIC failures in 2000. The fitted distribution predicts that degradation is increasing, while the lack of identified new failures from 1999 to 2000 indicates that the degradation process may have been arrested.

- The models assume 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 anchorage 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 significantly degraded in 1997. The remedial measures should 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.

This model was developed using the Unit 2 time base. However, inspections performed in 1997, 1999, and 2000 indicate that the current conditions of the tendons in the two units are comparable even though the tendons for Unit 1 have been tensioned approximately one year longer than those for Unit 2. Therefore, the model results are considered to be applicable for both Units 1 and 2 on a calendar year basis, i.e., there is no need to shift the time schedule when applying the model to Unit 1 to account for the one year longer service time under tension.

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. The model predicts that all tendons will be affected in about 26 more years of operation. Sampling inspections will be sufficient to verify that the model for affected tendons remains bounding. The models predict that within 11 years, any tendon chosen at random will have a 50% 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 reasonable 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 functions for broken wires per affected tendon remain conservatively bounding.

Table I-1

Combined General Corrosion and Hydrogen Induced Cracking Tendon Degradation Model Predictions for a Single Unit

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	18	68	3.78	18
2000	27	27	111	3.08	26
2005	32	47	284	6.04	44
2010	37	92	706	7.67	65
2015	42	153	1378	9.01	77
2020	47	194	1965	10.13	82
2025	52	203	2265	11.16	84
2030	57	204	2475	12.13	85
2034	61	204	2633	12.91	86
2035	62	204	2669	13.08	86
2036	63	204	2714	13.30	86

Notes

1. For Unit 1 there are only 202 tendons in service. Two tendons were abandoned and not tensioned during original construction. Six additional tendons at Unit 1 have been detensioned, but some of these may be retensioned. Model predictions are considered to be upper bound for both units, but for Unit 1 structural evaluations must recognize the fact that there are less tendons in service than for Unit 2.
2. These numbers correspond to the 99.75% = 203.5/204 cumulative failure level of the distribution.
3. The numbers for tendons affected and total broken wires for 1997 and 2000 are actual values for Unit 2. The 1997 numbers are for the as found condition prior to the lift off tests. The 2000 numbers include lift-off test wire failures.

Figure I-1. Total Number of Tendons With Broken Wires

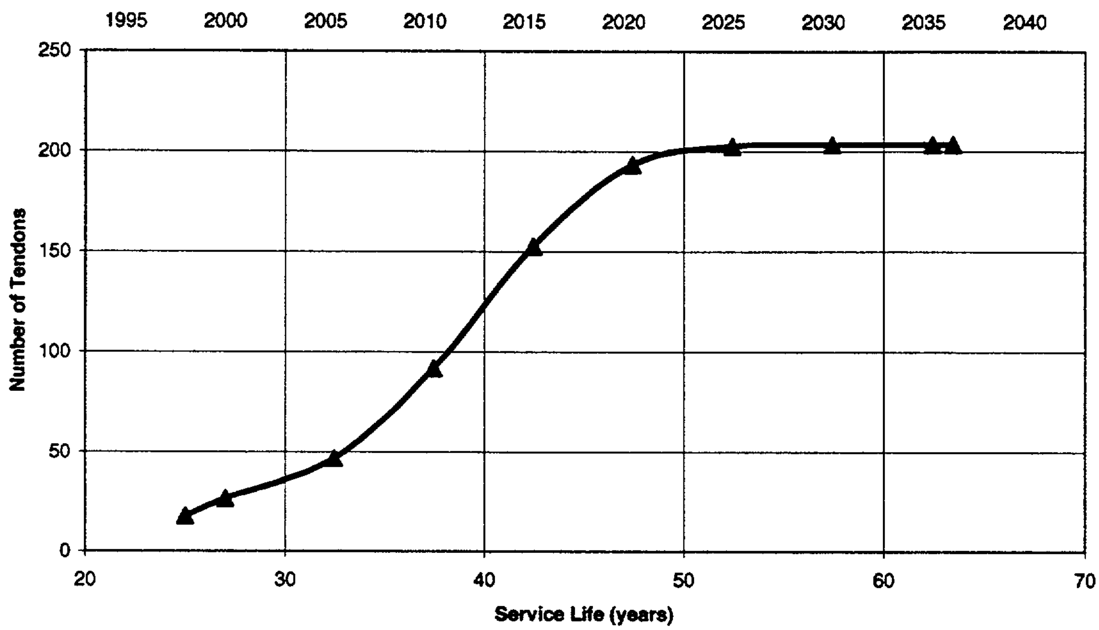
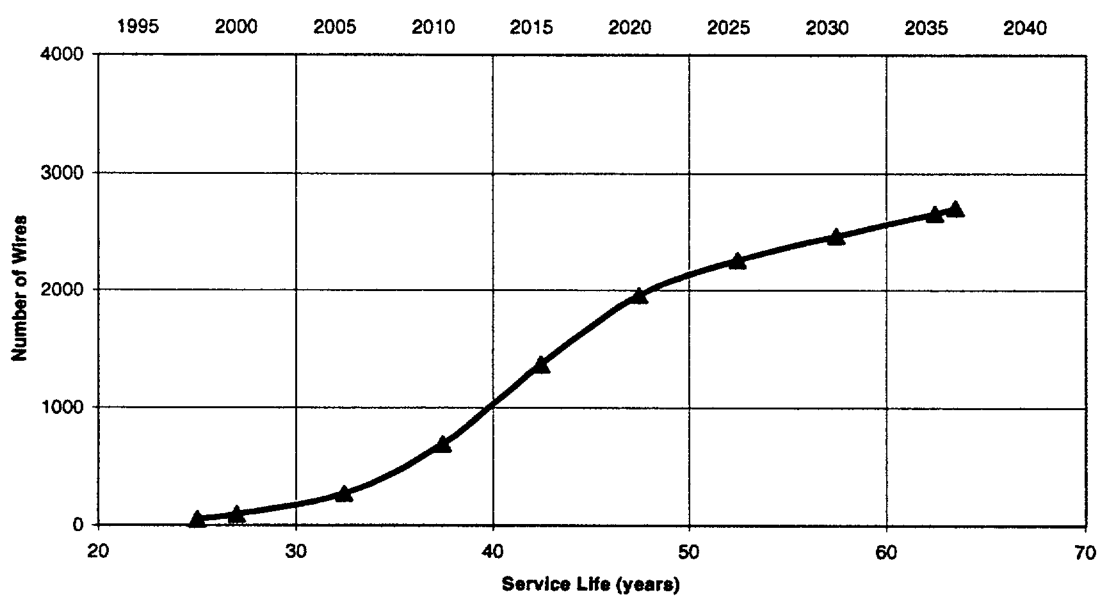


Figure I-2. Total Broken Wires in Vertical Tendon System



II. INTRODUCTION

Some tendon wire failures were noted during the 20-year in-service inspection (performed in 1997) of the Calvert Cliffs Unit 1 containment structure vertical tendons.[1] 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 (grease caps) to minimize degradation over the following few years while the need for longer term corrective actions could be evaluated.

