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FAILURE PROBABILITY ESTIMATE OF TYPE 304 STAINLESS STEEL PIPING (U)

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ABSTRACT

The primary source of in-service degradation of the SRS production reactor process water piping is intergranular stress corrosion cracking (IGSCC). IGSCC has occurred in a limited number of weld heat affected zones, areas known to be susceptible to IGSCC. A model has been developed to combine crack growth rates, crack size distributions, in-service examination reliability estimates and other considerations to estimate the pipe large-break frequency. This frequency estimates the probability that an IGSCC crack will initiate, escape detection by ultrasonic (UT) examination, and grow to instability prior to extending through-wall and being detected by the sensitive leak detection system. These events are combined as the product of four factors:

1. The probability that a given weld heat affected zone contains IGSCC.
2. The conditional probability, given the presence of IGSCC, that the cracking will escape detection during UT examination.
3. The conditional probability, given a crack escapes detection by UT, that it will not grow through-wall and be detected by leakage.
4. The conditional probability, given a crack is not detected by leakage, that it grows to instability prior to the next UT exam.

These four factors estimate the occurrence of several conditions that must coexist in order for a crack to lead to a large break of the process water piping. When evaluated for the SRS production reactors, they produce an extremely low break frequency. The objective of this paper is to present the assumptions, methodology, results and conclusions of a probabilistic evaluation for the direct failure of the primary coolant piping resulting from normal operation and seismic loads. This evaluation was performed to support the ongoing PRA effort and to complement deterministic analyses addressing the credibility of a double-ended guillotine break.

INTRODUCTION

The Savannah River Site production reactors operate at low temperature and pressure, permitting the use of relatively thin-walled piping for the primary coolant system. The material of construction for the primary pressure boundary is Type 304 stainless steel. These reactors were built in the 1950's, and have undergone various modifications and upgrades since that time. The maximum rate loss-of-coolant accident (LOCA) for the Savannah River production reactors is the hypothetical double-ended guillotine break (DEGB) of a large process water pipe [1]. These reactors operate at low temperature and pressure, permitting the use of relatively thin-walled piping for the primary coolant system. The material of construction for the primary pressure boundary is Type 304 stainless steel. Due to low applied stresses and the inherent toughness and ductility of the piping material, the probability of a DEGB is extremely low. The objective of this paper is to present the results and conclusions of a probabilistic evaluation for the direct failure of the primary coolant piping resulting from normal operation and seismic loads. The failure by indirect (seismic) means is addressed in a separate paper. This evaluation supports the ongoing PRA effort and to complements deterministic analyses addressing the credibility of a double-ended guillotine break.

DISCUSSION

The SRS production reactor process water piping has undergone limited degradation from intergranular stress corrosion cracking (IGSCC). IGSCC has occurred in a limited number of weld heat affected zones, areas susceptible to IGSCC. This evaluation combines crack growth rates, crack size distributions, in-service examination reliability estimates, and other considerations to estimate the pipe large break frequency. This frequency, P_{Break}, estimates the probability that an IGSCC crack will initiate, escape detection by ultrasonic (UT) examination, and grow to instability prior to extending through-wall and being detected by the sensitive leak detection system. The likelihood of these events leading to a large break is expressed as the product of four factors:

1. P_C: The probability that a given weld heat affected zone contains IGSCC.
2. P_{CND}: The conditional probability, given the presence of IGSCC, that the cracking will escape detection during UT examination.
3. P_{LND}: The conditional probability, given a crack escapes detection by UT, that it will not grow through-wall and be detected by leak age.
4. P_{CG}: The conditional probability, given a crack is not detected by leakage, that it grows to instability prior to the next UT exam.

These four elements describe the several conditions which would need to coexist in order for a crack to lead to a large break of the process water piping. Each is developed and discussed separately below.

WELD CRACKING PROBABILITY, P_C

Experience in the commercial nuclear industry shows that 6 to 8% of sensitized stainless weldments experience IGSCC. In the large process water piping, 48 weldments have been identified as containing IGSCC since UT inspection began in 1984 [2]. This same piping in the three operating reactors contains a total of 781 circumferential welds which were inspected. This gives an incidence rate of 6%. Hence the probability that a weldment contains IGSCC is taken as 0.08 which envelopes both SRS and commercial reactor experience.

