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INTRODUCTION

The nuclear materials production reactors at the Savannah River Plant (SRP) were designed and built in the 1950's and have operated successfully since that time. Unlike commercial power reactors, the production reactors are moderated and cooled by heavy water and are operated at moderately low temperatures and internal pressures. In addition, the entire primary coolant pressure boundary is constructed of Type 304 stainless steel or its cast equivalent, CF-8, except for seals, gaskets and other serviceable parts.

Due to the low applied stresses coupled with high material toughness, the primary coolant piping is highly tolerant of defects. In the operational history of the plant, several instances of minor leakage from stress corrosion cracks have occurred in the piping, thus exemplifying a Leak-Before-Break (LBB) capacity of the system. Fundamentally, LBB capability provides the assurance that a postulated through-wall crack could be detected by the resulting leakage before the onset of crack instability and the ensuing pipe failure. The Leak-Before-Break demonstration of the SRP primary coolant piping has been formalized through a detailed fracture assessment of postulated flaws in piping with the result that the through-wall crack length at instability conditions is well in excess of the crack length corresponding to the minimum detectable leak rate of the primary coolant system. Additional elements supporting the demonstration of SRP piping integrity include the in-service inspection program and the moderator leak detection system. The extent, frequency and method of non-destructive inspection for SRP piping conforms in general with Section XI of the ASME code and NUREG-0313 (1) requirements for commercial Boiling Water Reactors. The tritium activity of the heavy water moderator (primary coolant) provides a remote, highly-sensitive system capable of reliably detecting moderator leakage as little as 50 pounds per day (0.004 gallons per minute).

DISCUSSION

The NUREG-1061 criteria (2) developed by the NRC for commercial reactors were applied as guidelines to assess the LBB capability of the primary cooling system of the SRP production reactors. The objective of NUREG-1061 is to provide criteria to qualify light water reactors, specifically high energy fluid piping systems (the maximum operating temperature exceeds 200°F or the maximum operating pressure exceeds 275 psig), for exemption from the requirements of pipe whip restraints and jet impingement shields. The maximum full-power operating pressure in the SRP primary coolant system is approximately 225 psig; the maximum temperature is approximately 203°F. While the temperature limit slightly exceeds the high energy criteria, the low pressure and low stored strain-energy justify treating the primary system as a moderate energy system.

The criteria given in NUREG-1061 require addressing inspection, leak detection capabilities, material toughness and strength, maximum system stresses, and the probability of failures due to indirect causes. In the evaluation of SRP piping, one exception to strict compliance with NUREG-1061 criteria, i.e. susceptibility to Intergranular Stress Corrosion Cracking, is justified in consideration of SRP-specific leak detection capabilities, low applied stresses, large margins of safety against crack instability, in-service inspection and conservative pipe replacement criteria (3).

The evaluation of postulated flaws and the assessment of margins of safety against flaw instability are discussed below.

Pipe Fracture Assessment

The LBB analysis included postulated flaws along circumferential and axial pipe weldments. The piping analysis considered "large diameter" piping, 12 to 24-inches in diameter. A summary of the flaw stability analysis and the LBB assessment (3,4) for the large diameter piping is presented in this report.

Stress Analysis - Separate piping analyses were performed for dead weight and seismic loads (5), and for thermal expansion (6). The total bending stresses were calculated by combining bending moments and the torsional moment at each node of the pipe model using square root of the sum of the squares (SRSS). The membrane stresses were added linearly.

For each of the assumed four large diameter pipe sizes (12, 16, 20 and 24-inch), the stress results were reviewed to select locations most limiting to the LBB capacity in terms of margins of safety against crack instability. These locations are those which have relatively low normal operating stress (large reference leakage cracks) and high seismic stress (smaller instability cracks) and those which have relatively large applied stress (normal + seismic).

The normal and seismic loading conditions and the constituent stresses for the limiting locations are shown in Table 1 for the large diameter piping.

IGSC cracks were postulated to exist with a complex crack geometry as shown in Figure 1. The crack may be viewed as comprised of a partial through-wall depth 360^o around the pipe circumference and a fully through-wall length. Leak rate calculations and crack stability analyses were performed for various crack partial depths and through-wall lengths.

