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# DOUBLE-ENDED BREAK PROBABILITY ESTIMATE FOR THE 304 STAINLESS STEEL MAIN CIRCULATION PIPING OF A PRODUCTION REACTOR (U)

by

H. S. Mehta[1], W. L. Daugherty[2], N. G. Awadalla[2], and R. L. Sindelar[2]

[1] General Electric Company
San Jose, California

[2] Westinghouse Savannah River Company
Savannah River Site
Aiken, South Carolina 29808

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# Double-Ended Break Probability Estimate for the 304 Stainless Steel Main Circulation Piping of a Production Reactor

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H S Mehta
General Electric Company
San Jose, California, U.S.A.

W L Daugherty, N G Awadalla, R L Sindelar
Westinghouse Savannah River Company
Savannah River Laboratory, Aiken, S.C., U.S.A.

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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 growing through-wall and being detected by the ensuing leakage. The estimated large break frequency is $3.4 \times 10^{-8}$ per reactor-year.

## 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 probabilistic 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 high 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 cracking 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, given 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 which need to coexist in order for a crack to lead to a large break of the primary coolant piping.

## PROBABILITY ESTIMATION

The four factors described above are developed in this section. This development applies specifically to the main circulation loop of the primary coolant piping. The heat affected zones (HAZs) 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 5 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 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, 10 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.

Light Water Reactors (LWRs) 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. Reference 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.

The assumption of 50 percent throughwall cracks here is arbitrary. Tearing instability is not reached 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 probability 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 5 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 1, $P_{CND}$ is applied separately for each inspectionto produce:

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

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. Since 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 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 maxi- mum 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 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 10 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 $5 \times 10^{-5}$ 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 due to 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.

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 which 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 $1 \times 10^{-5}$ 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/year.

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

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

The parameter $\mu$ 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% of the circumference) and will be used. The curve calculated for $\mu = 0.05$ is shown in Figure 6 along with the 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:

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

where R equals mean pipe radius or 7.75 inches and $\mu$ equals crack size distribution parameter or 0.05. For this example, the crack growth probability equals $8.1 \times 10^{-6}$ for the 15 year period, or

$5.4 \times 10^{-7}$ 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, $3.6 \times 10^{-4}$, gives the seismic contribution for this range of:

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

Repeating this calculation for the other seismic ranges gives a total seismic contribution of $3.8 \times 10^{-9}$ per year. No significant contribution is made for seismic levels above 0.45g, due to 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 $3.4 \times 10^{-8}$ per reactor-year. This estimate is much less than $1 \times 10^{-6}$ per reactor-year that is identified as the goal for commercial reactor piping systems applying leak-before-break to eliminate the dymanic effects of a postulated pipe break. [6,7]

## CONCLUSIONS

The estimated large break frequency for the main primary coolant piping of the SRS production reactors is $3.4 \times 10^{-8}$ 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 $1 \times 10^{-6}$ 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 probabilistic risk assessment for the SRS reactors and as a complement to leak-before-break studies of the SRS primary coolant piping system.

