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From: WJ Shack <wjshack@anl.gov>
To: Nilesh Chokshi <NCC1@nrc.gov>, Ed Hackett <EMH1@nrc.gov>, Wallace Norris <WEN@nrc.gov> RES
Date: 8/27/01 9:05AM
Subject: CRDM Probabilistic Analysis

Attached is a revised version of the analysis of the probability of failure of CRDM nozzles. In the previous analysis, it was assumed that all cracked nozzles were susceptible to outer diameter SCC. Any cracks that initiate were assumed to be circumferential. The Weibull parameters were estimated from inspection data and previous results for the cracking of steam generator tubes. No credit is given for inspections to reveal leaking cracks. An initiated crack was assumed to grow instantaneously throughwall to a circumferential extent of 165*. The crack then grows to failure under the loads associated with the internal pressure.

The resulting probabilities of failure seem unrealistically high compared with actual experience. To try to address this, sensitivity studies were then performed in which it was assumed that it took 12, 24, and 36 months for the cracks on the outer surface to grow to a circumferential extent of 165*. Although the probabilities of failure are reduced, they still appear unrealistically high. Because initiation is assumed to be characterized by Weibull statistics, there is a significant chance for early initiation of a crack relatively early in life. In this case, by 20 years there is a relatively long time available for an early crack to grow to failure. Either the cracks take much longer to grow to 165* or the initiation model is overly conservative.

An alternate analysis was performed under the assumption that cracks that threaten structural integrity are the cracks initiated on the OD. The controlling step in the formation of an OD circumferential crack was assumed to be the formation of a crack in the Alloy 182 weld. The statistics of this cracking, which occurred only in Oconee*3, appear to be different than the statistics of the cracking of the nozzles. Estimates of the probability of failure for Oconee*3 based on this assumption are lower than those based on the assumption that all cracked nozzles were susceptible to rapid circumferential crack growth, but still high.

As in the case of Alloy 600, the susceptibility of Alloy 182 to cracking is expected to be described by Weibull statistics. Because such cracks have been identified to date only at Oconee*3, only one data point is available to describe the distribution of the Weibull parameters. However, we also know that no such cracking was observed at the other Oconee plants or at ANO*1. These results were used with a Maximum Likelihood argument to estimate the distribution of the Weibull parameters for the Alloy 182 cracking. This analysis suggests that Oconee*3 may be a "worst case" plant on the tail of the distribution and OD initiated circumferential cracking is much less likely at a "typical" plant, although the current data are too limited, and the resulting uncertainties too large to demonstrate this definitively. The analysis does, however, provide a framework in which new inspection results can be included to reduce uncertainties and better characterize the real probability of cracking.

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August 25, 2001

To: N Chokshi, USNRC

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Subject: Estimates of the probability of failure of CRDM nozzles

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xc O K. Chopra, S Majumdar, W Norris, USNRC, E. Hackett, USNRC

Estimates of the Probability of Failure of CRDM Nozzles

Probability of failure

The probability that a CRDM nozzle will fail at a time t_f less than T, $P(t_f < T)$, can be described as the integral over the operating history of the product of the probability that a crack will initiate at a time t, p(t), and the probability that a crack that initiates at t will fail at a time t_f less than T, $P_c(t_f < T-t)$

$$P(t_f < T) = \int_0^T p(t) P_c(t_f < T - t) dt \tag{1}$$

Equation 1 gives the probability that one tube will fail If we assume that all n penetrations can be considered as independent, the probability that one of the penetrations will fail at a time $t_f < T$ is

$$P_n = 1-(1-P)^n \tag{2}$$

Conditional probability of failure for a growing crack

The probability $P_c(t_f < T)$ can be determined by fraction mechanics analysis. Because the chemistry of the crevice and the details of the residual stress are uncertain, the assumption is made that once the crack initiates it instantaneously grows to a throughwall crack of circumferential extent 165°. The subsequent growth is assumed to controlled by the pressure loading stresses The crack growth rates are assumed to characteristic of a PWR primary environment, since with a throughwall crack of this length the crevice environment is able to communicate with the primary environment. As noted in my earlier report on CRDM cracking, if the data for the different heats of nozzle material are fit using the Scott correlation

$$\frac{da}{dt} = A(K - 9)^{1.16} \tag{3}$$

a value of A can be determined for each heat of material from the measured CGRs. As shown in Fig 1, the values of A for the different heats are reasonably well represented in terms of a lognormal distribution with a log mean of -26 21 and a log standard deviation of 0 92

