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

by

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ABSTRACT

The large break frequency resulting from intergranular stress corrosion cracking in the main circulation piping of the Savannah River Site (SRS) production reactors has been estimated. Four factors are developed to describe the likelihood that a crack exists that is not identified by ultrasonic inspection and that grows to instability prior to becoming through-wall and being detected by the ensuing leakage. The estimated large break frequency is 3.4 x 10^{-8} per reactor year. This result compares favorably to similar estimates made for commercial boiling water reactors.

BACKGROUND

The SRS production reactors operate at low temperature and pressure, permitting the use of relatively thin-walled piping for the primary coolant system as compared to commercial reactors. 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 objective of this paper is to present the methodology and results of a probability evaluation for the direct failure of the primary coolant piping. This evaluation was performed to support the ongoing PRA effort and to complement analyses addressing the credibility of a Double-Ended-Guillotine Break (DEGB).

The primary source of in-service degradation of the SRS reactor primary coolant piping is Intergranular Stress Corrosion Cracking (IGSCC). Other potential degradation modes, such as fatigue or water hammer, are insignificant based on analyses and over 100 reactor-years of operating experience. The piping material (Type 304 stainless steel) retains toughness and ductility over the entire range of operating conditions. IGSCC has occurred in a limited number of weld-heat-affected zones, areas known to be susceptible to IGSCC. The evaluation of the piping failure frequency combines crack growth rate data, the crack size distribution, in-service examination reliability estimates and system leak detection capabilities to determine the likelihood of an IGSC crack growing to instability.

APPROACH

This frequency estimates the probability that an IGSC crack will initiate, escape detection by Ultrasonic Testing (UT), and grow to instability prior to extending through-wall and being detected by the sensitive leak detection system. The combined likelihood of these events is expressed by the combination of four factors:

- The probability that a given weld-heat-affected zone contains IGSCC (P_C);
- The conditional probability, given the presence of IGSCC, that the crack will escape detection during UT examination (P_{CND});
- The conditional probability, if a crack escapes detection by UT, that it will not grow through-wall and be detected by leakage (P_{LND}); and
- The conditional probability, if a crack is not detected by leakage, that it will grow to instability prior to the next UT exam (P_{CG}).

These four elements describe the conditions that need to coexist in order for a crack to lead to a large break of the primary coolant piping.

DISCUSSION

The four factors described are developed in this discussion. This development applies specifically to the main circulation loop of the primary coolant piping. The Heat-Affected Zones (HAZ) of circumferential welds were not solution annealed and are therefore susceptible to IGSCC. These HAZs are associated either with butt welds (joining two pipe sections) or with flanges (joining the flange face to the pipe stub). (Some flanges are forged without requiring a lap weld; however, it is conservatively assumed at this time that all flanges are of welded construction.) These two types of circumferential weld will be discussed.

Those circumferential welds that are accessible are examined by UT every five years in accordance with the current in-service inspection plan. Other welds have limited access and have not yet received volumetric inspection. These limited access welds include the flange lap welds and several butt welds in piping that runs through the concrete building structure and biological shielding.

Because the estimated failure frequency depends on the local stresses in the piping (through the crack growth factor P_{CG}), the failure frequency is location dependent. The primary coolant piping is divided into several sections depending on pipe size and location. The maximum stresses in each section are used for this analysis. The result is a failure frequency that is dependent upon weld type (accessible or limited access), pipe size, and location. The failure frequency for each combination of weld type, pipe size, and location is multiplied by the corresponding number of welds; and the results are summed over all combinations to obtain a failure frequency for the entire reactor primary coolant system.

In this paper, a point estimate of the pipe failure frequency is developed. This estimate should be considered a mean value. Additional work is needed to ascribe an uncertainty band to the result and will not be addressed herein.

Weld Cracking Probability (P_C)

The primary coolant systems of P, K, and L reactors contain 781 accessible circumferential welds. Ultrasonic examinations to date have identified that 48 of these welds contain IGSCC in their heat-affected zones. Additionally, ten cracks have been found in the piping prior to initiating a regular UT program. Five of these cracks were in limited access welds. Hence, IGSCC has occurred in 58 of 786 welds, or 7.4%. This SRS experience is bounded by a weld cracking probability of 0.08.