## ACKNOWLEDGMENT

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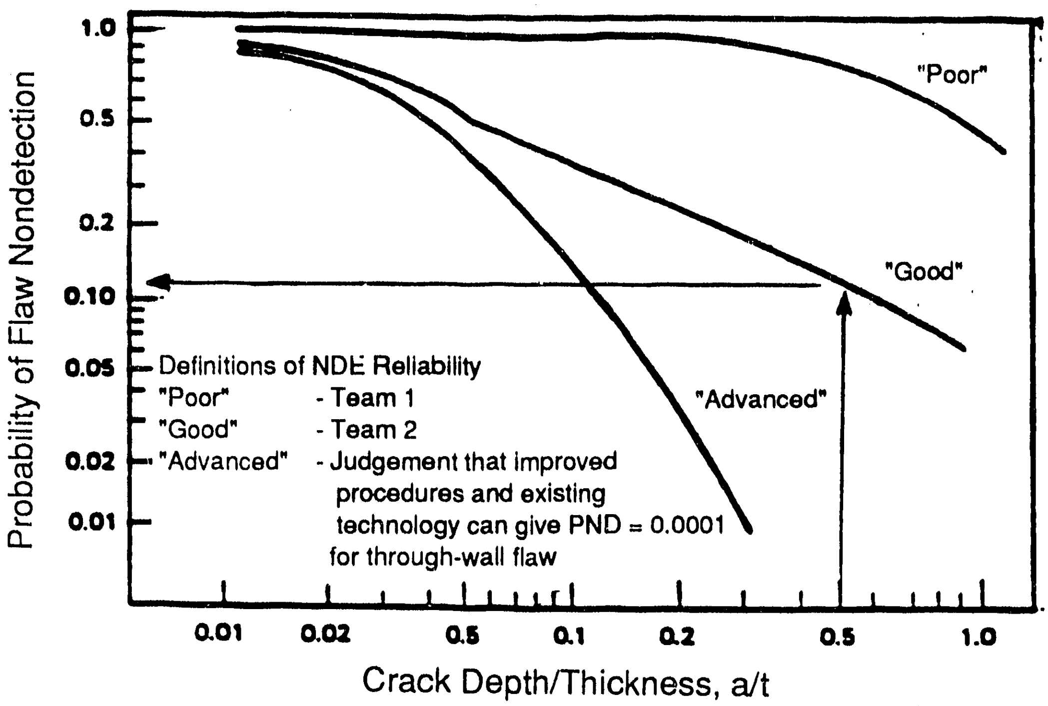