Corresponding to a particular choice of A a failure time can be calculated from a fracture mechanics analysis of the growing crack as shown in Fig 2 By performing a Monte Carlo analysis using the distribution for A given in Fig 1, the distribution of failure times, $P_c(t_f < T-t)$, can be obtained This distribution can be represented reasonably well by the lognormal distribution shown as a solid curve in Fig 3 with a log mean of 3.55 and a log standard deviation of 0 58 The dashed curves show the resulting distributions if the initial development of the 165° crack takes 12, 24, or 36 months

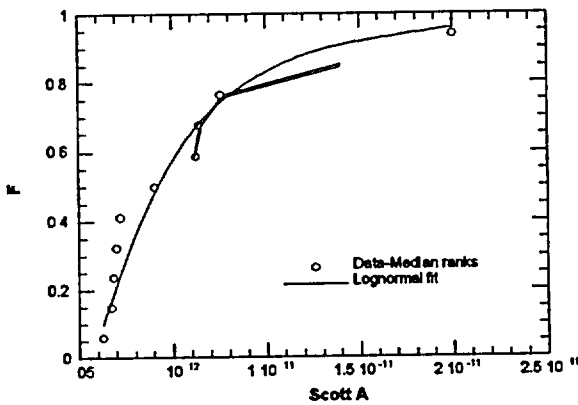

Figure 1 . Cumulative distribution of the parameter A in the Scott CGR correlation for heats of nozzle materials studied by Foster et al [1], Cassagne et al [2], and Gómez Briceño and Lapeña [5]

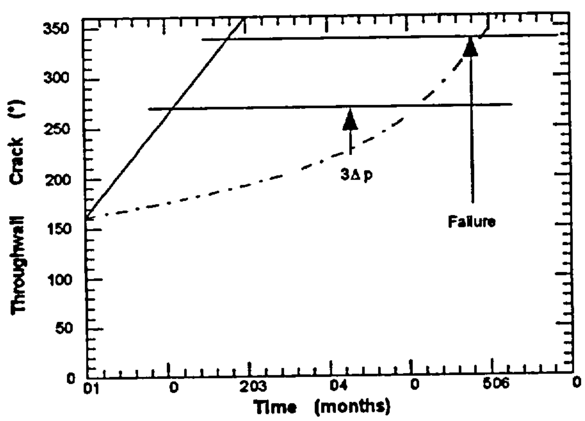

Figure 2 . Growth of a throughwall crack under pressure loads

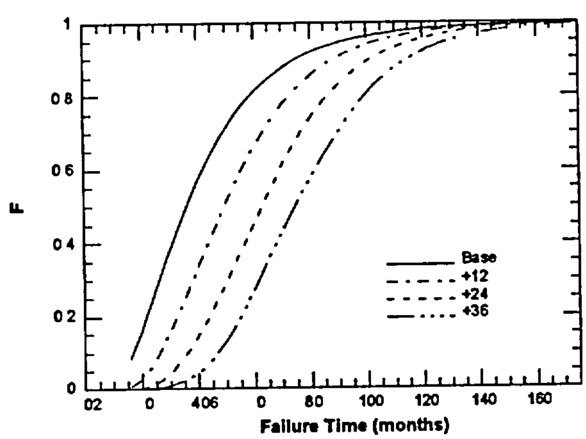

Figure 3 . Distribution of failure times for the growth of a 165° throughwall crack under pressure loads The dashed curves show the resulting distributions if the initial development of the 165° crack takes 12, 24, or 36 months

Probability of Initiation

Staelhe, Gorman and their coworkers have popularized the use of Weibull distributions to describe the initiation of SCC cracks 7 The Weibull probability density and cumulative probability functions are given by

$$p() = \frac{bx}{\theta\theta\alpha}\left(\ \right)^{b} \exp\left[-\left(\frac{x}{\alpha\theta}\right)^{b}\right] \qquad (4)$$

$$F() = 1 - \exp\left[-\left(\frac{x}{\alpha\theta}\right)^{b}\right]$$

In the recent response to the NRC review comments on MRP–44, MRP 2001–050, values of the scale parameter θ were estimated from the inspections results at the Oconee units and ANO–1 Since only the results from one inspection are available, the value of the Weibull slope b was assumed to be 3 However, the results for plant and laboratory data in Appendix C of Staelhe et al (7) show that b can have values ranging from 1 to 6 4 as shown in Fig 4 The median value of b from Fig 4 is 1 4 Peter Scott's analysis of CRDM cracking in France * was based on a value of 1.5 Lower values of b lead to higher probabilities of failure because they imply a wider scatter of initiation times so that the for the given observations of cracking, the first cracks appeared earlier in life and had more time to grow to failure The MRP value of 3 appears to not be representative