CRACK NON-DETECTION PROBABILITY, P_{CND}

The crack non-detection probability characterizes the conditional probability, given the existence of IGSCC in a weldment, that the crack is not detected by UT. The process water system piping has been subject to periodic ultrasonic (UT) examination since 1984. The UT inspectors who have performed these examinations have been certified for IGSCC detection by the Electric Power Research Institute (EPRI).

The reliability of detecting IGSCC has been characterized [3]. Figure 1, reproduced from reference [3], identifies that a relatively short crack, 50% through-wall, has approximately 0.1 probability of non-detection. As a crack grows in length or in depth, this probability decreases. This value is taken from the curve labeled "good" in Figure 1, based on the qualifications of the UT operators used at SRS. Based on these data, the crack non-detection probability is taken as 0.1 for weldments that receive UT examination. There also exist several

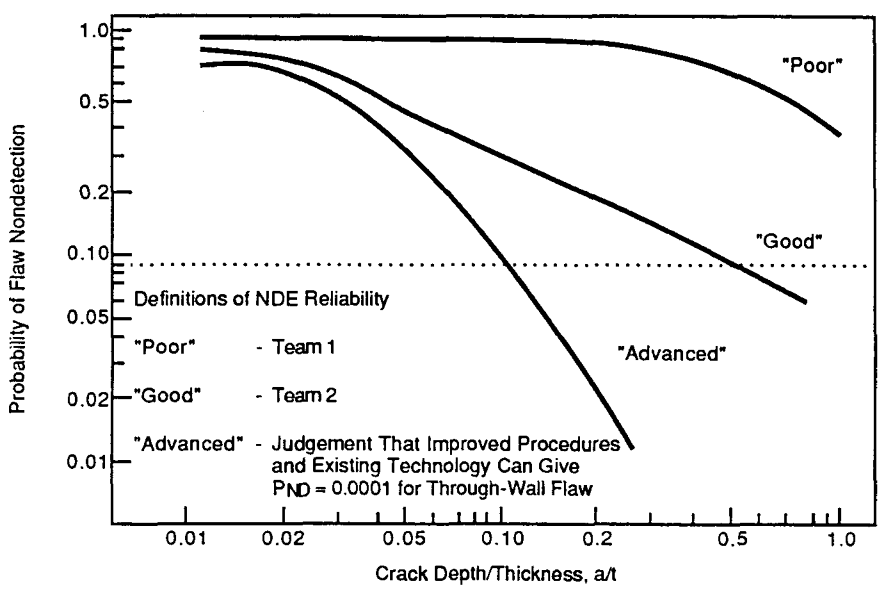

FIGURE 1. Detection of Intergranular Stress Corrosion Cracking in 10-Inch Stainless Steel Pipe (from reference 3)

welds that are not accessible for external inspection. A pipe crawler is being developed to inspect these weldments. Until the pipe crawler is available, the crack non-detection probability for these weldments is taken as 1.0.

LEAKAGE NON-DETECTION PROBABILITY, P_{LND}

The conditional probability, given a crack escapes detection by UT, that it will not grow through-wall and be detected by leakage is assessed in this section. The SRS reactors have experienced a number of cracks over the past 35 years. Before the periodic UT examination of the piping was begun in 1984, most of these cracks were detected by their leakage as they grew through-wall. A total of 16 such cracks have been detected in the main coolant loop (large piping and effluent nozzles) by the various leak detection systems. These systems include stack tritium monitors, closed circuit television surveillance, and visual examinations. Thus, no large breaks have occurred while 16 opportunities for a large break were averted as a result of the leak detection capabilities. A statistical treatment gives the likelihood of a large break that is not prevented by the leak detection systems:

$$P_{LND} = 1-(Prob_0)^{1/m} = 1-(0.5)^{1/16} = 4.2 \times 10^{-2} \quad \text{(eq 1)}$$

Here, the probability of having zero large breaks is 0.5, representing a statistical best estimate. Due to the small sample size, represented by the relatively small number of cracks in the piping, this statistical treatment produces an estimate much lower than would be expected from other approaches. Work is in progress to develop a less conservative estimate based on an evaluation of the leak detection system reliability. When complete, this factor will be revised accordingly.