Boiling Water Reactors (BWR) have also experienced IGSCC in Type 304 stainless steel piping. While operating temperature and water chemistry are different from that of the SRS reactors, it is interesting to note that a similar incidence rate has been observed (6 to 8%).[1]

Crack Non-Detection Probability (P_{CND})

The UT inspectors are qualified for IGSCC detection by the EPRI. S. R. Doctor[2] characterizes the likelihood of crack detection for EPRI-qualified inspectors. Figure 1 (reproduced from reference 2) suggests that the non-detection probability for short, deep (>50 percent through-wall) cracks is 0.1. The curve labeled "good" is used based on SRS inspector qualifications.

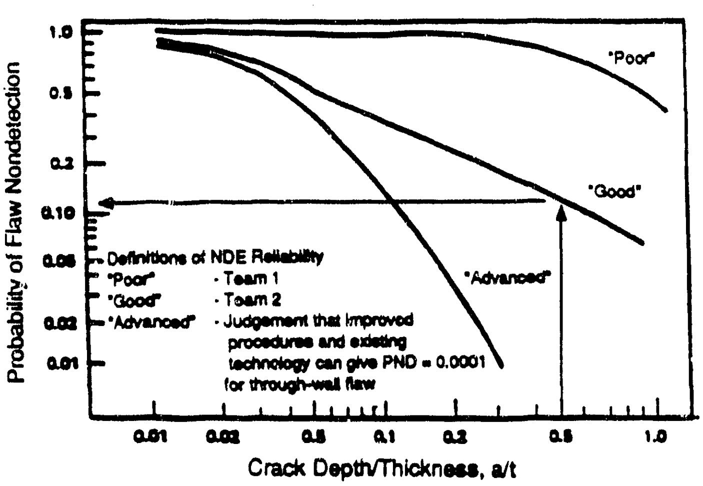

Figure 1. Detection Probability of IGSCC in Ten-Inch Stainless Steel Pipe (reproduced from reference 2)

The assumption of 50 percent throughwall cracks here is arbitrary. Tearing instability is not reached in the SRS piping until cracks exceed 50 percent of the circumference and 100 percent through-wall. Therefore, the possibility of the existence of shallower cracks with a lower detection reliability is offset by the need for such long cracks to approach instability. On this basis, a crack non-detection factor of 0.1 is considered conservative.

The crack non-detection probability is applicable to accessible welds that receive periodic inspection. The crack growth probability developed in equation (5) is based on a 15-year time period. Because UT is required every five years, there are three opportunities to discover a flaw in the 15-year period. Two inspections five years apart, even if performed by the same inspector, are sufficiently remote from each other to be considered independent. Assuming that UT is first performed in year one, P_{CND} is applied separately for each inspection to produce:

$$P_{CND}\,(avg) = [(5 * 0.1) + (5 * 0.01) + (5 * 0.001)] / 15 = 0.037 \quad . \tag{1}$$

Because the limited-access welds do not presently receive UT, a crack non-detection probability of unity is applied to them.

Leak Non-Detection Probability (P_{LND})

The SRS reactors utilize a very sensitive leak detection system. Because the heavy water coolant contains small amounts of tritium, a continuous sampling of the ventilation stream for tritium provides a rapid and sensitive indication of losses from the primary coolant system. The leak non-detection probability is comprised of two components: the likelihood that a crack grows through-wall before approaching instability length and the likelihood that the leak detection system will detect a leak from a through-wall crack.

Figure 2 shows that IGSC cracks in the SRS primary coolant piping preferentially tend to grow through-wall. The 58 welds identified earlier as containing IGSCC include a total of 109 "effective cracks". An effective crack length is plotted in Figure 2 where cracks sufficiently close together that they might combine within a 15-year period are treated as a single crack. The aspect ratio of each crack (out of a total population of 109 cracks) is preferentially through-wall.

While the concept of effective crack length is appropriate for characterizing the maximum length a crack might achieve, data from individual cracks is appropriate to describe the aspect ratio as cracks grow. After several cracks coalesce, the subsequent growth is that of a single crack. Single cracks in the SRS piping have a maximum aspect ratio (percent length divided by percent depth) of 0.49. Applying this aspect ratio as a bound for future growth of the effective crack data in Figure 2 gives a maximum projected crack length for a through-wall crack of 54 percent of the circumference. In comparison, the minimum instability length for a through-wall crack under normal operation plus seismic loads is 56 percent of the circumference. Hence a data base of 109 cracks contains zero cases of an aspect ratio such that instability would be reached before through-wall growth. Treating this data base

