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9/28

To: N. Chokshi, USNRC

From: W. J. Shack

Subject: Estimates of the probability of failure of CRDM nozzles

Attached is an assessment of the probability of failure of CRDM nozzles. The model assumes that the probability of initiating a crack can be estimated by the Weibull probability function. The Weibull parameters are determined by comparison with the data for the Oconee and ANO-1 units and data for the PWSCC of steam generator tubes. Any cracks that initiate are conservatively assumed to be circumferential. An initiated crack is conservatively 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 basic results are summarized in the table below in terms of the probability that the time to failure, t_f, will be less than the operating time T. The results are very sensitive to the values assumed for the Weibull parameters. Clearly the bounding 5th%tile values are very conservative since they imply we should have seen failures by this time. The mean or most probable values suggest that the probability of a failure over a 4 month time span for a 10 year plant is about 0.03. If only a fraction of the cracks are assumed to be circumferential, this number would be further reduced. The results for Oconee-3, the most susceptible plant for which inspection data are available, are also high, but this must be considered in terms of the conservatism in the analysis.

The results are normalized in terms of effective full power years at 600°F. Because the activation energies are different for initiation and crack growth, Arrhenius extrapolation cannot 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 of a CRDM nozzle in a head with 64 penetrations

T (years)	$P(t_f < T)$ Oconee-3	$P(t_f < T)$ median	$P(t_f < T)$ 5th%tile
2	3.34E-05	2.22e-05	0.087
4	0.005	0.001	0.553
6	0.035	0.009	0.860
8	0.120	0.030	0.963
10	0.276	0.074	0.991
12	0.485	0.146	0.998
14	0.696	0.247	0.999
16	0.858	0.371	1.000
18	0.950	0.508	1.000
20	0.987	0.643	1.000
25	1.000	0.893	1.000
30	1.000	0.984	1.000
40	1.000	1.000	1.000
50	1.000	1.000	1.000

No inspection through year 20 →

B-19

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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, $P_c(t_f < T-t)$

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

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

$$P_n = 1-(1-P)^n \qquad (2)$$

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

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

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 in Fig. 3 with a log mean of 3.55 and a log standard deviation of 0.58

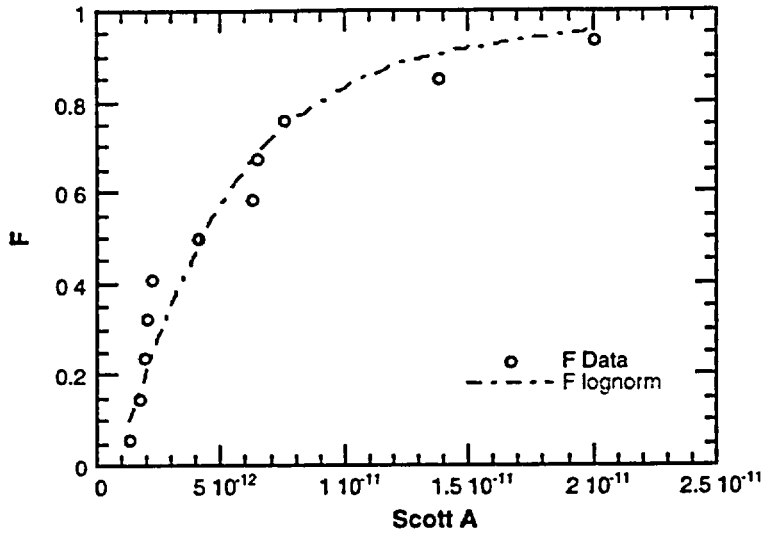

Figure 1.
Cumulative distribution of the parameter A in the Scott CGR correlation for heats of nozzle materials studied by Foster et al.[1], Cassagne et al.[2], and Gómez Briceño and Lapeña[5]