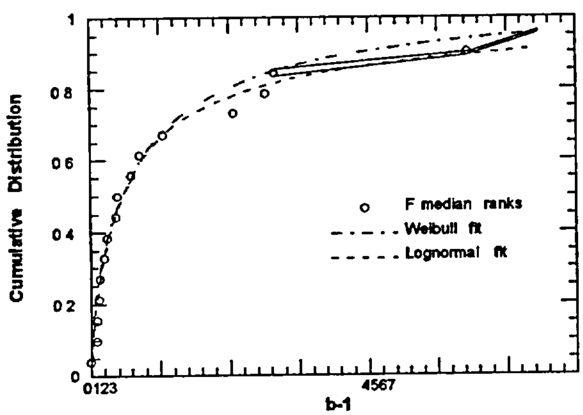

Figure 4
Distribution of the Weibull slope b for cracking of steam generator tubes. By expressing the results in terms of b–1 the results can be fit by Weibull or lognormal distibutions

* Tenth Symposium on Environmental Degradation of Materials in Nuclear Power Systems—Water Reactors, Lake Tahoe, NV, August 5–9, 2001

Weibull Scale Parameters for Cracking of Alloy 600 CRDM Nozzles

For a given value of the slope b, the corresponding Weibull scale parameters can be calculated from the inspection results at each plant re is clearly a range of scale parameters observed for different plants Because only one observation is available scale parameter θ can be calculated from the observed failure fraction F at time T

$$\theta = T\left(\ln\frac{1}{1-F}\right)^{-\frac{1}{b}} \tag{5}$$

where the observed failure fraction is the median rank value, i e, the observed fraction multiplied by

$$\frac{i - 03}{n + 04} \tag{6}$$

where i is the rank order number and n the sample size (i=1, n=1 for this case) Table 1 shows the values θ for the different plants for values of b ranging from 1 to 5

Table 1 Values of the Weibull scale parameter based on inspection results at Oconee and ANO–1 for values of the Weibull slope b from 1–5

b	1	1 5	2	2.5	3	3 5	4	4 5	5
Oconee–3	157.3	80 4	57.5	47.0	41 1	37.3	34 7	32 8	31 4
Oconee–2	391 1	148 3	91 3	68 2	56 2	48 9	44 1	40 7	38 1
Oconee–1	2068 7	447.9	208 4	131.7	97 0	77.9	66 2	58 2	52 6
ANO–1	1871 7	405 3	188 6	119 2	87.7	70 5	59.9	52 7	47 6

To estimate the range of possible scale factors, it was assumed that for a given value of the Weibull slope the values of the scale parameter follow a lognormal distribution and the values from the four plants were used to estimate the lognormal parameters The results are summarized in Table 2 Although the data are from a limited sample of plants, the results for b=1 5 suggest that the variability in times to failure for different heats of Alloy 600 will be about a factor of 15 Scott working with a much larger database gets a factor of 20–30. A smaller sample would be expected to somewhat underestimate the variability

For comparison with inspection results it is useful to consider just the probability of initiating cracks in nozzles rather than failure as in Eq (1), since we expect to have a much larger database on initiated cracks rather than structural failures For a given set of Weibull parameters this is just given by the cumulative distribution F(t) from Eq (1) Because we know only the distribution of b and the corresponding scale parameters, a Monte Carlo analysis can be performed by choosing a value of b from the distribution given in Fig 4, then selecting a value of the scale parameter based on the distributions described by the values in Table 2 , For a specific plant instead of using distributions for the scale parameter, one would sample b and then determine the scale parameter for the plant rather than sampling from the distribution of scale parameters The expected fractions of nozzles that are expected to have *initiated* cracks in terms of EFPYs at 600° F are shown in Table 3 Arrhenius extrapolation can be used to extrapolate to other operating temperatures using an activation energy for initiation of 40–50 kcal/mole °C The results are given in terms of the median values and the 90/10 percentiles to avoid the large uncertainties associated with the tails of the distributions

Table 2 Mean and standard deviation for lognormal distributions of the Weibull scale parameter as a function of the assumed Weibull slope

b	Mean	Stan Dev
1	6 55	1 25
1 5	5 37	0 83
2	4 79	0.61
2 5	4 43	0 48
3	4 20	0 40
3 5	4 03	0 34
4	3 90	0 29
4 5	3 81	0 26
5	3 73	0 23