The tendons at both units were inspected again in 1999 and 2000.[2] The scope 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 severely corroded and had no broken wires in 1997.
3. A random sample of 40 Unit 2 tendons to assess the increase in the number of affected tendons.[3,4]

There was some overlap of the random sample on Unit 2 and the "severely 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 "severely corroded" was to assess the progression of degradation of the tendons known to be affected.

One tendon from the random sample on Unit 2 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.

Additional inspections of all tendons for both Unit 1 and Unit 2 that have no reported broken wires and were not categorized as severely corroded (non-degraded tendons) were performed in the summer of 2000. The primary purpose of the work performed in the summer of 2000 was to replace grease caps on tendons that have showed no evidence of degradation and are not candidates for replacement. In conjunction with the grease cap replacements, the tendons were inspected for popped up broken wires. Only one new broken wire was identified. That wire was found on a Unit 2 tendon. The pop-up occurred at the bottom anchorage. It is not clear when this failure occurred, because previous inspections were concentrated on the upper anchorages. The wire may have failed from damage incurred during construction. Because of its location at a bottom anchorage, the broken wire found in 2000 at Unit 2 is considered to be anomalous and not associated with the corrosion problems experienced near the top anchorage. Thirteen tendons that were previously classified as corroded or have previously identified broken wires were added to the scope of the inspections in 2000 because they were observed to be leaking grease from the old style grease caps.[5] These included seven corroded tendons and four tendons with broken wires on Unit 1 and one corroded tendon and one tendon with broken wires on Unit 2. None of these tendons with previous degradation was found to have any new broken wires. This observation gives approximately a 60% confidence that no new wire breaks have occurred in degraded tendons since August 1999.

The objective of this report is to develop models 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 assumption that the short term corrective actions (re-application of grease and re-sealing of tendon top grease caps) are not fully effective in stopping the corrosion degradation. The models are to be conservative upper bounds for the rate of wire failures for the extended licensed lives of the units (2034 for Unit 1 and 2036 for Unit 2). The models were developed using the Unit 2 time line. The tendons of Unit 1 have been tensioned for approximately one year longer than those of Unit 2. However, the inspections of 1997, 1999, and 2000 indicate that the conditions of the tendons at the two units are comparable at the current time. Thus, it is considered that 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 are based on previous models developed in 1997 and 1999 using the then available data.[6,7] The models described in this report use the additional data derived from the 1999 and 2000 inspections to extend the postulated period of validity to the end of plant life. The model for ductile/general corrosion wire failures also uses the observed failures of wires during lift-off tests performed in 1997 to develop an additional data point for failures from that degradation mode. This 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 total predicted wire failures.

III. BACKGROUND INFORMATION

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.[8] 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 (Visconorust 2090P) to minimize corrosion. The top anchorage of each tendon is enclosed in a sealed steel container (grease cap) that is intended to protect the tendon from the environment.

There were originally 204 vertical tendons in the containment structure design. In Unit 1, two of these tendons were not used during original construction, leaving 202 tendons put into service.[9,10] 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 in-service 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 possibly 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 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 grease caps were resealed.

The years given above for the times of the surveillance inspections are the nominal in-service 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 these models 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 CCNPPI, 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.[11]

IV. TENDON WIRE DEGRADATION MODEL

Evaluation of 1999 and 2000 Inspection Results

Results of the 1999 inspections are shown in Table IV-1.[12] 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. All tendons at both units with no previously identified broken wires were inspected for broken wires in 2000. Only one new broken wire was identified. That failure was near a bottom anchorage on a Unit 2 tendon. Because of its location, the break is assumed to not be related to the corrosion degradation near the top anchorage that was identified in 1997. The wire break may not be service induced, but may be the result of damage sustained during construction. Thus, all tendons that had no broken wires in 1997 have been inspected. Of these tendons, only Unit 2 tendon 12V9 has experienced a wire failure since 1997. All of the

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

wire failures identified in 1999 were hydrogen induced cracking (HIC) failures except for one that was indeterminate. Because HIC was the dominant failure mode observed in 1999, the one indeterminate failure was also put in that category for analysis purposes.

Thirteen previously degraded tendons (11 at Unit 1 and 2 at Unit 2) were added to the scope of the 2000 inspections because they were observed to be leaking grease. No new broken wires were found in any of these thirteen tendons. These results were evaluated to provide a basis for estimating the current rate of degradation for the degraded tendons. The evaluation is shown in Table IV-2. Of the 13 tendons inspected, five had previously broken wires and eight were classified as severely corroded. Based on inspection result data from 1999,[13] considering both units together, there are 47 tendons with broken wires and 106 tendons classified as severely corroded. This gives a total degraded tendon population of 153. The inspections of degraded tendons performed in 2000 are slightly less than 10% samples of the populations.

Considering three populations of tendons, (1) tendons with broken wires, (2) corroded tendons, and (3) all degraded tendons, an evaluation was performed as documented in Table IV-2 to determine the level of confidence provided by the inspections that there have been no additional wire breaks in the degraded tendon population. The evaluation used the statistics of confidence levels for sampling inspections. Statistical methods can be used to determine limits on the true failure rate in the entire population given a particular result from a sampling inspection. For the cases considered here, no failures were observed so the lower limit of the failure rate for the entire population is clearly zero. A limit on the maximum failure rate at a given confidence can be determined from statistics. For the purpose of evaluating the significance of finding no additional failed wires in the 13 degraded tendons inspected in 2000, it is desired to determine the confidence that there have been no additional wire failures in the entire broken wire, corroded, and degraded tendon populations. The statistical evaluation cannot produce a limit of 0% failures. Instead, the evaluation considered a maximum failure fraction corresponding to 0.5 tendons in the population being considered, i.e., the maximum number of failures rounds to zero. These values are given for the three populations in Table IV-2 as "Desired Maximum Fraction Failed."

For a given number of trials N of an event which has two possible outcomes, "failure" and "success," the mean number of failures for many sets of trials μ_p and the standard deviation σ_p are given by

$$\mu_p = p \qquad (1)$$

$$\sigma_p = \sqrt{\frac{pq}{N}} = \sqrt{\frac{p(1-p)}{N}} \tag{2}$$

where p is the probability of "failure" and q = (1-p) is the probability of success and N is the number of trials in the set.[14] If P is the observed fraction of "failures" in a given set of trials, the actual fraction of "failures" in the whole population can be estimated with various levels of confidence. For a finite population without replacement of the samples, the limits of the confidence bands on p are given by

$$p = P \pm z_c \sqrt{\frac{pq}{N}} \sqrt{\frac{N_P - N}{N_P - 1}} \tag{3}$$

where p is the estimated true failure probability at a specified confidence level, N_p is the number of objects in the population, N is sample size, and z_c (defined as the confidence coordinate) is the number of standard deviations of a normal distribution corresponding to the desired confidence level (e.g., for 95% confidence $z_c = 1.645$ because 95% of the standard normal distribution is less than +1.645 standard deviations). z_c values were determined using the NORMSINV function in MS Excel with the confidence level as the argument.