**Figure 1. Detection probability of IGSCC in 10 inch stainless steel pipe. (reproduced from reference 2)**

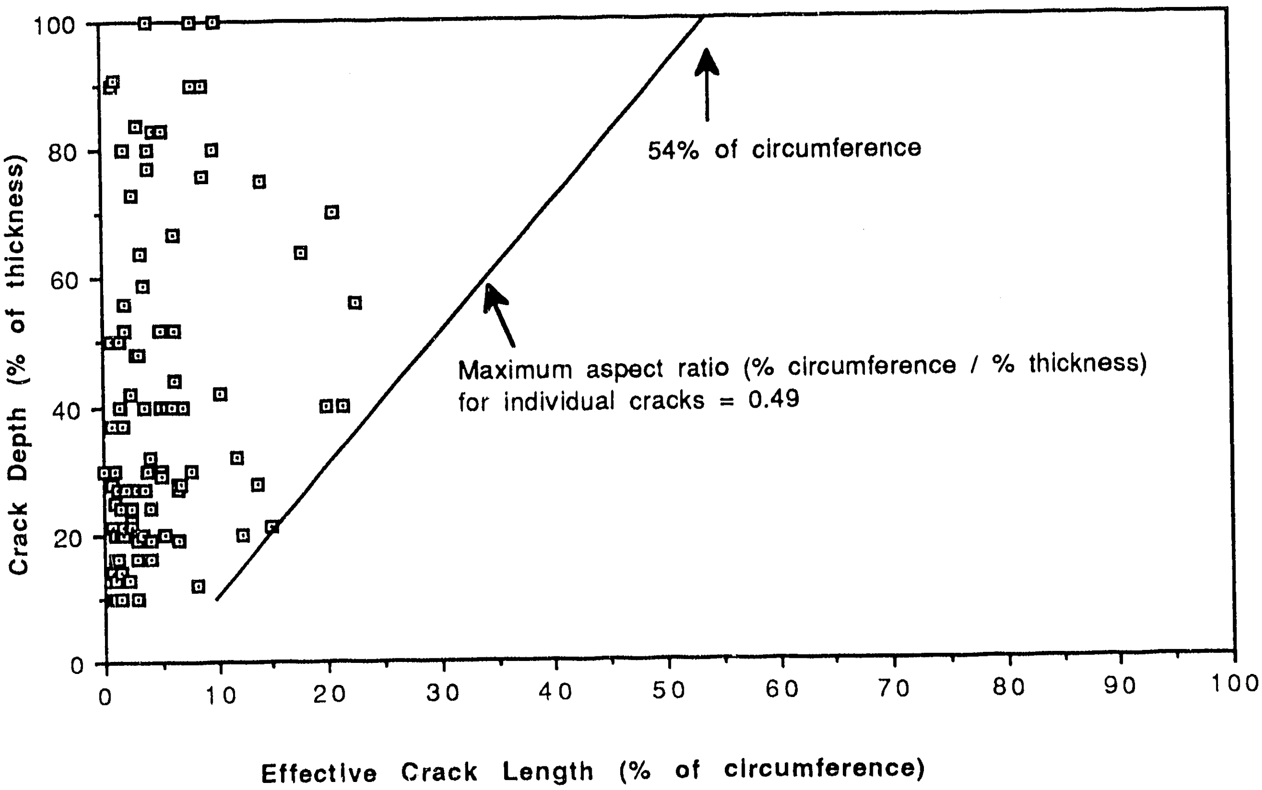


**Figure 2. SRS IGSC crack shape data.