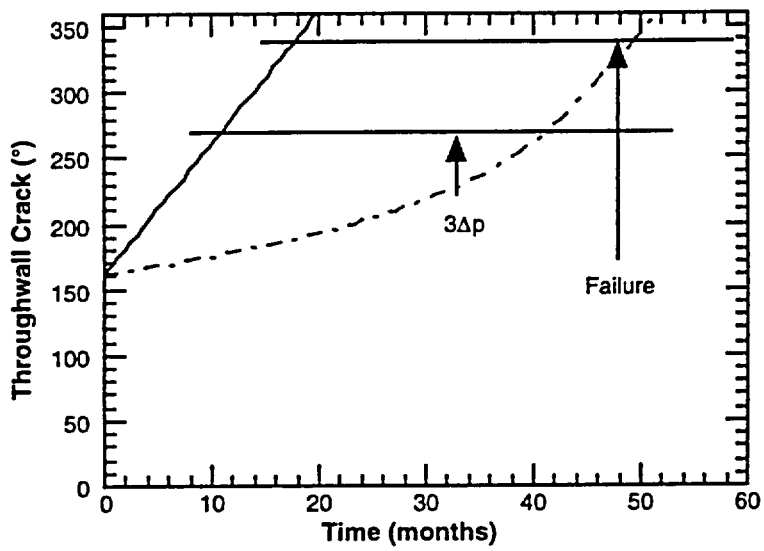

Figure 2.
Growth of a throughwall crack under pressure loads

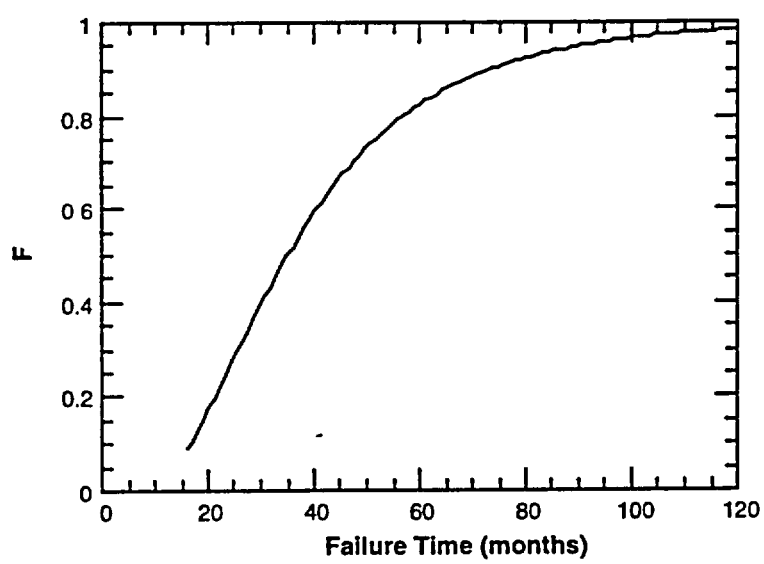

Figure 3.
Distribution of failure times for the growth of a 165° throughwall crack under pressure loads

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

$$p(t) = \frac{b}{\theta}\left(\frac{x}{\theta}\right)^b \exp\left[-\left(\frac{x}{\theta}\right)^b\right]$$
$$F(t) = 1 - \exp\left[-\left(\frac{x}{\theta}\right)^b\right] \qquad (4)$$

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. A value of 3 is indeed typical for PWSCC, but 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 7 with the weighted average of the laboratory data about 2.8. 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. 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

For a given value of the slope b, there is clearly a range of scale parameters observed for different plants. 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.

Once a value is chosen for the Weibull slope and scale parameter, 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 the trapezoidal rule for integrals.

Ideally a Monte Carlo analysis could be performed by choosing a value of b, then selecting a value of the scale parameter based on the distributions described by the values in Table 2, and then performing the numerical integration of Eq. (1) and the evaluation of Eq. (2). This would given a distribution of probabilities of failure at each time T. An appropriate distribution for b is might be a uniform distribution from b=1 to 4.