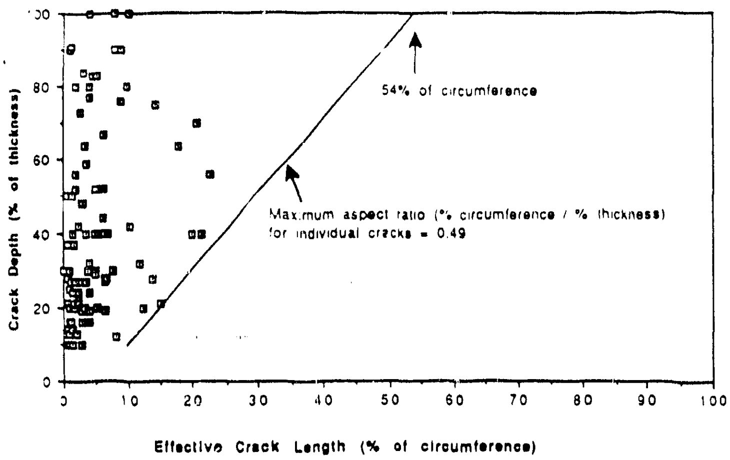

Figure 2. SRS IGSCC Shape Data

statistically provides a basis for predicting the probability that a crack will not grow through-wall before reaching instability.

$$P \text{ (not through-wall)} = 1 - (0.5)^{1/109} = 6.3 \times 10^{-3} \quad (2)$$

where the factor 0.5 is based on a nominal 50 percent confidence level.

The application of the bounding crack aspect ratio discussed before is conservative based on observed variations in the weld residual stress around the pipe circumference. Figure 3 (reproduced from reference 3) shows the pipe inner surface longitudinal residual stress near the weld line in a ten-inch pipe. Large variations exist in the residual stress with alternating regions of tension and compression. The relatively small operating stresses in SRS piping are not large enough to overcome large compressive residual stresses to initiate IGSCC. Therefore, any crack growing in a weld-heat-affected zone will reach a compressive stress region and stop before reaching a length of 50 percent of the circumference. Figure 4 shows a plot of the relative angular orientation of cracks in SRS piping. Two distinct regions, 180 degrees apart, are crack free. Each crack-free region extends about 55 degrees around the circumference (about 15 percent). This data provides evidence suggesting that variations in the residual stresses will limit the length growth of IGSC cracks.

The probability that a long through-wall crack is not detected by its leakage is based on a reliability study of the leak detection system. The presence of tritium in the heavy water moderator provides the basis for a very sensitive leak detection system. The reliability of the airborne tritium detectors and associated electronics, ductwork, and support systems has been characterized using standard fault tree techniques. A very high reliability for the leak detection system has been demonstrated, with a likelihood of 5×10^{-5} of not detecting a given leak of 50 pounds per day (0.004 gpm) within a 24-hour period.[4] This assessment included the possibility of human error caused by faulty maintainance or improper response to indicated leak rates. The dominant failure scenarios involve the failure of ductwork or of the main exhaust fans. Without these components, tritiated water vapor from the leak cannot reach the detectors.