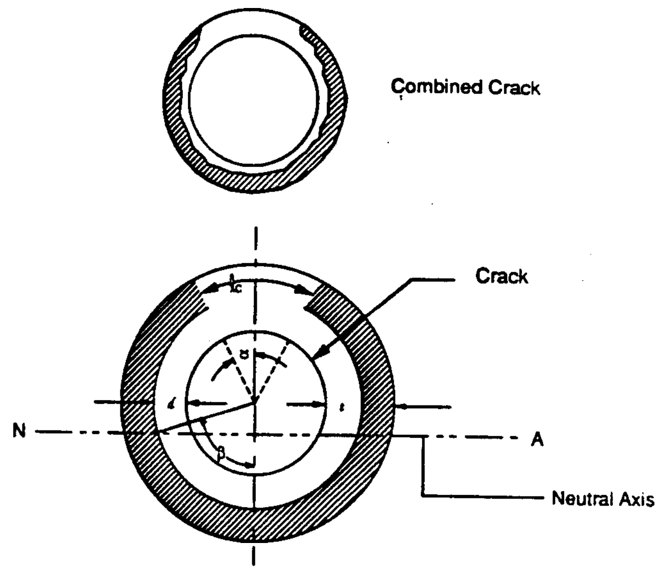

Figure 1. Idealized Through-Wall + Part-Through Cracking

Leak Rate Evaluation - Circumferential Cracks - A review of the leak rate calculations and crack stability assessment for circumferentially-oriented cracks are presented in this report. Complete details for axial cracks is contained in reference 4.

The analytical predictions of leak rates (4) consist of two separate tasks: 1) the calculation of crack opening area and 2) the estimation of fluid flow rate per opening area. The crack opening areas were calculated using Linear Elastic Fracture Mechanics procedures with the customary plastic zone correction. The normal operation loads applied to the crack produce limited plasticity and the approach is therefore appropriate. Mathematical expressions given by Tada and Paris (7) are used in the crack opening area formulation. The total crack opening area as a function of crack length was calculated at each of the limiting LBB locations using the normal operation loads given in Table 1.

TABLE 1

STRESS SUMMARY FOR LEAK-BEFORE-BREAK CALCULATIONS
TWO LIMITING LOCATIONS PER PIPE SIZE
(See Footnote for Explanation of Table Headings)

ASSUMED PIPE SIZE (Inches)	LOCATION	PR MEM (psi)	DW MEM (psi)	DW BEND (psi)	TE MEM (psi)	TE BEND (psi)	S MEM (psi)	S BEND (psi)	NORMAL OPERATION PR+DW+TE MEM (psi)	NORMAL OPERATION PR+DW+TE BEND (psi)	NORMAL OPERATION PLUS SEISMIC PR+DW+TE+S MEM (psi)	NORMAL OPERATION PLUS SEISMIC PR+DW+TE+S BEND (psi)
12	1	1629	51	700	12	254	113	1605	1692	954	1805	2559
	2	1629	73	704	1080	6799	350	2169	2782	7303	3132	9672
16	1	1524	50	227	56	681	105	3410	1630	908	1735	4318
	2	2105	192	4141	68	155	222	2328	2365	4296	2587	6624
20	1	252	175	2148	42	367	104	2747	469	2514	572	5261
	2	252	34	60	42	168	174	2700	328	227	502	2927
24	1	305	326	4164	35	191	102	3053	666	4354	767	7408
	2	305	125	256	35	115	201	2957	464	371	665	3328

EXPLANATION OF TABLE HEADINGS:

"MEM" •• Axial Membrane Stress in Pipe

"BEND" •• Axial Bending Stress Acting over Pipe Cross Section

"PR" •• Stress Component due to Internal Pressure

"DW" •• Stress Component due to Gravity (Deadweight)