CRACK GROWTH PROBABILITY, P_{CG}

The fourth factor estimates the conditional probability, given a crack that escapes detection by UT and leak detection, that the crack grows to instability prior to the next UT exam. The likelihood of a crack also escaping detection during the subsequent examination is modeled by a second application of the leak non-detection factor. The crack growth probability is based on three considerations: the crack size distribution, crack growth rate, and the local stresses in the pipe.

Crack Size Distribution

The crack size distribution is based on UT measurements on SRS piping. The cumulative crack probability as a function of crack length is shown in Figure 2, along with an exponential fit. This fit is expressed by the equation [4]:

$$P(L) = (1/\mu)\exp(-L/2\pi R\, \mu) \quad \text{(eq 2)}$$

where L is the circumferential crack length, m is a parameter fit to the data (a best estimate value of 0.05 is shown in Figure 2) and R is the mean pipe radius. To develop the probability that a crack exists with a length between two specific values, this equation is integrated between those two values to obtain:

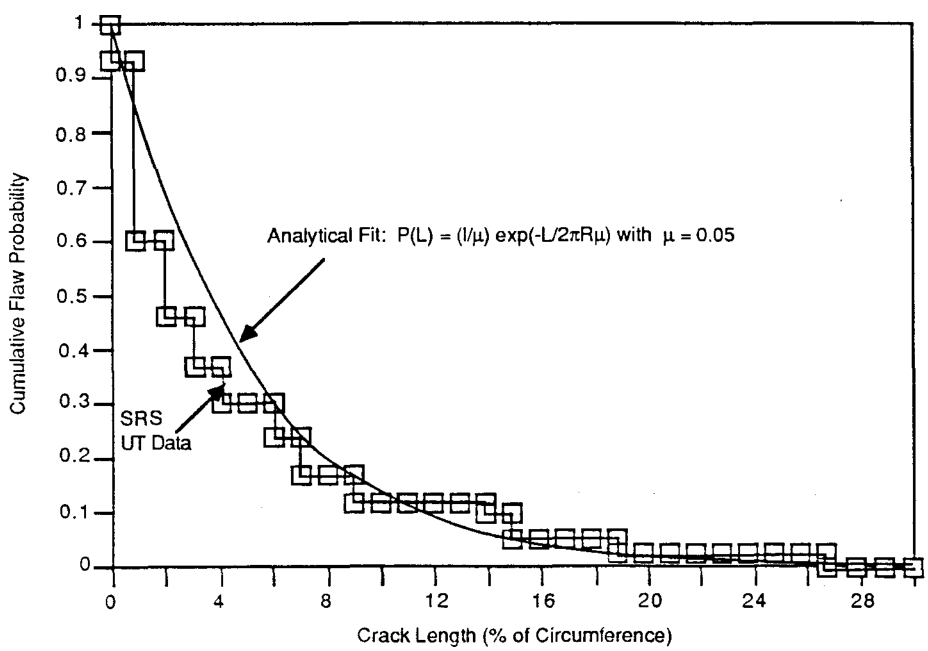

FIGURE 2. SRS Pipe Crack Probability UT-Detected with Exponential Fit

$$P_{CG}(L_1 \leq L \leq L_2) = [\exp(-L_1/2\pi R\mu) - \exp(-L_2/2\pi R\mu)]/[1-\exp(-1/\mu)] \quad \text{(eq 3)}$$

Crack Growth Rate

A reasonable crack growth rate is obtained from laboratory test data [5]. Growth rate tests indicate steady state crack tip extension rates of 10^{-6} inch/hour or less at prototypic conditions. The introduction of transients (temperature, load), such as might be produced by startup/shutdown cycles and other reactor evolutions, produces effective crack tip extension rates up to 10^{-4} inch/hour; however, this maximum rate is not indicative of a long-term average growth rate in the piping. Additionally, variations in stresses and microstructure favorable for such rates are generally localized. Once a crack grew beyond such local regions, the growth rate would decrease. Therefore, a long-term average crack tip extension rate of 10^{-5} inch/hour is used.