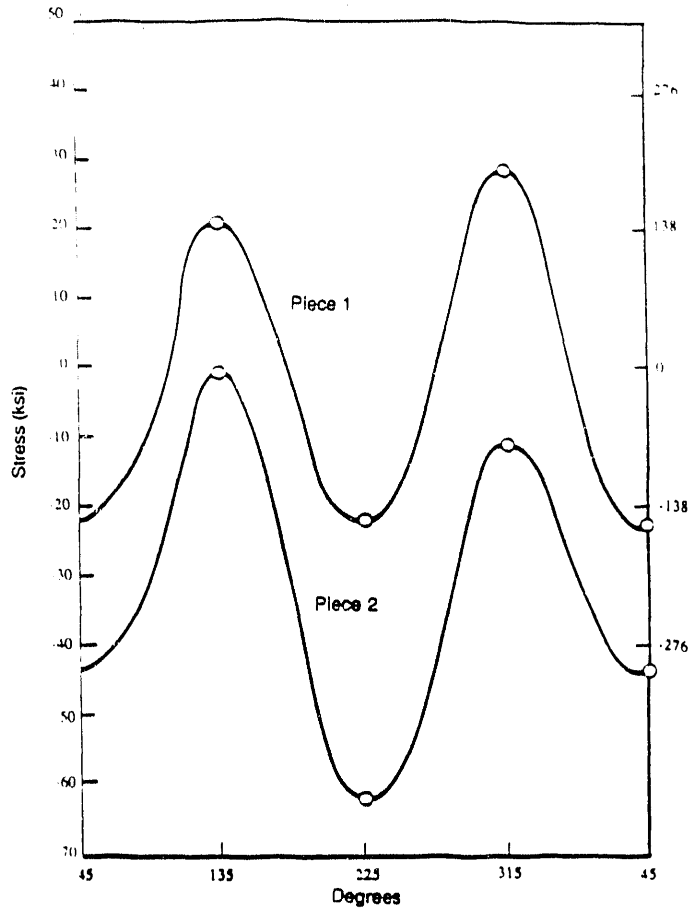

Figure 3. Ten-Inch Pipe Inside Surface Longitudinal Residual Stress Measurements Taken 0.1-Inch from Weld Line (reproduced from reference 3)

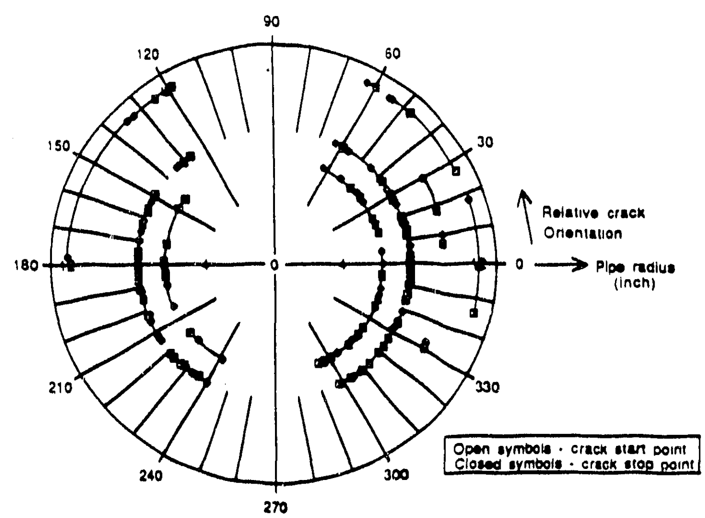

Figure 4. SRS Crack Angular Orientation Data

Combining the leak detection system reliability with the likelihood of a crack not growing through-wall gives a leak non-detection probability of:

$$P_{LND} = 1 - [(1 - 6.3 \times 10^{-3}) * (1 - 5 \times 10^{-5})] = 6.3 \times 10^{-3} \quad (3)$$

We see from this formulation that the probability of a crack not growing through-wall dominates the leak non-detection factor.

Crack Growth Probability (P_{CG})

The crack growth probability estimates the probability that a crack exists that can grow to instability within a given time period. This factor is developed from estimates of the crack growth rate, the crack size distribution, and the instability crack length for a given pipe size and location. In this paper, an example is provided of 16-inch diameter pipe with a calculated tearing instability length of 29.3 inches (60 percent of the circumference) and a time period of 15 years.

A nominal crack growth rate of 1×10^{-5} inch per hour (or 0.09 inch per year) is derived from UT sizing data and is consistent with literature data for SRS conditions and laboratory experimental data.[5] The crack size distribution data are plotted in Figure 5, which shows the number of cracked HAZs versus crack length. This crack-size distribution data is plotted from the same group of 109 effective cracks discussed previously. These cracks are distributed between one or both of the HAZs associated with the 58 weldments containing IGSCC, giving an average of 1.6 effective cracks per HAZ. Therefore, the crack growth rate for an assumed single unidentified large crack is taken as 1.6 times the nominal growth rate, or 0.14 inch per year.