Table 3 Fraction of CRDM nozzles with cracks as a function of EFPY at 600° F

EFPY	Median	90th %tile	10th %tile
15	0 016	0 135	0 002
20	0 040	0 369	0 004
25	0 062	0 540	0 007

Weibull Scale Parameters for Cracking of Alloy 600 182 J Groove Welds

The cracks of greatest concern are circumferential cracks above the weld initiated on the OD, which grow in an environment that could be more aggressive than the primary coolant environment. The controlling step in the formation of these cracks is the formation of a crack in the Alloy 182 weld The statistics of this cracking appear to be different than the statistics of the nozzle cracking Such cracking occurred only in Oconee–3 and so only one data point is available to describe the distribution of the Weibull scale parameter. However, we also know that no such cracking was observed at the other Oconee plants or are ANO–1. These results can be used with a Maximum Likelihood argument to estimate the distribution of the Weibull scale parameter for the Alloy 182 cracking

We assume that the distribution of the Weibull scale parameter is again lognormal as in the case of the Alloy 600 nozzles We also assume that the variability in susceptibility of the Alloy 182 is similar to that of Alloy 600

The inspection results show that we have no above weld circumferential cracks in Oconee 1 and 2 and ANO–1 after 21, 21,3, and 19 EFPY of operations There were 2 such cracks in Oconee–3 after 21 EFPY. The Weibull scale parameter for Oconee–2 can be computed from the fraction failed and the operating time as a function of the assumed slope b For b=1 5, θ=260 4

The other inspection results can be used to give some information on the distribution of the shape parameter for Alloy 182 cracking If F_1, F_2, F_3, and F_4 are the corresponding probabilities of initiating such cracks, the likelihood function L for the observed results (3 plants with no failures and 1 plant with 2 failures) is then

$$L = (1 - F_1)^{69} (1 - F_2)^{69} (1 - F_3)^{69} \binom{69}{2} F_4^2 (1 - F_4)^{67} \quad (7)$$

The parameters of the lognormal distribution for the Weibull shape parameter (which determine F_1–F_4) are chosen to maximize L. Choosing the parameters for the lognormal distribution doesn't actually determine L, because one then samples from the distribution to determine F_i The calculation is done by taking a 1000 samples and then choosing the lognormal parameters to maximize the average value of ln (L) for 1000 samples. After the value that maximizes L is determined, one can estimate the uncertainty in the estimate by determining the change in the parameter that causes L to drop to half its value (recall that the standard deviation measures the half width of the normal distribution) The value of the log mean of the distribution and the more conservative one and two σ estimates are given in Table 4 along with the corresponding percentile rank of the observed value for Oconee-3

Table 4 Maximum likelihood estimate of log mean of the lognormal distribution for the Weibull shape parameter with an assumed log standard deviation 0 8 and Weibull slope of 1.5

	Log mean of distribution for θ	%tile rank of Oconee-3
ML Estimate	6 89	0 04
-1 σ	6 30	0.17
-2 σ	5.74	0 39

The maximum likelihood estimate suggests that Oconee-3 is a "worst case" plant on the tail of the distribution and OD initiated circumferential cracking would be much less likely at a "typical" plant. The uncertainties are large, however, and the percentile rank for the two σ value is close to the median. Additional inspection results could reduce the uncertainties

The analysis can be extended to consider other values for the Weibull slope, but for the present the analysis is limited to just the case when b=1.5

Probability of Failure Using the Weibull Distributions for Alloy 600 and Alloy 182 cracking

Once the probability of initiation is characterized by choosing a value for the Weibull slope and scale parameter, and the conditional probability of failure is determined by selecting one of the curves in Fig 3, the probability of failure can be obtained from Eq (1) The evaluation of Eq (1) must be done numerically A simple Excel macro was written which does this using a Romberg integration scheme

The proposed calculations assume that the probability of initiation and the conditional probability of failure are independent. This is probably not true It is likely that materials more prone to initiation also have higher growth rates and hence shorter times to failure

However, it seems likely based on results for Alloy 600 that the correlation is weak enough that the assumption of independence does not significantly distort the results

The results are normalized in terms of effective full power years (EFPYs) at 600°F. Because the activation energies are different for initiation and crack growth, Arrhenius extrapolation cannot strictly be used extrapolate to other operating temperatures, but using the lower value associated with crack growth rates (33 kcal/mole °C) should give conservative results