**

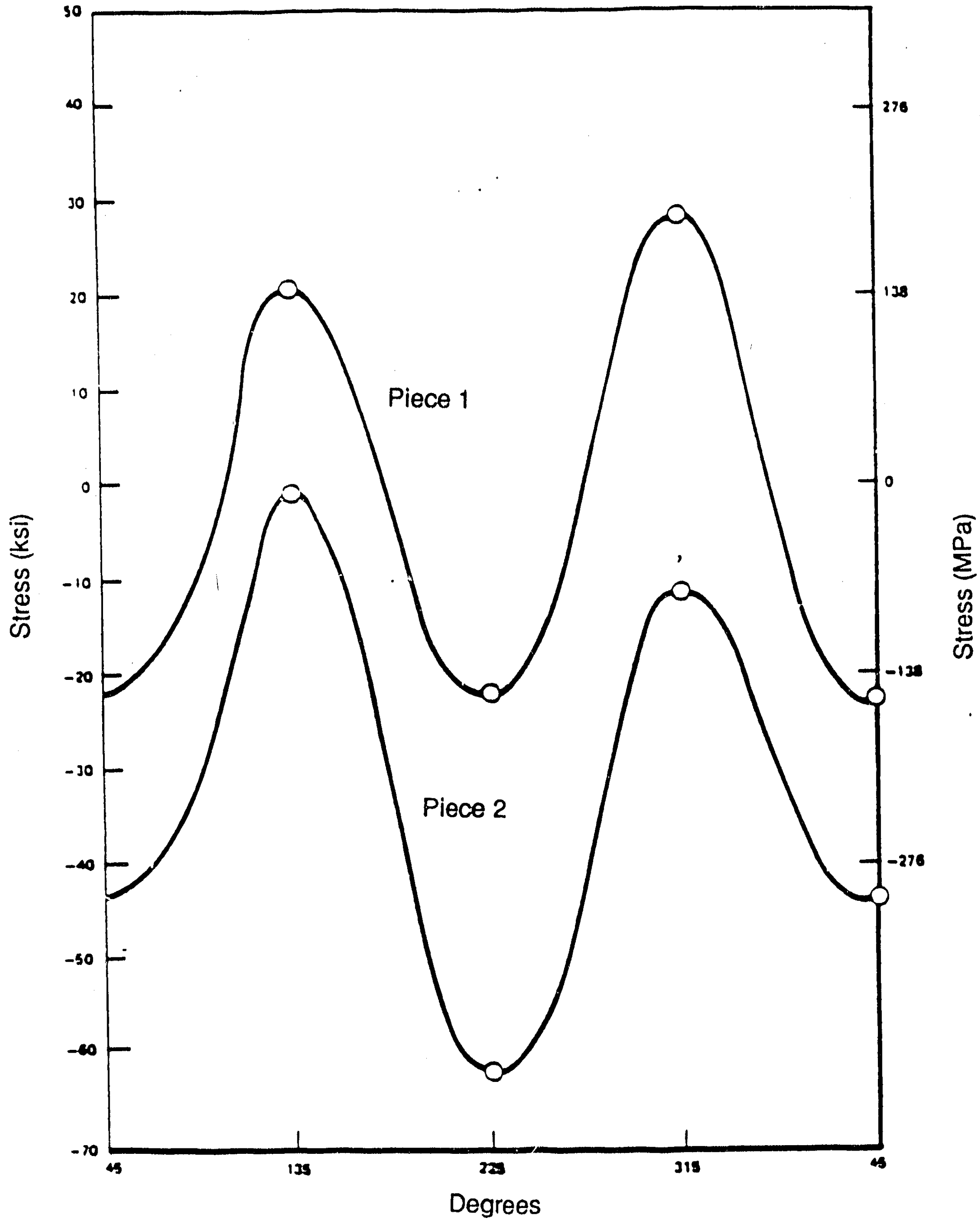


Figure 3. **Ten inch pipe inside surface longitudinal residual stress measurements taken 0.1 inch from weld line. (reproduced from reference 3)**