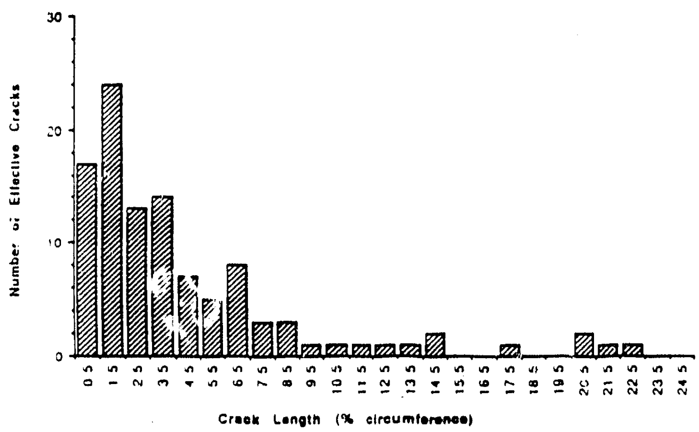

Figure 5. Crack Size Distribution for IGSCC in SRS Primary Coolant Piping

In Figure 6, the complementary cumulative distribution for the crack data is plotted. This distribution is fit with a mathematical model of the form:

$$P(\geq L) = 1 - [1 - \exp(-L/2\pi R\mu)] / [1 - \exp(-1/\mu)] \quad . \tag{4}$$

The parameter μ is selected to provide the best fit to the data. A value of 0.05 provides a good fit for longer cracks (greater than 12 percent of circumference) and will be used. The curve calculated for $\mu = 0.05$ is shown in Figure 6 along with the data.

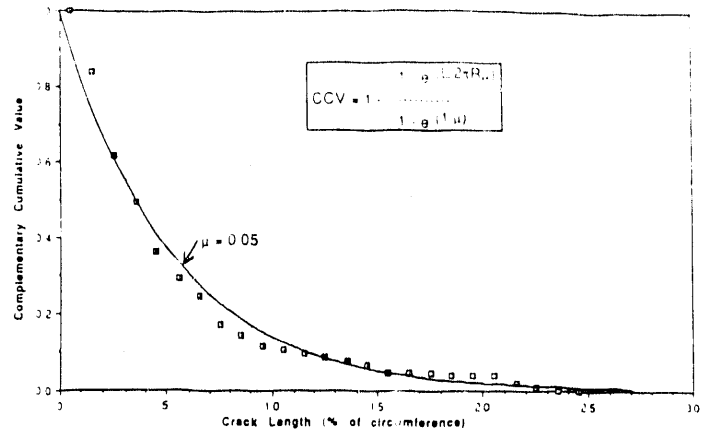

Figure 6. Complementary Cumulative Distribution for SRS Data

The probability that a crack exists that can grow to instability within a 15-year period equals the probability that a crack exists presently whose length is less than instability but long enough that it can grow to instability within 15 years. For an effective crack growth rate of 0.14 inch per year, the crack growth expected over a period of 15 years is 2.1 inches. Equation (5) is integrated from the instability length minus 2.1 inches (L_1) to the instability length (L_2) to get the crack growth probability:

$$P_{CG} = [\exp(-L_1/2\pi R\mu) - \exp(-L_2/2\pi R\mu)] / [1 - \exp(-1/\mu)] \tag{5}$$

where R equals mean pipe radius or 7.75 inches and μ equals crack size distribution parameter or 0.05. For this example, the crack growth probability equals 8.1×10^{-6} for the 15-year period or 5.4×10^{-7} per year. Since the instability length of 29.3 inches corresponds to normal operating loads only, this estimate of P_{CG} does not include seismic effects.

A separate calculation considers loads from normal operation plus earthquake and multiplies the result by the probability of earthquake occurrence. This result is added to the non-seismic contribution for the total crack growth probability. The seismic contribution is calculated stepwise for earthquakes up to 0.45g peak ground acceleration in increments of 0.1g. Hence, for the interval 0.15 to 0.25g, the instability length for normal operation plus 0.2g seismic loads is calculated. This length (27.1 inches) gives an estimate of $P_{CG} = 1.3 \times 10^{-6}$ per year. Multiplying this result by the probability of an earthquake between 0.15 and 0.25g, 3.6×10^{-4} gives the seismic contribution for this range of:

$$P_{CG}\,(0.15 \text{ to } 0.25g) = 1.3 \times 10^{-6} * 3.6 \times 10^{-4} = 4.7 \times 10^{-10} \text{ per year.} \tag{6}$$

Repeating this calculation for the other seismic ranges gives a total seismic contribution of 3.8×10^{-9} per year. No significant contribution is made for seismic levels above 0.45g because of the extremely low probability of occurrence of such earthquakes. However, no credit is taken for leak detection because of the short duration of an earthquake. Therefore, the leak non-detection factor is not combined with the seismic crack growth probability.

Repeating this procedure for each pipe size, location, and type and summing the results for all welds in the main primary coolant system piping gives a total break frequency of 3.4×10^{-8} per reactor year.