"TE" •• Stress Component due to System Thermal Expansion

"S" •• Stress Component due to Seismic Loading

The second task to predict the leak rate for a specified crack opening area was calculated using a single-phase flow model (4). Previous leak rate studies (8,9) pertaining to Light Water Reactor conditions predict water mass transfer under "flashing" conditions, where $T_{coolant} > T_{sat}$ ambient. The maximum temperature of the SRP coolant is 203°F which is well below the saturation temperature for heavy water at ambient pressure. Since the heavy water will stay in the liquid phase, single-phase, incompressible flow may be assumed. The application of Bernoulli's equation for steady flow of an incompressible fluid between the pipe inner volume at pressure P and the fluid at the exit pressure P_e (ambient) is given by:

$$P/w = P_e/w + V^2/2g + ftV^2/D_h 2g \quad (1)$$

where
- V = fluid velocity
- t = wall thickness
- w = specific weight of fluid
- f = coefficient of friction
- D_h = hydraulic diameter
  = 4 x flow area / wetted perimeter
  = $4l\delta/(2l + 2\delta) \sim 2\delta$ since $l >>> \delta$

where
- l = crack length
- δ = crack opening

The total crack opening area, A_c, is equal to the product δl and thus equation (1) can be re-written in terms of the volume flow rate, Q:

$$Q = A_c \times V = A_c \times [2g(P - Pe)/w\{1 + ft/2\delta\}]^{1/2} \qquad (2)$$

A key variable which may be used to calibrate the flow rate model is the friction factor, f. It may be influenced by the surface roughness of the crack (for laminar flow) plus the path tortuosity through the IGSC crack (9). Measured leakage through an actual IGSC crack in the SRP piping was used to establish the effective friction factor of 25, independent of flow rate through the crack (4). The results of the leak rate predictive model are shown in Figure 2. The laminar flow friction factor is small compared to 25 at and above detectable leak rates (above 50 lb/day) and thus a constant friction factor of 25 justified.

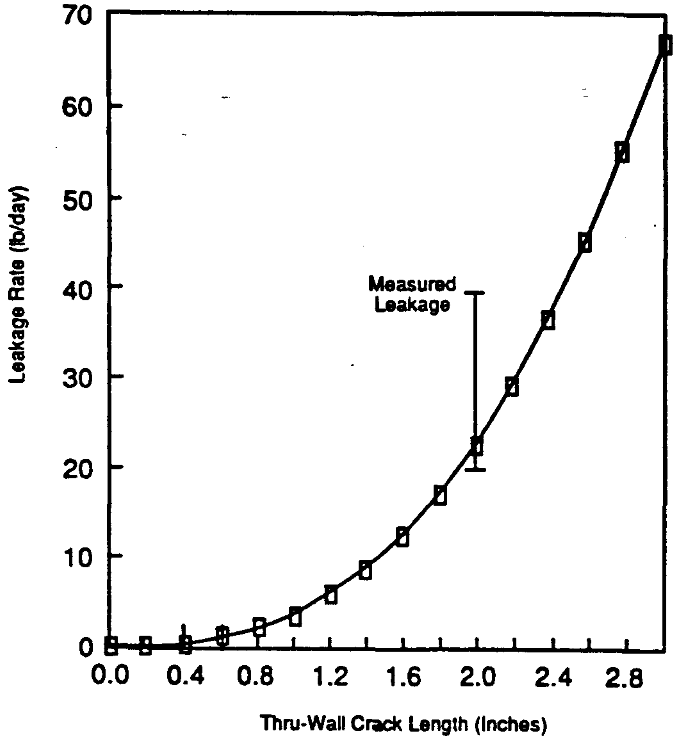

Figure 2. Leakage vs. Crack Size Based on Measured Leak Rates

Instability Flaw Size and Load Evaluation - The instability flaw sizes for each of the four large diameter pipe sizes were calculated using a modified limit load analysis (4):

$$\beta = [(\pi - \nu)(1 - d/t) - \pi P_m/\sigma_f] / [2 - d/t]$$

$$P_b' = (2\sigma_f/\pi)[(1 - d/t)(\sin\beta - \sin\nu) + \sin\beta]$$

$$(P_m + P_b)_{limit} = (P_m + P_b') / M$$

where,

σ_f	=	flow stress
P_m	=	calculated nominal axial stress due to pressure, dead weight, thermal expansion, and seismic
P_b	=	instability bending stress
d/t	=	ratio of part-through crack depth to wall thickness
M	=	pipe size (diameter and schedule) modification factor

Elastic-plastic fracture mechanics methods coupled with an extensive SRP process piping material specific fracture property data base were used in determining the values of M.