Determination of p requires solving the equation [3] for p. The solution is (Reference 14 problem 9.2, page 201)

$$p = \frac{P + \frac{z_c^2}{2N} \pm z_c \sqrt{\frac{P(1-P)}{N} + \frac{z_c^2}{4N^2}}}{1 + \frac{z_c^2}{N}} \tag{4}$$

for the infinite population case. The result for the finite population without replacement is obtained from the infinite population by making the substitution

$$z' = z_c \sqrt{\frac{N_P - N}{N_P - 1}} \tag{5}$$

to obtain the adjusted confidence coordinate z′. The term in the square root in equation (5) is called the "Finite Population Factor" in Table IV-2.

The maximum fractions failed for each of the three populations were calculated iteratively to find the confidence levels that give calculated maximum fractions failed equal to the desired maximum fractions failed. The parameter values for which the calculations converged are shown in Table IV-2. As shown in the table, the inspections performed in 2000 on degraded tendons give approximately 60% confidence that there have been no new wire breaks in degraded tendons since 1999. Although this is not a high level of confidence, it is considered to be a sufficient basis for assuming no new wire breaks in the best estimate tendon degradation models presented in this report.

Table IV-2
Evaluation of 2000 Inspection Results

Tendon Condition Summary
(as of completion of 1999 inspections)

Total Tendons (Unit 1 and Unit 2)	**406**	
Tendons with Broken Wires	**47**	Ref. a
Tendons with Severe Corosion	**106**	Ref. a
Degraded Tendons	**153**	Ref. a
Non-degraded Tendons	**253**	Ref. a

Inspections 2000

Tendons with Broken Wires	**5**	Ref. b
Tendons with Severe Corosion	**8**	Ref. b
Degraded Tendons	**13**	Ref. b
Non-degraded Tendons	**253**	

Inspection Results Evaluation			
	Population		
Parameter	Degraded Tendons	Tendons with Broken Wires	Corroded Tendons
Number of Tendons in Population, Np	153	47	106
Number of Tendons Inspected, N	13	5	8
Observed Wire Failures	0	0	0
Success Rate	1.00	1.00	1.00
Desired Maximum Fraction Failed (less than 0.5 tendons)	0.0033	0.0106	0.0047
Confidence Level	59%	60%	58%
Confidence Coordinate, zc	0.2151	0.2426	0.2015
Finite Population Factor	0.9597	0.9555	0.9661
Adjusted Confidence Coordinate, z'	0.2065	0.2318	0.1947
Calculated Maximum Fraction Failed (at given confidence level)	0.0033	0.0106	0.0047

References

a. J. C. Poehler letter to A. P. L. Turner, August 26, 1999.
b. R. Dufresne, email to J. C. Poehler, et al., September 18, 2000, 2:03 PM, forwarded to A. P. L. Turner by email September 18, 2000, 15:09.

Evaluation of Wire Failures During 1997 Lift-off Tests

A significant fraction (about half) of the tendon wires that were broken due to general corrosion by the end of the 1997 inspection effort actually failed during lift-off tests performed to evaluate the prestress in the tendons. These are considered to be accelerated failures that would not have occurred in 1997 without the perturbation of the lift-off tests. All of the lift-off test wire failures were determined by examination of the broken wire end to be ductile failures resulting from general corrosion. Wires failed during the lift-off tests in tendons that had broken wires in the as-found condition and in tendons that had no broken wires as-found. Therefore, the lift-off failures increased the number of tendons affected and changed the distribution of number of broken wires in the affected tendons.

A lift-off test consists of stretching a tendon until the load on the shim stack below the stressing washer is relieved and a gap opens between the stressing washer and shims sufficient to insert a 0.030 in. shim. Thus, the additional stretch imparted to the tendons during a lift-off test is 0.030 in. for the clearance created and an additional amount to account for elastic relaxation of the shims and anchorage components (e.g., flexing of the stressing washer). These elastic relaxations of the mating components are difficult to determine accurately, but it is estimated that they account for no more than an additional 0.030 in. of tendon stretch. This gives a total additional stretch of a tendon during a lift-off test of approximately 0.060 in. When the tendons were loaded to prestress the concrete, they were stretched by a nominal 11.4 in. (based on a nominal length of 178 ft). This corresponds to a stress of 160 ksi. By comparing the 0.060 in. of stretch during the lift-off test to the initial prestressing stretch of 11.4 in., it is concluded that a lift-off test increases the stress in a non-degraded wire by less than 1 ksi. In some cases, tendons may have been extended more than required during lift-off tests because of the way that the hydraulic loading equipment functions. Even if the tendons were stretched as much as 0.250 in. during the lift-off tests the increase in stress would not have been more than 4 ksi.

This small increase in stress appears to be inconsistent with the number of wire failures observed during the tests. The most plausible explanation for the observed lift-off failures is that, when a wire is badly corroded, the strain imposed during the lift off test is concentrated into a short effective gage length at the point of maximum material loss from corrosion. An elongation of 0.060 in., if concentrated in a 0.5 in. effective length is 12% strain, which far exceeds the material ductility of approximately 4%. For a wire that has suffered sufficient corrosion to be in the plastic regime at the minimum cross section, factors that lead to concentration of the lift-off test strain include:

- Geometric stress/strain concentrators created by corrosion.
- The low work hardening capacity of the deformation strengthened wires (low slope of the stress strain curve above the yield strength). The tendon wires are in a highly strain hardened condition such that their stress strain curve above the yield transition is relatively flat with little capacity for additional strain hardening.
- Viscous shear resistance of the grease in the tendon conduit that makes the additional force in the wire during the test greatest near the end where the lift-off loading is applied.

One reason that no HIC failures were observed during lift-off tests is that wires containing hydrogen induced cracks behave, during a lift-off test, like non-degraded wires. That is, there is no mechanism for concentrating the strain in the region of the wire where the hydrogen induced cracks exist. The cracks experience only a small increase in stress during the test so it is unlikely that a critical stress intensity is reached.

Based on these considerations, it is concluded that the wires that failed during lift-off tests in 1997 were sufficiently corroded that the stress at the minimum section was greater than the material nominal yield strength (204 ksi), but less than the nominal tensile strength (240 ksi). Because the short corroded length of a degraded tendon wire cannot absorb a significant portion of the nominal 11.4 in. prestressing elongation, there is no significant relaxation of the force in a tendon wire when the minimum section becomes plastic. Therefore, the force in a wire corresponds to the prestress in the non-degraded wire of 150 to 160 ksi.

For the purpose of the predictive models for tendon wire failures, it is assumed that the only wire failures that would have been observed in 1997 without lift-off testing are the "as-found" condition failures. It is assumed that the lift-off test failures are accelerated failures that would have occurred at a later date. This is consistent with the observation of no further ductile failures between 1997 and 2000. The acceleration of failures by lift-off testing has created a delay in observation of failures because failures expected between 1997 and 2000 were accelerated into 1997. The duration of this delay will only be known when additional failures start to occur, but its minimum duration is from the end of the 1997 inspections to the time of the 2000 inspections. This is based on the above evaluation of the inspections in 2000 of 13 degraded tendons, which showed no additional failed wires.