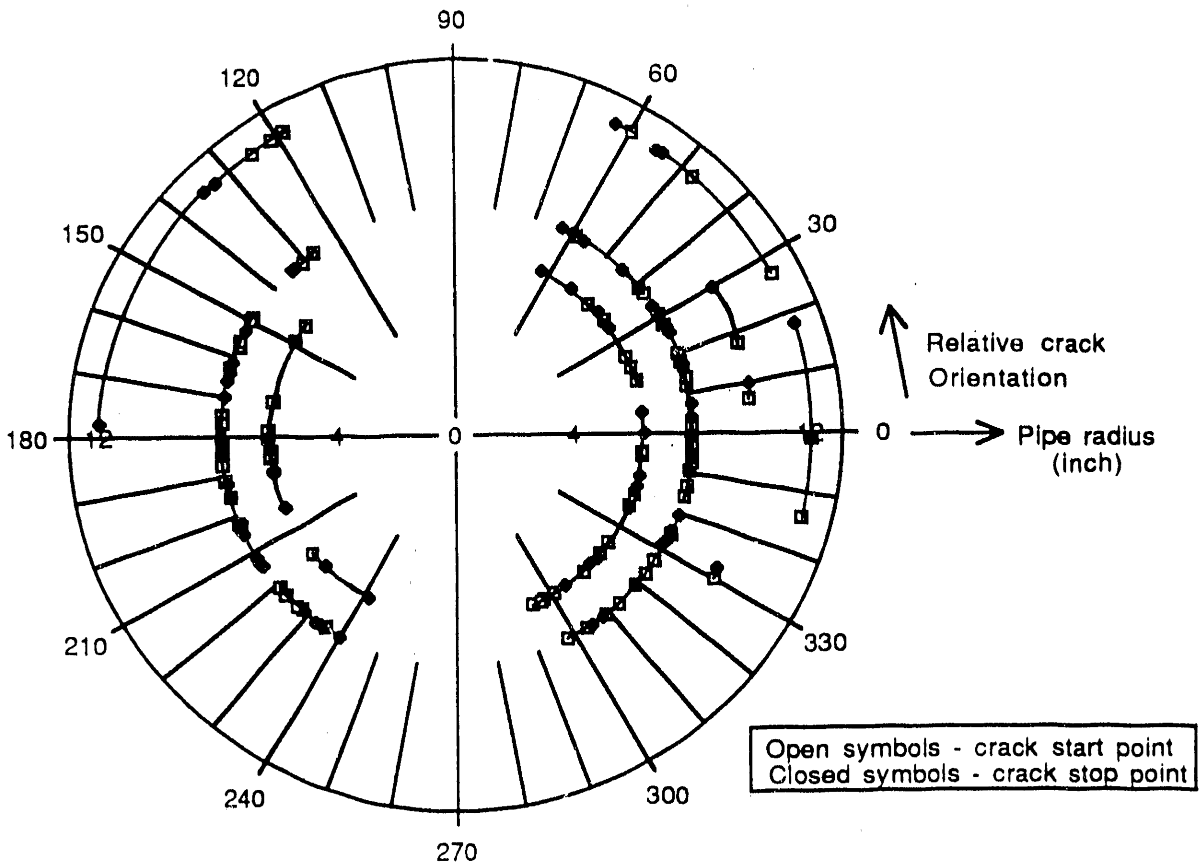


**Figure 4. SRS crack angular orientation data.**

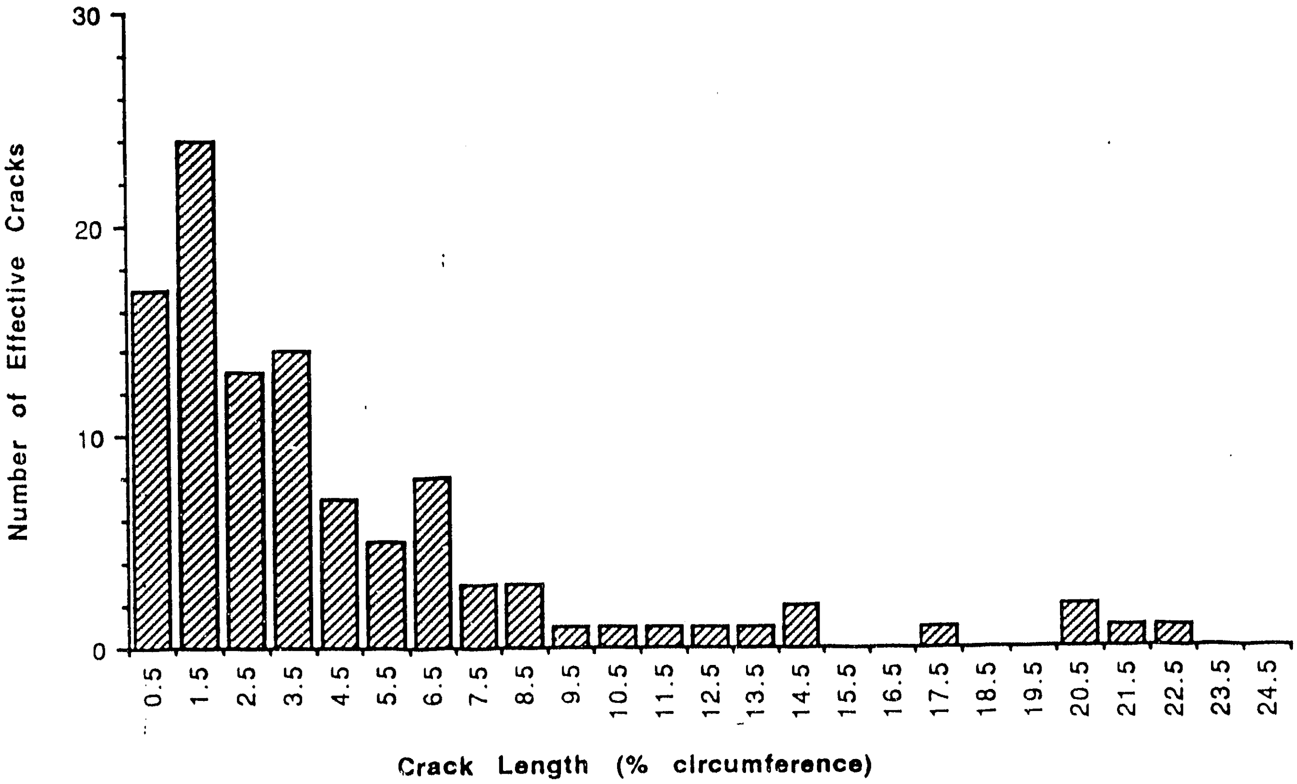


**Figure 5. Crack size distribution for IGSCC in SRS primary coolant piping.