Since a crack can grow from both ends, the crack tip extension rate is doubled to obtain the crack growth rate. Further, to account for the possibility of multiple cracks in a single weld heat-affected zone, it is assumed that two cracks exist that combine just before reaching instability. Hence, the total crack growth rate within the heat affected zone is 4×10^{-5} inch/hour, or approximately 0.4 inch/year.

Local Stresses

The local stresses in the pipe determine the length at which a crack reaches instability (L_I). For purposes of calculating the instability length, it is conservatively assumed that the crack is through-wall along its entire length. Since the operating history shows that no pipes have ever broken, it is certain that no existing crack has yet reached instability. Also, from the crack growth rate developed above and knowledge of the time before the next UT examination, a second crack length (L_2) is calculated such that a crack shorter than L_2 will not grow to instability prior to the next examination. Therefore, the crack growth probability is the probability that an existing crack has a length shorter than L_1 but longer than L_2.

The instability length for a given pipe section varies depending on pipe dimensions and local stresses. All instability lengths are greater than or equal to 58% of the pipe circumference. Hence, if one considered a 16-inch-diameter pipe section, the instability length would be 28.2 inches (using the mean radius of 7.75 inches). Future work may survey all local stresses to take credit for pipe sections in which the instability length is greater than 58% of the circumference.

The in-service inspection plan for the SRS reactors process water system calls for UT examination of pipe weldments every five years. During the interval between inspections, therefore, a crack would have the opportunity to grow (0.4 inch/year) x (5 year) = 2.0 inches. Hence, the crack growth probability over a 5 year interval is calculated from equation 3, using $L_I = 26.2$ inches and $L_2 = 28.2$ inches. The corresponding average value per year is obtained by dividing this result by 5. This procedure gives a crack growth probability of 2.4×10^{-6} per year. If a weld were not inspected for a period of 10 years, the corresponding average crack growth probability over that period would be 3.9×10^{-6} per year.

For welds that are inspected every 5 years, a crack growth probability for a longer period can still be calculated. The crack growth probability for a second 5-year period would be combined with the crack non-detection probability a second time. The crack growth probability for a second 5-year period equals the crack growth probability for a 10-year period minus the crack growth probability for the first 5 years. This gives:

$$P_{CG}(\text{2nd 5 years}) = (3.9 \times 10^{-5} - 1.2 \times 10^{-5})/5 \text{ years} = 5.4 \times 10^{-6} \text{ per year}$$

Therefore, the average crack growth probability over a 10-year period for inspected weldments is:

$$P_{CG}(\text{10 years}) = P_{CG}(\text{1st 5 years} + P_{CG}(\text{2nd 5 years}) \times P_{CND} = 2.94 \times 10^{-6} \text{ per year}$$

Seismic Contribution

The instability length developed above is based on loads present during normal operation. A separate case to be considered is the addition of seismic loads. During an earthquake there is insufficient time to depend on crack identification by leak detection means. Therefore, the crack growth probability for the seismic case will be combined with a leak non-detection probability of unity. When the seismic loads are added to normal operation loads, the instability length decreases slightly. The corresponding crack growth probability must be multiplied by the earthquake probability. In practice, the instability length for each of a range of seismic loads is used in combination with the probability of that particular magnitude earthquake, and the results summed for a total seismic contribution to the crack growth probability. A parametric study (not yet published) shows that the seismic contribution equals 0.7% of the non-seismic contribution.

RESULTS

Two categories of weldment are considered. Most of the welds are accessible for UT examination and are examined every five years. A few welds have limited access: these include the weld attaching a flange lap to the pipe end and welds in piping that runs through concrete structures. Therefore, two cases are developed; the limited access welds, which currently receive no UT examination, and the accessible welds, which are examined every 5 years. The four factors developed above are combined to produce the total piping direct break frequency. These factors are summarized in Table 1.