LBB Margins of Safety - Two separate margins of safety against crack instability are calculated in accordance with NUREG-1061 criteria. The first margin of safety is calculated by dividing the instability flaw size by the reference leakage flaw size for normal plus SSE loads; a minimum margin of 2 is required by 1061 criteria. The second margin of safety is calculated by dividing the stresses required to cause instability to the reference leakage crack by the sum of the normal plus SSE loads; a minimum margin of 1.4 is required by 1061 criteria. Table 2 lists a summary of these margins of safety at the most limiting locations for the SRP large diameter piping for a reference leakage rate of 50 lb/day. The minimum margins of safety are maintained for reference leakage rates over 700 lb/day.

TABLE 2

CALCULATED LEAK-BEFORE-BREAK MARGINS

ASSUMED PIPE SIZE O.D. (Inches)	WALL THICK (Inch)	LOCATION	d/t*	REF. LEAK CRACK SIZE (Inches)	INSTABILITY CRACK SIZE (Inches)	SIZE MARGIN	STRESS MARGIN
12.75	0.375	1	0	3	24.34	8.11	11.98
			0.2	2.85	23.53	8.26	10.56
			0.4	2.68	22.24	8.3	8.73
			0.6	2.44	20.02	8.2	6.38
			0.8	2.07	14.87	7.18	3.37
		2	0	1.38	18.46	13.38	4.48
			0.2	1.32	17.19	13.02	3.92
			0.4	1.24	15.22	12.27	3.21
			0.6	1.15	11.77	10.23	2.3
			0.8	1	3.1	3.1	1.16
16	0.5	1	0	3.31	28.8	8.7	8.8
			0.2	3.16	27.65	8.75	7.75
			0.4	2.97	25.89	8.72	6.4
			0.6	2.71	22.81	8.42	4.68
			0.8	2.31	15.58	6.74	2.47
		2	0	1.8	25.79	14.33	6.18
			0.2	1.72	24.37	14.17	5.42
			0.4	1.62	22.27	13.75	4.46
			0.6	1.5	18.52	12.35	3.21
			0.8	1.3	9.57	7.36	1.64
20	0.375	1	0	4.46	36.33	8.15	8
			0.2	4.25	34.92	8.22	6.85
			0.4	4.03	32.74	8.12	5.7
			0.6	3.73	28.97	7.77	4.21
			0.8	3.24	20.03	6.18	2.3
		2	0	9.85	40.4	4.1	10.86
			0.2	9.33	39.2	4.2	9.69
			0.4	8.69	37.45	4.31	8.16
			0.6	7.82	34.32	4.39	6.14
			0.8	6.46	27.22	4.21	3.47
24	0.375	1	0	3.39	39.15	11.55	5.46
			0.2	3.24	37.14	11.46	4.82
			0.4	3.07	34.05	11.09	4
			0.6	2.83	28.59	10.1	2.95
			0.8	2.47	15.46	6.26	1.59
		2	0	8.48	46.62	5.5	9.74
			0.2	8.05	45.08	5.6	8.64
			0.4	7.51	42.76	5.69	7.23
			0.6	6.8	38.69	5.69	5.38
			0.8	5.7	29.21	5.12	2.97

* d/t - Ratio of Part-Through Crack Depth to Nominal Wall Thickness

The highly sensitive SRP leak detection system allows the detection of system leak rates with a resolution of approximately 1 lb/day (0.0001 gpm) and error (+/-) 30%. Due to normal coolant losses, a leak rate of 50 lb/day is chosen as the baseline reference leakage rate. In addition to system losses measured as heavy water vapor, leak detection from inventory checks, closed circuit television and visual inspection during hydraulic start-up provide auxiliary systems.

CONCLUSIONS

The deterministic LBB assessment of the SRP primary coolant piping was performed in accordance with NUREG-1061 criteria. Detailed and comprehensive evaluation for each of the criteria show the LBB assessment to be in general compliance with the criteria. The principle conclusions are:

1) Calculated LBB margins of safety on stress and crack instability length are in excess of the margins required in NUREG-1061.

2) Circumferential weldments will not fail causing a sudden DEGB. Similarly, longitudinal weldments will not fail causing an abrupt large failure. Rather, the analysis shows that if failure were to occur, these failures are preceded by detectable leakage well in advance of the pipe break.

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