**

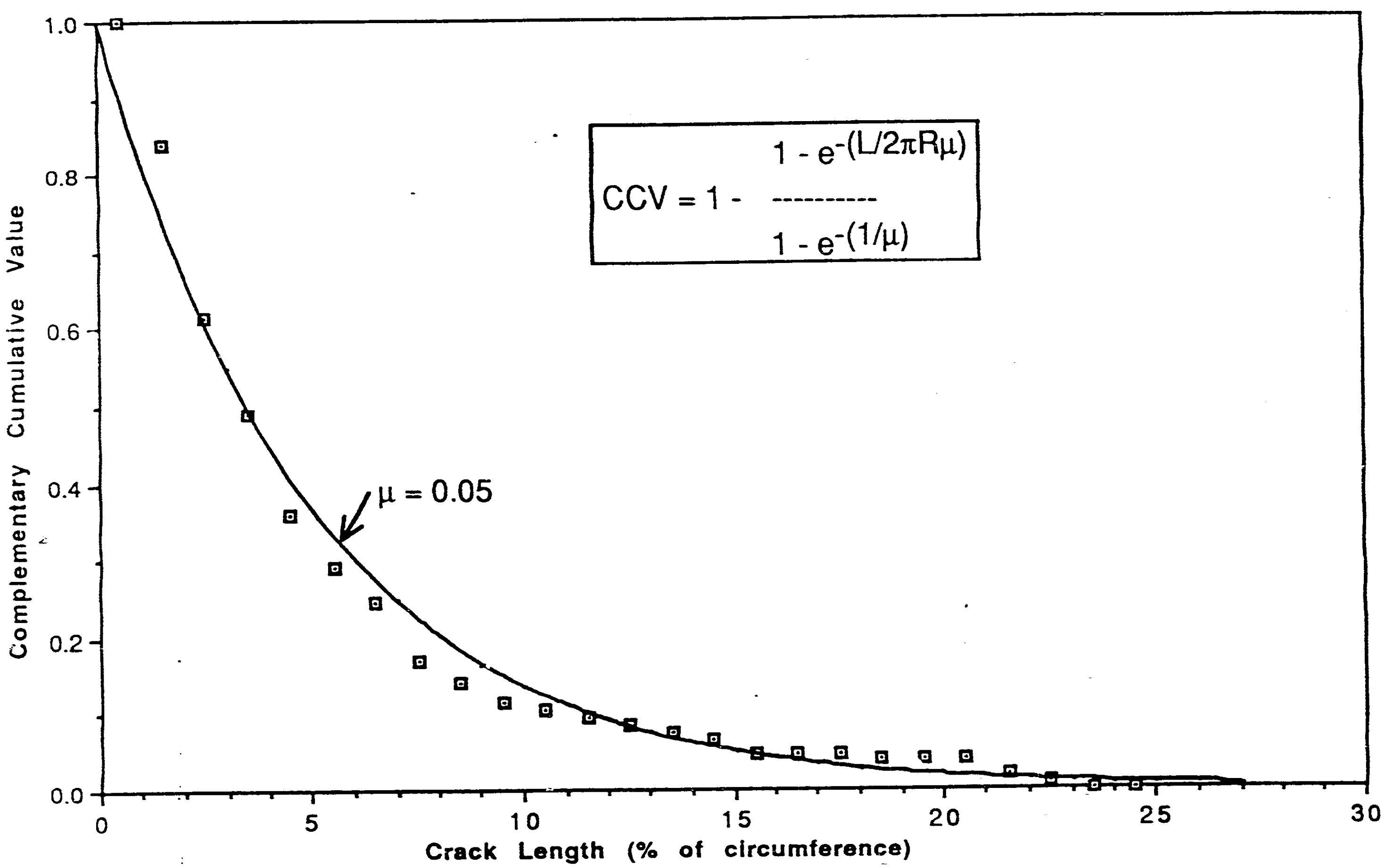


**Figure 6.** Complementary cumulative distribution for SRS data.

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