Predictive Modeling of Progression of Tendon Wire Failures

Because the lift-off testing perturbation only seems to have affected the ductile/general corrosion failure mechanism, it was concluded that separate models should be developed for prediction of wire failure by the two degradation mechanisms. The modeling approach used for each mechanism is similar to that used in a report prepared after the 1999 inspections.[15] For each degradation mechanism, a Weibull probability distribution is used to describe how rapidly additional tendons become affected (i.e., suffer one or more broken wires). The numbers of broken wires in affected tendons are modeled assuming that the distributions of numbers of wires are described by a gamma probability distribution. The mean and variance of the gamma distributions are allowed to increase with time as the degradation progresses. The rates of increase of the gamma distribution means and variances are determined from the observations to date.

Predictions 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.[16 17 18 19] 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).[20] Because of its flexibility and wide use, the Weibull distribution was selected for this part of these models, 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:

$$F = 1 - \exp\left(-\left(\frac{t}{\theta} \right)^b \right) \qquad (6)$$

where

F = fraction of population failed (one or 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

Data points are available for each degradation mechanism to determine the two adjustable parameters (b and θ) of the Weibull distributions. For the HIC mechanism Unit 2 data were used. Because there have been no additional tendons at Unit 1 affected by HIC degradation since 1997, using Unit 2 data only, rather than combined Unit 1 and Unit 2 data, gives a more conservative prediction. There are three data points. There were 12 Unit 2 tendons affected by HIC in 1997 (24.7 service years). One additional tendon was found with a HIC wire failure in 1999 (26.5 service years). No additional HIC failures were found by sampling inspections in 2000 (27.5 service years). A Weibull distribution was fit to these three data points using least squares regression. The fitted distribution has $b = 0.836$ and $\theta = 702$ years. The resulting Weibull distribution is shown in Figure IV-1.

For general corrosion wire failures, combined Unit 1 and Unit 2 data were used. Of the 406 tendons in service at the two units in 1997, 11 were affected by general corrosion wire failures in the as-found condition in 1997. Twelve (12) additional tendons experienced wire failures during lift-off tests. It is assumed that the wire failures in the additional tendons would have occurred naturally by the time of the 2000 inspections if the lift-off tests had not been done. This is based on the fact that no new general corrosion wire failures were observed in 1999 or 2000. This is a conservative assumption because the delay before observation of new general corrosion wire failures may extend well beyond 2000. A Weibull distribution was fit through the two data points giving $b = 7.132$ and $\theta = 40.89$ years. This Weibull distribution is shown in Figure IV-2. The Weibull distributions were used to predict the number of tendons affected by each degradation mechanism at times in the future.

Figure IV-1
Calvert Cliffs Tendon Degradation Model
Tendons With HIC Broken Wires

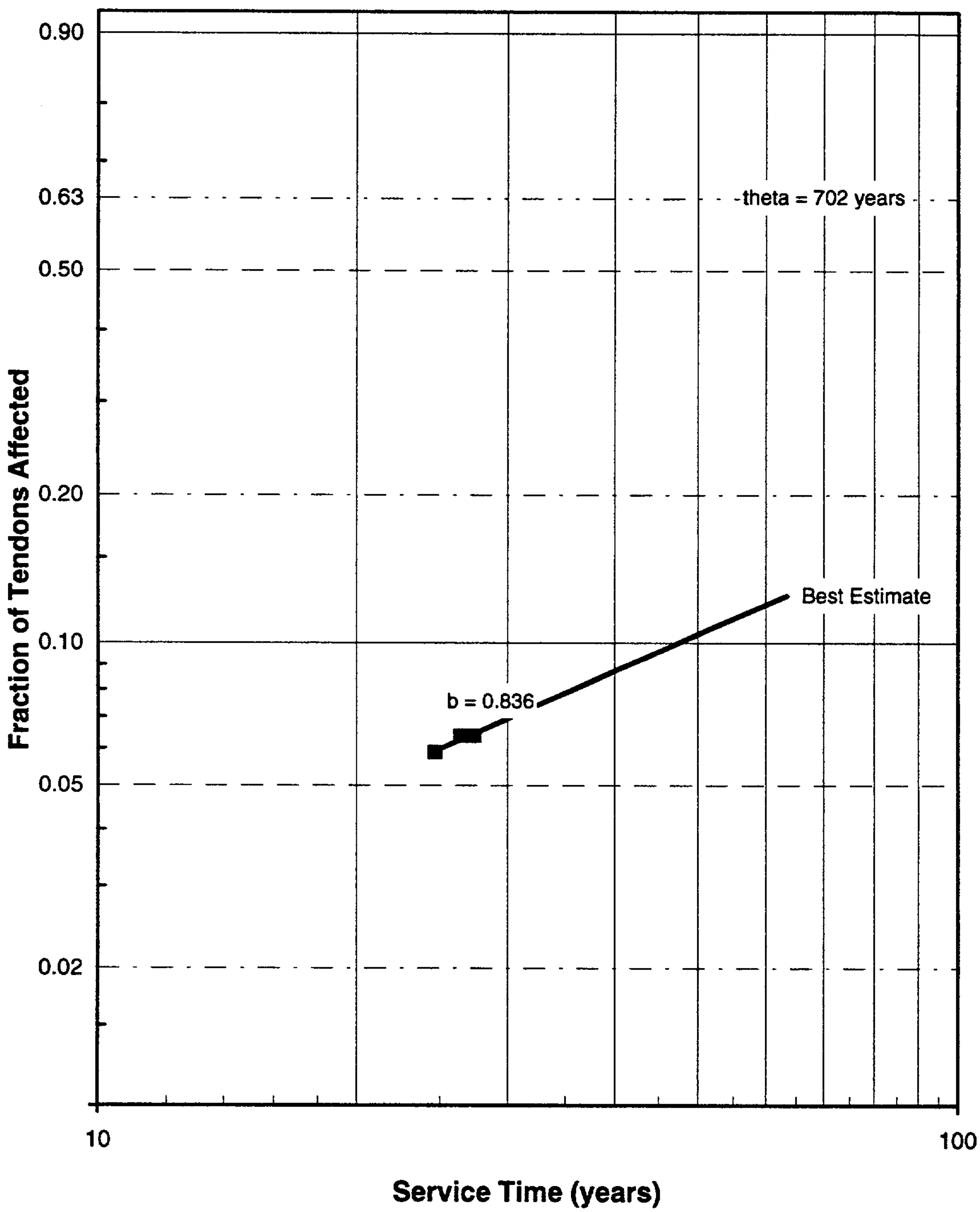
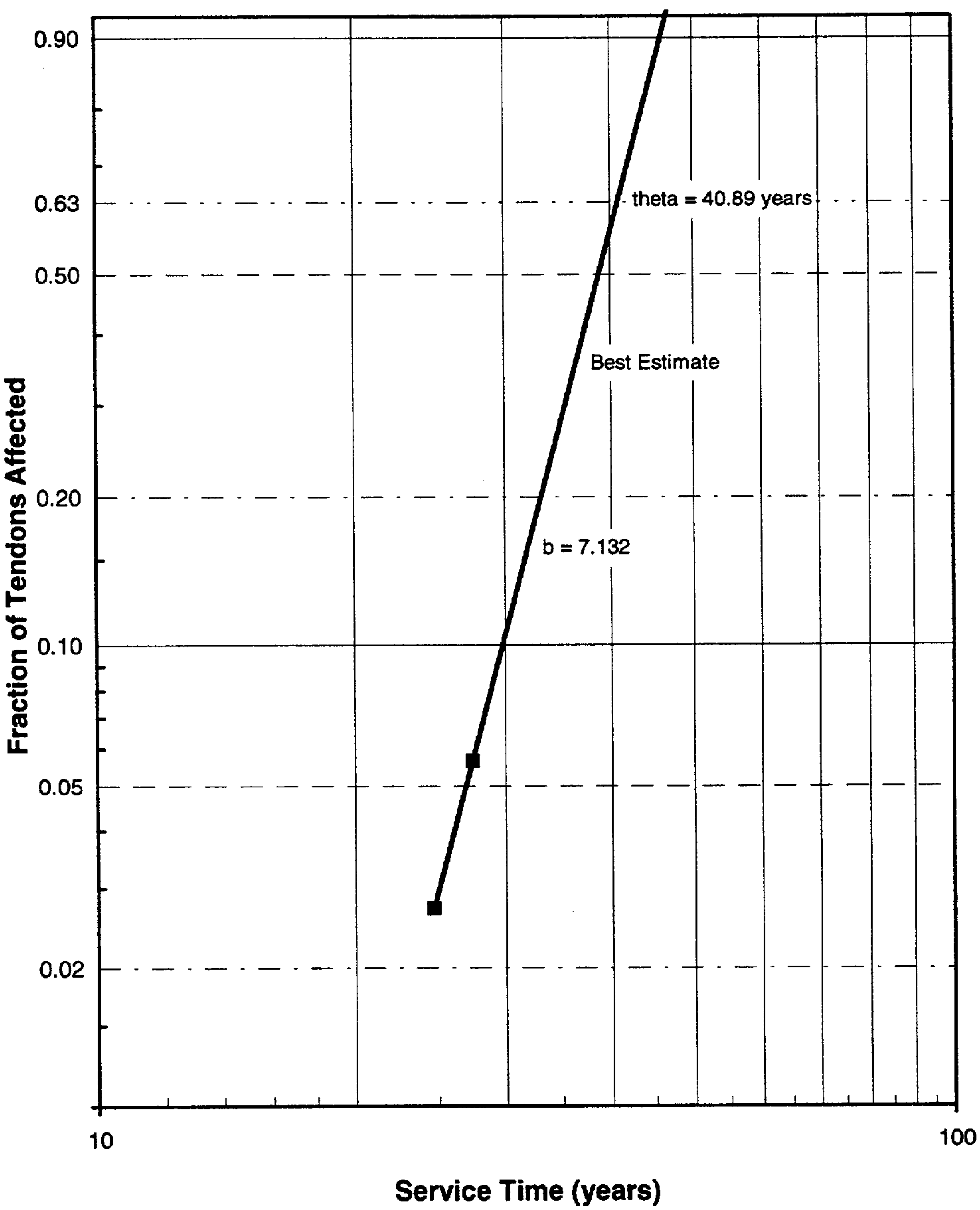