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

Since such an effort would require additional time, a few selected cases were analyzed to get some feel for what the model suggests about the probabilities of failure. Three cases are presented here. Two of the cases use the "typical" Weibull slope of 3. The scale parameter in one case corresponds to the actual results at Oconee–3, the "worst–case" plant, in the other it corresponds to the median of the lognormal distribution for θ. Thus might be considered the most probable case. The last case is the conservative bounding case with b=1 and the 5th percentile value of the corresponding θ. The results of these calculation for a collection of 64 nozzles are summarized in Table 3. The 5th%tile bounding results are very conservative. Any meaningful estimate of the distribution of probabilities of failure will require Monte Carlo analysis, although the results for the Oconee–3 and median cases are already sufficiently high that it seems likely that values will be pretty high after 10 EFPY. The corresponding results for a *single* nozzle are given in Table 4.

Table 3 Estimates of the probability of failure of at least one CRDM nozzle in a head with 64 penetrations

T (years)	$P(t_f < T)$ Oconee–3	$P(t_f < T)$ median	$P(t_f < T)$ 5th%tile
2	3.34E-05	2.22e-05	0.087
4	0.005	0.001	0.553
6	0.035	0.009	0.860
8	0.120	0.030	0.963
10	0.276	0.074	0.991
12	0.485	0.146	0.998
14	0.696	0.247	0.999
16	0.858	0.371	1.000
18	0.950	0.508	1.000
20	0.987	0.643	1.000
25	1.000	0.893	1.000
30	1.000	0.984	1.000
40	1.000	1.000	1.000
50	1.000	1.000	1.000

Table 4 Estimates of the probability of failure of an individual CRDM nozzle

T (years)	$P(t_f < T)$ Oconee–3	$P(t_f < T)$ median	$P(t_f < T)$ 5th%tile
2	5.21E-07	1.23e-07	0.001
4	7.08E-05	1.66e-05	0.012
6	5.50e-04	1.29e-04	0.030
8	0.002	4.69e-04	0.050
10	0.005	0.001	0.071
12	0.010	0.002	0.091
14	0.018	0.004	0.111
16	0.030	0.007	0.131
18	0.046	0.011	0.150
20	0.066	0.016	0.169
25	0.137	0.034	0.214
30	0.239	0.062	0.257
40	0.505	0.153	0.336
50	0.764	0.290	0.406

The failure probability as a function of time for Oconee–3 and the "typical" vessel head are shown in Fig. 4. For Oconee–3 the curve is already very steep at 10 EFPY. For a more typical plant the curve would not be expected to get steep before 10–12 EFPY.

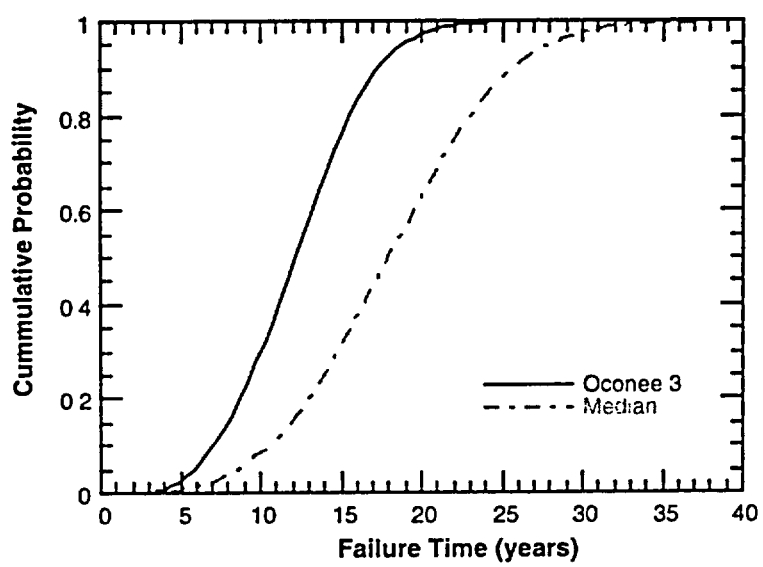

Figure 4.
Probability of failure of a nozzle in the vessel head

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