COMPARISON TO COMMERCIAL INDUSTRY

Probabilistic evaluations of BWR reactor piping failure rates have been performed recently.[6,7] Since BWRs have experienced a similar incidence of IGSCC, comparison to the SRS system is appropriate. Figure 7 (reproduced from reference 6) gives the proportion of leaks versus plant age for intermediate size piping in commercial reactors. The leak incidence is used as a point of initial comparison because both SRS reactors and BWRs have experienced leaks, while neither has experienced a sudden rupture. In 30 years of reactor operation at SRS, approximately one percent of the large piping circumferential welds have developed a leak. By comparison, this same percentage is seen in BWRs with an age of 12 years. This is indicative that the conditions of the SRS reactors are less severe than those of commercial reactors.

The cumulative DEGB probability for BWRs is shown in Figure 8 (reproduced from reference 6). The methodology used to develop this probability is compared to that of this paper by adjusting the results to SRS conditions. Assuming that the DEGB frequency is less at SRS than in BWRs in the same manner that the leak frequency was observed to be less, then the probability of such a break in the next 15 years corresponds to the region between 12 and 18 years in Figure 8. The estimated break frequency for this time period is about

$$(1.5 \times 10^{-2} - 1.2 \times 10^{-2}) / (50 \text{ welds} * 15 \text{ years}) = 4 \times 10^{-6} \text{ per weld-year.}$$

This estimate does not include any credit for in-service inspection or the sensitive SRS leak detection system. Multiplying by these two factors (3.7×10^{-2} and 6.3×10^{-3}, respectively) reduces this break frequency to about 1×10^{-9} per weld year or about 3×10^{-7} per reactor year. The estimate derived from calculations for 304SS BWR piping is somewhat higher than that developed in this paper for SRS piping, illustrating that the relatively mild conditions of the SRS reactors (low temperature and pressure) lead to a less degrading environment than is present in BWRs.

An indication of the overall conservatism of the model in reference 6 is seen in a comparison of the results for 316NG stainless steel. While this material is not used at SRS, other estimates of the DEGB frequency in BWRs have been made for 316NG piping. Figure 8 shows a cumulative DEGB probability of 1.6×10^{-3} per recirculation loop over a 40-year lifetime. Applying the same factors for in-service inspection and leak detection leads to a DEGB probability of about 8×10^{-7} over a 40-year period for two recirculation loops per reactor. In contrast, a separate study estimated a much more optimistic DEGB probability for a 316NG BWR recirculation system of 1.5×10^{-10} over a 40-year lifetime.[7]

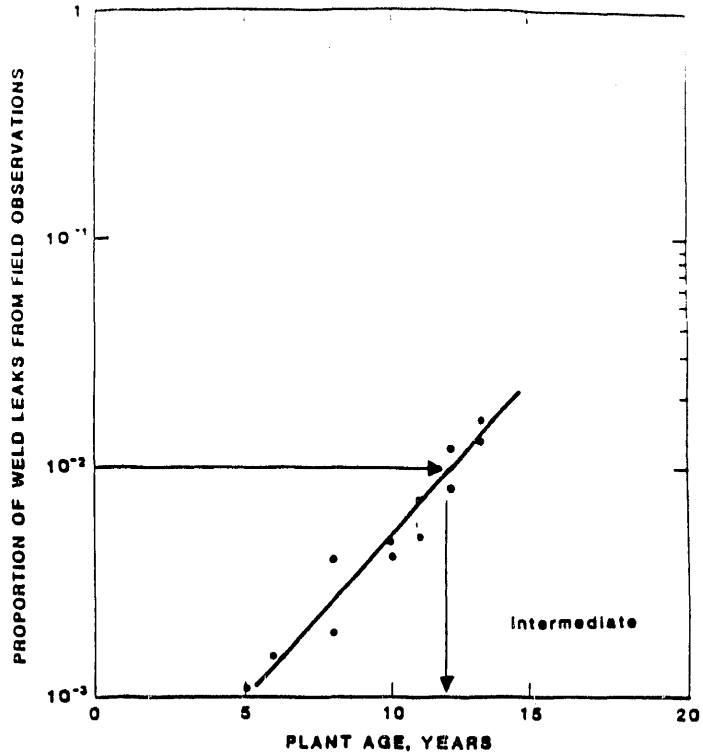

Figure 7. Proportion of Welds With Leaks as a Function of Plant Age for Field Observations for Pipes With Outside Diameters Between 10 and 20 Inches (reproduced from reference 6)