Figure IV-2
Calvert Cliffs Tendon Degradation Model
Tendons With General Corrosion Broken Wires



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 were developed using the entire set of affected tendons from Units 1 and 2 combined. Tables IV-3 and IV-4 show the numbers of tendons with given numbers of broken wires for each inspection. For HIC degradation, the data are from the 1997 and 1999 inspections. For ductile/general corrosion degradation, the data are the 1997 as found condition and the 1997 after lift-off test condition. As with the Weibull distributions, the after lift-off test data are considered to be representative of the time of the 2000 inspections. The mean numbers of broken wires per tendon and the variances of the observed distributions are shown at the bottoms of Tables IV-3 and IV-4.

In Report R-3632-01-02[21] 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

$$\beta = \frac{V}{m} \qquad (7)$$

$$\alpha = \frac{m}{\beta} \qquad (8)$$

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. For the values of α and β appropriate for tendon wires, the peak of the density distribution g(x) (mode of the distribution) is usually 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 (7) and (8). The continuous distribution is discretized by assigning the

Table IV-3

Calvert Cliffs Units 1 and 2 Combined

Hydrogen Induced Cracking Mechanism

Cumulative Tendons with Broken Wires

Wires Failed per Tendon	1997		1999	
	No. Tendons	Total Wires Failed	No. Tendons	Total Wires Failed
1	10	10	11	11
2	3	6	3	6
3	1	3	1	3
4	0	0	0	0
5	1	5	1	5
6	2	12	1	6
7	0	0	1	7
8	1	8	0	0
9	2	18	1	9
10	0	0	1	10
11	1	11	2	22
12	1	12	0	0
13	0	0	0	0
14	0	0	1	14
15	0	0	0	0
Totals	**22**	**85**	**23**	**93**
	mean =	**3.86**	**mean =**	**4.04**
	variance =	**13.2**	**Variance =**	**16.7**

Table IV-4

Calvert Cliffs Units 1 and 2 Combined

General Corrosion Degradation

Cumulative Tendons with Broken Wires

Wires Failed per Tendon	1997 As-found		1997 Post Lift-off	
	No. Tendons	Total Wires Failed	No. Tendons	Total Wires Failed
1	2	2	9	9
2	1	2	2	4
3	2	6	2	6
4	1	4	2	8
5	2	10	2	10
6	1	6	0	0
7	1	7	1	7
8	0	0	0	0
9	0	0	0	0
10	0	0	1	10
11	0	0	0	0
12	0	0	1	12
13	0	0	1	13
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	0	0	0	0
18	1	18	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	0	0	1	25
26	0	0	1	26
Totals	**11**	**55**	**23**	**130**
	mean =	**5.00**	**mean =**	**5.65**
	variance =	**20.4**	**Variance =**	**49.8**

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 is an important correction for the general corrosion mechanism model because the variance becomes large before end of plant life. When the variance is large, truncation of the gamma distribution at 90 and renormalization has the affect that the mean number of broken wires in the truncated distribution is less than for the complete gamma distribution extending to infinity. This is because the truncation eliminates the small probability that there are a very large number broken wires. A consequence of this is that the predicted total number of broken wires cannot be calculated from the mean of the complete gamma distribution.