These factors are combined as discussed above. The resulting non-seismic contribution is:

P_{Break}(non-seis.) = $(0.08)(4.2\text{x}10^{-2})(0.1)(2.94\text{x}10^{-6})$ = $9.9\text{x}10^{-10}$ per weld-year, accessible weldments.

P_{Break}(non-seis.) = $(0.08)(4.2\text{x}10^{-2})(1.0)(3.9\text{x}10^{-6})$ = $1.3\text{x}10^{-8}$ per weld-year, limited access weldments.

The corresponding seismic contribution is:

P_{Break}(seismic) = $(0.08)(0.1)(2.1\text{x}10^{-8})$ = $1.7\text{x}10^{-10}$ per weld-year, accessible weldments.

P_{Break}(seismic) = $(0.08)(1.0)(2.7\text{x}10^{-8})$ - $2.2\text{x}10^{-9}$ per weld-year, limited access weldments.

Combining these respective contributions, the total pipe direct break frequency is:

P_{Break}(total) = $1.2\text{x}10^{-9}$ per weld-year, accessible weldments.

P_{Break}(total) = $1.5\text{x}10^{-8}$ per weld-year, limited access weldments.

Multiplying these two frequencies by the number of welds in each category yields the total direct break frequency for each reactor of $1.8\text{x}10^{-6}$ per year, averaged over a period of 10 years. For further extrapolations into the future, this estimate would increase.

CONCLUSIONS

The direct failure frequency for the process water piping of the Savannah River production reactors has been conservatively estimated to be $1.8\text{x}10^{-6}$ per year. Several areas of further refinements have been identified. Additionally, work is underway to develop a pipe crawler to inspect the limited access weldments from the inside. Upon completion of crawler develoment and inspection of the limited access welds, further reductions in the failure frequency can be realized.

This work is part of a larger effort to characterize the integrity of the process water system and define the maximum credible LOCA for the Savannah River production reactors. This larger effort, combining this probabilistic work with deterministic analyses, has demonstrated that the hypothetical double-ended guillotine break is not a credible scenario. One long-term goal of this work is to define a maximum credible LOCA for use in accident analyses and the establishment of power limits.

REFERENCES

[1] DPSTA-100-1, "Safety Analysis of Savannah River Production Reactor Operation", coordinated by J. P. Church, revised September 1983.

[2] WSRC-RP-89-126, "Leak History Reactor Primary Coolant Systems', G. R. Caskey et al., April 1989.

[3] NUREG/CR-4469, Semi-Annual Report, Volumes 1-4, "Nondestructive Examination (NDE) Reliability for Inservice Inspection of Light Water Reactors", S. R. Doctor et al.

Table 1. Pipe Break Frequency Input Factors

Factor	Value	Special Notes
Weld cracking, P_C	0.08	Applies to all weldments
Crack non-detection, P_{CND}	0.1	Accessible weldments
	1.0	Limited access weldments
Leak non-detection, P_{LND}	$4.2\text{x}10^{-2}$	Applies to non-seismic contribution only
Crack growth, P_{CG}	$2.94\text{x}10^{-6}$	Per year avg., 10-year period, accessible weldments
	$3.9\text{x}10^{-6}$	Per year avg., 10-year period, limited access weldments
	$2.1\text{x}10^{-8}$	Seismic contribution, accessible weldments
	$2.7\text{x}10^{-8}$	Seismic contribution, limited access weldments

[4] DPST-88-468, "Reactor Materials Program Process Water Piping Direct Failure Probability", W. L. Daugherty, April 1988.

[5] GE-88-006, "Stress Corrosion and Fracture Assessment Program, Monthly Program Letter #35, Reporting Period Ending March 31, 1988", P. Aldred, General Electric Company, and GE-88-020, "Stress Corrosion and Fracture Assessment Program, Monthly Program Letter #40, Reporting Period Ending August 31, 19888", P. Aldred, General Electric Company.

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