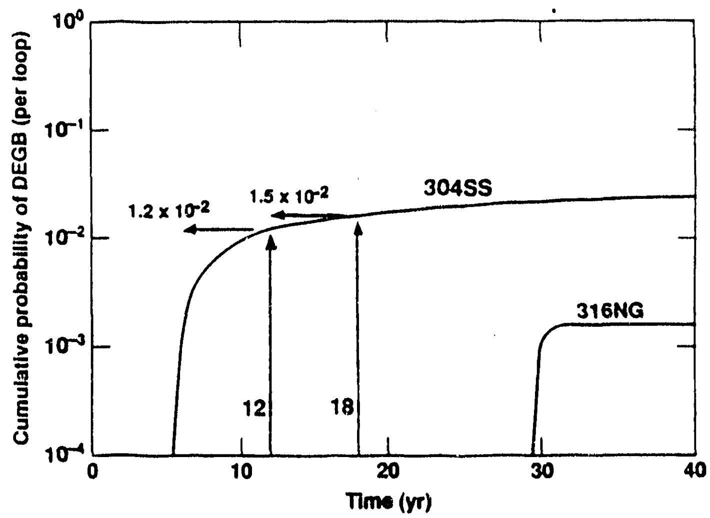

Figure 8. Cumulative System Probability of DEGB for One Pilot Plant Recirculation Loop of the Existing Configuration (reproduced from reference 6)

All of these estimates demonstrate a break frequency much less than 1×10^{-6} per reactor year that is identified as the goal for commercial reactor piping systems applying leak-before-break to eliminate the dynamic effects of a postulated pipe break.[8,9]

CONCLUSIONS

The estimated large break frequency for the main primary coolant piping of the SRS production reactors is 3.4×10^{-8} per reactor year. This estimate is averaged over 15 years of operation and would vary somewhat for different time periods. At the present, only this point estimate has been made. The development of uncertainties will be the subject of future work. This estimate compares favorably with the guideline of 1×10^{-6} per reactor year established by the NRC in support of the leak-before-break demonstration for commercial nuclear reactors. This frequency will be used in the probability risk assessment for the SRS reactors and as a complement to leak-before-break studies of the SRS process water piping system.

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REFERENCES

1. H. S. MEHTA,"An Estimate of Annual Large Break Frequency in the Process Piping of Savannah River Reactors", SASR-87-37, General Electric, for E. I. duPont de Nemours and Company, Savanah River Laboratory (April 1988).

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

3. A. J. GIANNUZZI, "Studies on AISI Type-304 Stainless Steel Piping Weldments for Use in BWR Application", EPRI NP-944, (December 1978); and B. M. GORDON AND H. S. MEHTA, NEDC-30837, "Stress Corrosion Cracking Literature Review and Analysis for the Savannah River Plant", General Electric, for E. I. duPont de Nemours and Company, Savanah River Laboratory (December 1984).

4. R. L. SINDELAR and W. L. DAUGHERTY, "Reactor Materials Program Leak Detection System Reliability",WSRC-RP-90-99, Savannah River Laboratory (March 1990).

5. K. J. STONER, G. R. CASKEY, JR. AND W. L. DAUGHERTY, "Reactor Materials Program - A Derivation of a Nominal IGSCC Growth Rate for SRS Reactors", WSRC-RP-90-95, Savannah River Laboratory (March 1990).

6. G. S. HOLMAN and C. K. CHOU, "Probability of Failure in BWR Reactor Coolant Piping", NUREG/CR-4792, Volumes 1-4.

7. H. S. MEHTA, "An Assessment of the Probability of Double-Ended Guillotine Break in a BWR Recirculation Piping", *Proceedings of International Conference on Nuclear Power Plant Aging, Availability Factor, and Reliability Analysis*, San Diego, Ca. (July 1985).

8. "Report of the U. S. Nuclear Regulatory Commission Piping Review Committee", NUREG-1061,Volumes 1-5, U. S. NRC (November 1984).

9. "Modification of General Design Criterion 4 Requirements for Protection Against Dynamic Effects of Postulated Pipe Ruptures", Proposed Rules, 10 CFR Part 50, Federal Register Volume 51, No. 141, 26393-26398 (July 23, 1986).

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