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

$$f(x') = \frac{\beta^{-\alpha} x'^{\alpha-1} e^{-x'/\beta}}{\Gamma(\alpha)} \quad \text{for } x' > 0 \qquad (9)$$

where $\Gamma(\alpha)$ is the standard gamma function, α and β are parameters of the distribution defined by equations (7) and (8) 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 were defined using equations (7) and (8) with adjusted mean values m'. The data and distribution functions are compared in Figures IV-3 and IV-4 on a cumulative probability plot. It can be seen that the data are reasonably 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. The data for the 1997 (as-found and after lift-off tests), and 1999 inspections show that the assumption of a constant failed wire distribution is not precisely observed. Both the mean and variance of the distributions for failed wires increase with time. The rates of increase of the means and variances of the failed wire distributions were determined for the two degradation mechanisms from the data given in Tables IV-3 and IV-4. For hydrogen induced cracking, the mean increased from 3.86 to 4.04 in a 1.75 year interval from November 1997 to August 1999. This gives a rate of increase of 0.103/year. For hydrogen induced cracking the variance increased from 13.2 to 16.7 in 1.75 years for a rate of increase of 2.016/year. For general corrosion, the mean increased from 5.00 to 5.65 in an assumed period of 2.75 years from November 1997 to August 2000. This assumes, based on the sampling inspections in 2000, that no new wires in the degraded tendon population have failed since 1997. Thus, in August 2000, the system was still in the delay period caused by accelerating failures by doing lift-off tests in 1997. With this assumption, the rate of increase of the distribution mean is 0.237/year. The variance increased from 20.4 to 49.8 in the assumed 2.75 years for a rate of increase of 10.70/year. It is assumed that these rates of increase will be constant for the remaining life of the tendon system. Therefore, these rates of increase were applied to calculate distribution function mean and variance values for future times. From the mean and variance values, the parameters of the gamma distributions were calculated using equations (7) and (8) for various future times. The complete gamma distributions were truncated at 90 wires per tendon and renormalized such that the cumulative probability of having less than or equal to 90 broken wires is 1.00.

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

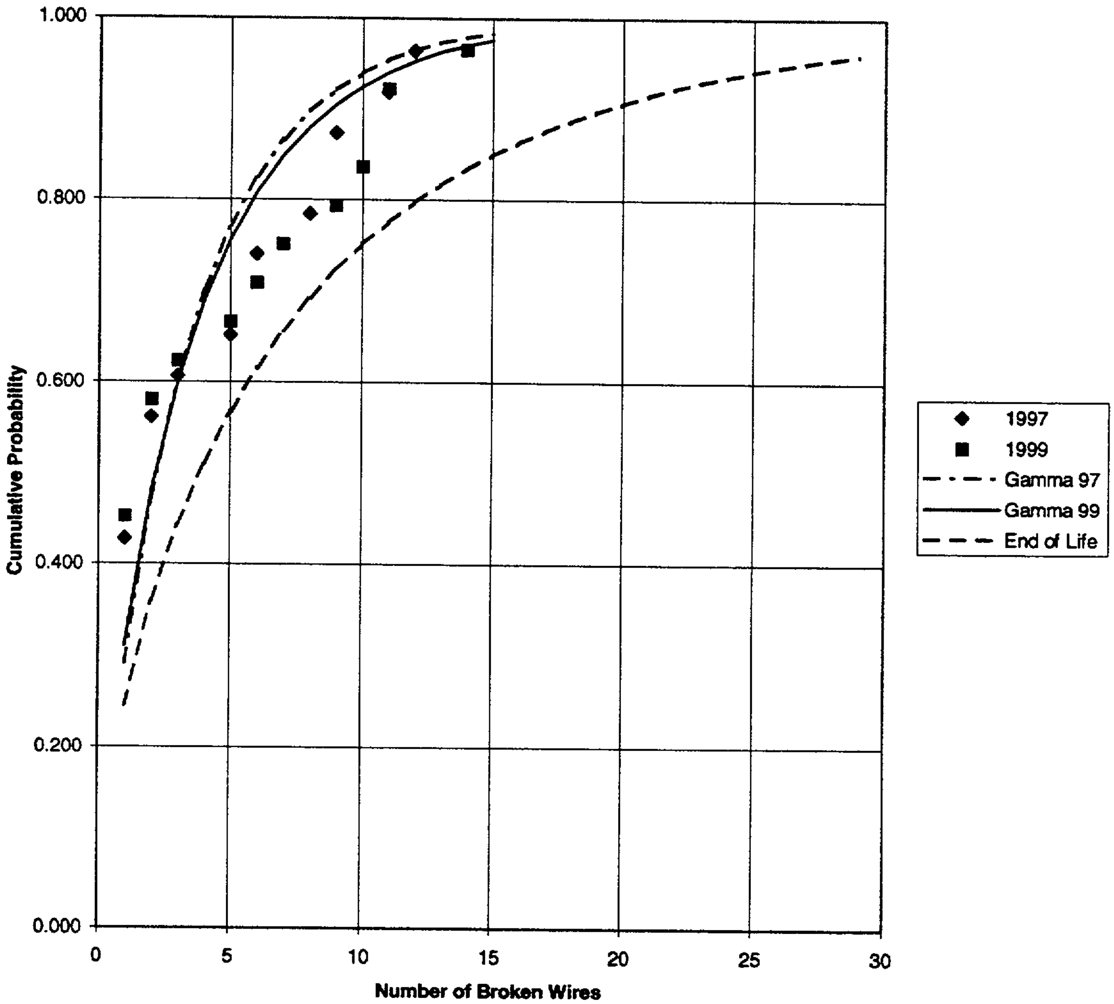
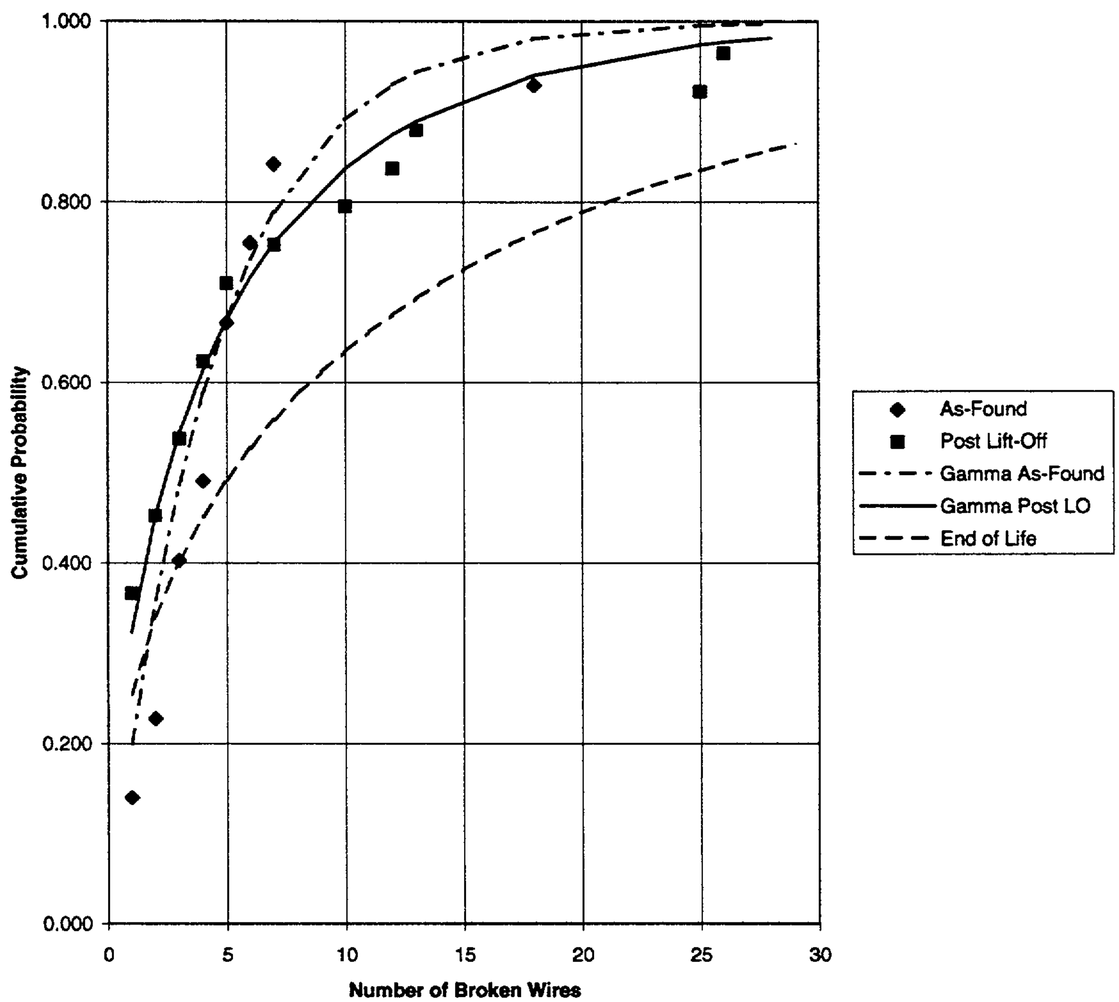