Probability of Failure Assuming All Alloy 600 Cracks are Circumferential

The initiation of cracking in the Alloy 600 nozzles is described by the distribution for b given in Fig 4 and the corresponding distributions for the scale parameters described by the values in Table 2 The conditional failure of probability given that a crack has initiated is determined by selecting one of the distributions shown in Fig 3 Equation (1) is then integrated numerically and the probability of failure determined from Eq (2) This can be done either deterministically by choosing a single value of b and θ or as a Monte Carlo calculation sampling from the distributions for b and θ No credit is taken in the calculations for detection of an initiated crack before failure. The results of the calculations are summarized in Table 5 For a given time T, a range of probabilities of failure are calculated The table shows the median, 90th, and 10th percentiles Deterministic calculations for Oconee-3 are shown in Table 6 The probabilities appear unrealistically high even if the time to failure after initiation of the crack is increased by 3 years (such a change of course could have a substantial impact on the chances of detecting a crack before failure) This suggests that the limiting process is not the initiation of cracks in the nozzles

Table 5 Estimate s of the probability of failure of at least one CRDM nozzle in a head with 69 penetrations for the whole population of plants based on EFPY at 600°F

	$P(t_f < T)$ Instantaneous growth 165°			$P(t_f < T)$ 36 months to 165°		
T (years)	median	90%tile	10%tile	median	90%tile	10%tile
15	0 497	0 993	0 092	0 489	0 989	0 097
20	0 836	1 000	0 229	0 803	1 000	0 239
25	0.958	1 000	0 354	0 951	1 000	0 367

Table 6 Estimates of the probability of failure of at least one CRDM nozzle in Oconee-3 based on EFPY at 600°F

	$P(t_f < T)$ Instantaneous growth 165°		$P(t_f < T)$ 36 months to 165°	
T (years)	b=1.5	b=3	b=1.5	b=3
5	0 258	0 024	0 003	0 000
10	0 810	0 332	0 429	0 122
15	0 977	0 808	0 909	0 444
17 5	0 993	0 945	0 970	0 766
20	0 998	0 990	0 991	0 925
22 5	1.000	0 999	0 998	0 985
25	1.000	1 000	0 999	0 998

Probability of Failure Assuming Limiting Process is Cracking of Alloy 182 J Groove Weld

The initiation of cracking in the Alloy 182 welds is given in terms of a lognormal distribution for the Weibull shape parameter θ with log mean values as given in Table 4 for a Weibull slope of 1.5 For Oconee-3 the observed value of θ is 250 4 with b = 1 5. Estimates of the probability of failure for Oconee-3 are shown in Table 7. The probabilities are lower than the corresponding case when all Alloy 600 cracks were considered to be circumferential, but still fairly high Lengthening the conditional time to failure by 36 months has only a small effect on the probability of failure, but it would make a more significant difference if credit for inspection and early detection of circumferential cracking were included in the analysis.

The probability of failure of a "typical", i.e , median, plant is given in Table 8 The distribution of susceptibility was determined through the Maximum Likelihood analysis described previously. Results are given both for the median value determined by the analysis (denoted as MLE in Table 8) and for the more conservative estimate of the median based on the estimated uncertainty in the Maximum Likelihood analysis (denoted as 2 σ in Table 8) Again the inclusion of extra 36 months in the conditional time to failure does not have a large impact on the estimated probability of failure

Table 7 Estimates of the probability of failure of at least one CRDM nozzle in Oconee-3 based on EFPY at 600°F based on Alloy 182 J groove weld cracking

T (years)	$P(t_f < T)$ Instantaneous growth 165°	$P(t_f < T)$ 36 months to 165°
5	0 05	0 00
10	0 27	0 10
15	0 49	0 41
17 5	0 60	0 44
20	0 69	0 58
22.5	0 77	0 67
25	0 83	0 75

Table 8 Estimates of the probability of failure of at least one CRDM nozzle in a "typical" plant based on EFPY at 600°F based on Alloy 182 J groove weld cracking

	$P(t_f < T)$ Instantaneous growth 165°		$P(t_f < T)$ 36 months to 165°	
Time	MLE	2 σ	MLE	2 σ
5	0 01	0 04	0 00	0 00
10	0 04	0 21	0 01	0 07
15	0 08	0 39	0 06	0 31
17 5	0 11	0 47	0 09	0 43
20	0 13	0 57	0 12	0 44
22 5	0 15	0 65	0 15	0 56
25	0 18	0 72	0 18	0 63

References

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