Figure IV-4
Calvert Cliffs Units 1 and 2 Combined
General Corrosion Wire Failures
Gamma Distributions (Adjusted) for Number of Broken Wires Per Tendon



Composite Tendon Wire Failure Models.

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

1. The Weibull distribution equation (6) is used to calculate the fraction of the tendon population that will have one or more failed wires at any time of interest.
2. Gamma distribution function parameters for any future time are determined from the rates of increase in mean and variance as described above. Using the gamma distributions, the complete predicted distributions of failed wires can be calculated.

Failed wire distributions for each degradation mechanism were determined for several times during the remaining life of the plant. The predicted end-of-life distributions for hydrogen induced cracking failures and general corrosion failures are presented in Tables IV-5 and IV-6, respectively. Results for other times are tabulated in Appendix A.

Convolution of the Two Degradation Mechanisms

Combining the two degradation models to obtain predictions of the total numbers of degraded tendons and distributions of failed wires must be done using convolution techniques. To date, no tendon has experienced wire failures from both HIC and GC. However, there is no known physical reason why the two degradation mechanisms cannot affect different wires in the same tendon. This is considered to become more likely as the degradation spreads to a larger fraction of the tendons. For the purposes of this modeling effort, it was assumed that the two degradation mechanisms are statistically independent and they each potentially affect the entire population of tendons.

The predicted total number of tendons affected is calculated from the two mechanism fractions using a statistical aggregation method because a given tendon may become affected by both degradation mechanisms. The total number of affected tendons M_A is given by

$$M_A = N_T\left(1-\left(1-F_{GC}\right)\left(1-F_{HIC}\right)\right) \qquad (10)$$

where N_T is the total number of tendons for the containment, F_{GC} is the fraction of tendons affected by general corrosion, and F_{HIC} is the fraction of tendons affected by hydrogen induced cracking.

Calculation of the distributions of total wires failed is done by a numerical convolution of the two distributions for discrete integer values. For HIC failures, the probability of observing a given number n_{HIC} of broken wires is determined by integrating the gamma distribution density function for HIC over the interval n_{HIC}-0.5 to n_{HIC}+0.5. Similarly for GC, the probability of observing n_{GC} is the integral of the GC gamma distribution density function from n_{GC}-0.5 to n_{GC}+0.5. The probability of observing a total number of wire failures m_T is the sum of the probabilities of observing each combination of HIC and GC failures that add up to m_T. For example, three wire failures in a tendon can be any of the following:

0 HIC	3 GC
1 HIC	2 GC
2 HIC	1 GC
3 HIC	0 GC

If the probability of n_{HIC} failures is $p_{HIC}(n_{HIC})$ and the probability of n_{GC} failures is $p_{GC}(n_{GC})$, then the probability of having n_{HIC} and n_{GC} is $p_{HIC}(n_{HIC})* p_{GC}(n_{GC})$ (e.g., the probability of 0 HIC and 3 GC failures is $p_{HIC}(0)*p_{GC}(3)$). This is the joint probability. The probability of observing m_T total failures $p_T(m_T)$ is the sum of the probabilities of the possible combinations. For the example of three total failures (m_T=3), the probability is

$$p_T(3) = p_{HIC}(0)*p_{GC}(3)+ p_{HIC}(1)*p_{GC}(2)+ p_{HIC}(2)*p_{GC}(1)+ p_{HIC}(3)*p_{GC}(0) \quad (11)$$

The number of possible combinations increases as m_T increases. The possible combinations are m_T+1. For m_T=90, there are 91 possible combinations for which probabilities must be computed. To obtain the distribution for total failed wires, a spreadsheet was used to compute and sum the joint probabilities for the possible combinations using the probabilities computed for each mechanism from the gamma distributions. Because there are combinations that add up to more than 90 total failed wires, the sum of the probabilities calculated this way for 0 to 90 total failed wires is less than 1.00. To correct this error, the probabilities were renormalized to make the sum exactly equal to 1.00.

The predicted distribution of total failed wires for end of the Unit 2 extended license in 2036 is given in Table IV-7. Predictions for other times are given in Appendix A.

Table IV-5
Predicted Distribution of Broken Wires by HIC for End of Unit 2 Extended License in 2036

Wires Failed per Tendon	Cumulative Probability	Cumulative No. Tendons	No. Tendons	Failed Wires
1	24.5%	6	6	6
2	35.9%	9	3	6
3	44.3%	12	3	9
4	51.1%	13	1	4
5	56.8%	15	2	10
6	61.5%	16	1	6
7	65.7%	17	1	7
8	69.2%	18	1	8
9	72.4%	19	1	9
10	75.2%	20	1	10
11	77.6%	20	0	0
12	79.8%	21	1	12
13	81.7%	21	0	0
14	83.5%	22	1	14
15	85.0%	22	0	0
16	86.4%	22	0	0
17	87.7%	23	1	17
18	88.8%	23	0	0
19	89.9%	23	0	0
20	90.8%	24	1	20
21	91.6%	24	0	0
22	92.4%	24	0	0
23	93.0%	24	0	0
24	93.7%	24	0	0
25	94.2%	25	1	25
26	94.7%	25	0	0
27	95.2%	25	0	0
28	95.6%	25	0	0
29	96.0%	25	0	0
30	96.4%	25	0	0
38	98.2%	26	1	38
			Total Broken Wires =	**201**
			Mean Number Broken Wires =	**7.73**

Table IV-6
Predicted Distribution of Broken Wires by General Corrosion for End of Unit 2 Extended License in 2036

Wires Failed per Tendon	Cumulative Probability	Cumulative No. Tendons	No. Tendons	Failed Wires
1	25.55%	52	52	52
2	34.12%	70	18	36
3	40.25%	82	12	36
4	45.15%	92	10	40
5	49.25%	100	8	40
6	52.80%	108	8	48
7	55.92%	114	6	42
8	58.71%	120	6	48
9	61.23%	125	5	45
10	63.52%	130	5	50
11	65.61%	134	4	44
12	67.54%	138	4	48
13	69.32%	141	3	39
14	70.97%	145	4	56
15	72.51%	148	3	45
16	73.94%	151	3	48
17	75.28%	154	3	51
18	76.54%	156	2	36
19	77.72%	159	3	57
20	78.83%	161	2	40
21	79.87%	163	2	42
22	80.86%	165	2	44
23	81.79%	167	2	46
24	82.67%	169	2	48
25	83.50%	170	1	25
26	84.29%	172	2	52
27	85.03%	173	1	27
28	85.74%	175	2	56
29	86.42%	176	1	29
30	87.06%	178	2	60
31	87.66%	179	1	31
32	88.24%	180	1	32
33	88.79%	181	1	33
34	89.32%	182	1	34
35	89.82%	183	1	35
36	90.29%	184	1	36
37	90.75%	185	1	37
38	91.18%	186	1	38
39	91.60%	187	1	39
40	91.99%	188	1	40
41	92.37%	188	0	0

Table IV-6 (cont.)

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

Wires Failed per Tendon	Cumulative Probability	Cumulative No. Tendons	No. Tendons	Failed Wires
42	92.73%	189	1	42
43	93.08%	190	1	43
44	93.41%	191	1	44
45	93.72%	191	0	0
46	94.02%	192	1	46
47	94.31%	192	0	0
48	94.59%	193	1	48
49	94.86%	194	1	49
50	95.11%	194	0	0
51	95.35%	195	1	51
52	95.59%	195	0	0
53	95.81%	195	0	0
54	96.02%	196	1	54
55	96.23%	196	0	0
56	96.43%	197	1	56
57	96.61%	197	0	0
58	96.80%	197	0	0
59	96.97%	198	1	59
60	97.14%	198	0	0
61	97.30%	198	0	0
62	97.45%	199	1	62
63	97.60%	199	0	0
64	97.74%	199	0	0
65	97.88%	200	1	65
66	98.01%	200	0	0
67	98.13%	200	0	0
68	98.25%	200	0	0
69	98.37%	201	1	69
70	98.48%	201	0	0
71	98.59%	201	0	0
72	98.69%	201	0	0
73	98.79%	202	1	73
74	98.89%	202	0	0
75	98.98%	202	0	0
76	99.07%	202	0	0
79	99.31%	203	1	79
86	99.78%	204	1	86
			Total Broken Wires =	**2611**
			Mean Number Broken Wires =	**12.8**

Table IV-7
Predicted Distribution of Total Broken Wires – Combined Both Mechanisms
End of Unit 2 Extended License in 2036

Wires Failed per Tendon	Cumulative Probability	Cumulative No. Tendons	No. Tendons	Failed Wires
1	23.35%	48	48	48
2	32.01%	65	17	34
3	38.29%	78	13	39
4	43.38%	88	10	40
5	47.52%	97	9	45
6	51.10%	104	7	42
7	54.26%	111	7	49
8	57.09%	116	5	40
9	59.65%	122	6	54
10	61.99%	126	4	40
11	64.13%	131	5	55
12	66.12%	135	4	48
13	67.95%	139	4	52
14	69.66%	142	3	42
15	71.25%	145	3	45
16	72.74%	148	3	48
17	74.13%	151	3	51
18	75.43%	154	3	54
19	76.66%	156	2	38
20	77.82%	159	3	60
21	78.91%	161	2	42
22	79.93%	163	2	44
23	80.90%	165	2	46
24	81.82%	167	2	48
25	82.69%	169	2	50
26	83.52%	170	1	26
27	84.30%	172	2	54
28	85.04%	173	1	28
29	85.75%	175	2	58
30	86.42%	176	1	30
31	87.05%	178	2	62
32	87.66%	179	1	32
33	88.24%	180	1	33
34	88.79%	181	1	34
35	89.31%	182	1	35
36	89.81%	183	1	36
37	90.29%	184	1	37
38	90.75%	185	1	38
39	91.18%	186	1	39
40	91.60%	187	1	40
41	91.99%	188	1	41

Table IV-7 (cont.)
Predicted Distribution of Total Broken Wires – Combined Both Mechanisms
End of Unit 2 Extended License in 2036

Wires Failed per Tendon	Cumulative Probability	Cumulative No. Tendons	No. Tendons	Failed Wires
42	92.37%	188	0	0
43	92.73%	189	1	43
44	93.08%	190	1	44
45	93.41%	191	1	45
46	93.73%	191	0	0
47	94.03%	192	1	47
48	94.32%	192	0	0
49	94.60%	193	1	49
50	94.87%	194	1	50
51	95.12%	194	0	0
52	95.37%	195	1	52
53	95.60%	195	0	0
54	95.82%	195	0	0
55	96.04%	196	1	55
56	96.25%	196	0	0
57	96.45%	197	1	57
58	96.64%	197	0	0
59	96.82%	198	1	59
60	96.99%	198	0	0
61	97.16%	198	0	0
62	97.32%	199	1	62
63	97.48%	199	0	0
64	97.63%	199	0	0
65	97.77%	199	0	0
66	97.91%	200	1	66
67	98.04%	200	0	0
68	98.17%	200	0	0
69	98.29%	201	1	69
70	98.41%	201	0	0
71	98.52%	201	0	0
72	98.63%	201	0	0
73	98.73%	201	0	0
74	98.83%	202	1	74
75	98.93%	202	0	0
79	99.28%	203	1	79
86	99.77%	204	1	86
			Total Broken Wires =	**2714**
			Mean Number Broken Wires =	**13.3**

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. Unit 1 had less affected tendons than Unit 2 in 1997, slightly more broken wires than Unit 2 in 1997, and only 6 more broken wires than Unit 2 in 1999.

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.

It is noted that there have been several anomalous tendon wire failures observed at Calvert Cliffs. These include 4 cut wires in a Unit 1 tendon, and the wire failure near a lower anchor of a Unit 2 tendon found in 2000. Such failures are not included in the predictive models presented in this report. In evaluating these predictions, it must be recognized that some margin must be provided to accommodate wire failures that may occur in the future resulting from other mechanisms. To date, the number of these "anomalous" wire failures has been much smaller than the uncertainties in the predictive models.

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