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FRACTURE MECHANICS EVALUATION OF SOME
LOFT BLOWDOWN SYSTEM AND PRIMARY
COOLANT COLDLEG WELDS

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ABSTRACT

Fracture mechanics evaluations were performed for three welds in the LOFT blowdown system and one weld in the LOFT primary coolant system. Because the applied stress is not known, a sensitivity analysis was run. The assumed initial defect size was one that had a small probability of being missed; applied stresses of 68.9, 137.8, 206.7, and 344.8 MPa were used. It was found that at the lowest stress (68.9 MPa or 10 ksi) the number of cycles from the initial size to rupture was over 6×10^6 . The current calculations indicate that with the worst crack configuration--depth-to-length ratio ($a/2c$) of 0.10-- about 1000 cycles with a peak stress of 227.5 MPa (33 ksi) will be needed to propagate the 0.5 x 5.1 cm (0.2 x 2.0 in.) crack to failure.

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FRACTURE MECHANICS EVALUATION OF SOME LOFT BLOWDOWN AND PRIMARY COOLANT COLDLEG WELDS

I. INTRODUCTION

Fuels and Materials Division personnel were asked to perform a crack propagation analysis on four welds in the LOFT system. The items of interest were weld 212 in ANC drawing 204270 Rev G (Fig. 1), and welds 246, 247, and 249* in ANC drawing 204318 (Fig. 2). Weld 212 is the joint between an AISI 316 stainless steel (SS) Schedule 160 pipe and the PC-P-2 AISI 304 SS cast pump nozzle in the primary coolant cold-leg^[1]. Weld 246 joins an AISI 316 SS Schedule 140 pipe (P6-4) to a similar sized elbow of AISI 316 SS. Weld 247 is the joint between an AISI 316 SS Schedule 140 pipe (P6-1) and a similar sized "T" of AISI 316 SS. Both welds 246 and 247 are in the LOFT blowdown system. The weld filler material was assumed to be AISI 316 SS.** The maximum anticipated stress would be applied during a faulted condition. This stress is the sum of the stresses during Safe Shutdown Earthquake (SSE) and Loss of Coolant Accident (LOCA)^[3]. The operating temperature is 594K (610°F)^[4]. This is the temperature on which all the calculations are made.

The interest in the above welds was initiated early in February 1977 by the discovery of some reportable indications. The indications were found in the base metal immediately outside the weld fusion line, but their exact nature is not known at this time^[5].

The purpose of this analysis was to establish whether or not a leak-before-break concept would apply and to calculate cycles to failure

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* The request to analyze BS 249 was received at a later date. The analysis of this weld is shown in the Appendix.

**The records on ANC Form 452 were sketchy and incomplete, but since an AISI 316 SS insert was used, the filler metal was assumed to be AISI 316 SS^[2].

and critical defect size. Both axially and circumferentially oriented defects were evaluated in the analysis.

The approach used in this analysis was to assume that a defect existed whose size was such that the probability of its not being detected was low. Calculations were made to determine the number of cycles necessary to propagate the defect through the wall of the pipe. This was the "pop"-through crack size. The rupture crack size was compared to the "pop"-through crack size. If the latter was smaller than the former, then a leak-before-break condition existed. If vice versa, then the pipe ruptured before it leaked. In both cases the number of cycles to rupture was calculated.

Because the magnitude of the stresses are not available at this time*, a sensitivity analysis was run. Stresses of 68.9, 137.8, 206.7 and 344.8 MPa (10, 20, 30 and 50 ksi) were applied to the crack and crack growth rates calculated.

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* The calculated stresses supplied by Applied Mechanics Division are stress intensity data. The stress intensity is the difference of the highest and lowest stresses. The data needed are the highest and lowest stresses (calculated from the primary and secondary stresses), and their respective algebraic signs.

II. CONCLUSIONS

A fracture mechanics evaluations of selected LOFT blowdown system and primary coolant coldleg welds -- Bs 246, 247, and 249 -- were performed.

1. BS 246 and 247 (Body of Report)

Since only stress intensity--twice the maximum shear stress--and not stress data are available on these welds, a sensitivity analysis was performed using various assumed values of membrane stress, and various values of the crack depth-to-length ratio on both axially and circumferentially oriented cracks. The results show that for the lowest assumed faulted condition membrane stress, 68.9 MPa (10 ksi), and a maximum initial surface defect size of 0.5 X 1.7 cm (0.2 X 0.667 in.) ($a/2C = 0.3$), the number of cycles to failure exceeds 6×10^6 . The results also indicate that as long as the applied membrane stress due to faulted conditions does not exceed 227.5 MPa (33 ksi) and the largest surface crack that can be missed is 0.5 cm (0.2 in.) deep, the welds should withstand over 1000 cycles of this stress magnitude.

2. BS 249 (APPENDIX)

Subsurface defects were detected by UT (ultrasonic tests). An elastic finite element stress analysis was run to determine the LOCE temperature gradient stresses. The sum of the above and heat up and cool down stresses were the highest that the welds would have to withstand. The fracture mechanics analysis followed standard ASME techniques and indicated that the defect would not propagate in 1300 cycles--10 times the number of LOCE's for which the LOFT system is designed.

III. ANALYTICAL PROCEDURE AND RESULTS

Linear elastic fracture mechanics (LEFM) concepts may be appropriate for this analysis but values of critical plane stress intensity factor (K_{IC}) are not available for AISI 316 SS weld metal, especially for the specific thickness of interest. LEFM concepts are appropriate for predicting the amount of crack growth (da) for a particular number of fatigue cycles (dN), but are not capable of predicting critical defect sizes in the absence of K_{IC} . Therefore, analytical techniques developed by Battelle - Columbus [6,7], based upon empirical correlation of experimental test results from pipe sections of austenitic stainless steel and ferritic steel, were used in this analysis. Two methods were used in calculating the critical crack size at rupture for a pipe containing a through-the-wall defect.

1. CALCULATIONS FOR RUPTURE CRACK SIZE USING BATTELLE APPROACH FOR AXIALLY ORIENTED DEFECTS*

1.1 General Equation

$$M_T \sigma_T = \bar{\sigma}$$

where M_T = Folias Correction Factor

σ_T = Hoop stress from internal pressure at failure (the hoop stress is converted to a pipe circumferential stress)

$$\bar{\sigma} = \text{Flow stress} = \frac{\sigma_{ys} + \sigma_{uts}}{2}$$

where σ_{ys} = yield tensile strength

σ_{uts} = ultimate tensile strength

---

*The techniques used are laid out in greater detail here than for the other parts of the analysis so that the reader may be able to understand the calculation.

1.2 Calculation of σ_T

$\sigma_T = \sigma_{app}$ if σ_{app} was determined from an elastic-plastic analysis.

$\sigma_T \leq \sigma_{app}$ if σ_{app} was determined from an elastic analysis.

For this particular problem, $\sigma_{app} = 68.9$ MPa (10.0 ksi). This value was developed from an elastic analysis^[4]. Other analyses were run and the results are incorporated in the Appendix [4a & 4b].

1.3 Calculation of $\bar{\sigma}$

Data from reference 8 indicate that for the base metal $\sigma_{ys} = 129.3$ MPa (18.76 ksi), $\sigma_{uts} = 453.1$ MPa (65.72 ksi) at 589K (600°F). Therefore,

$$\sigma = \frac{18.76 + 65.72}{2} = 42.24 \text{ ksi.}$$

Base metal data are used because the leading edges of an axially oriented defect will be in base metal at rupture.

1.4 Calculation of M_T

$$M_T \sigma_T = \bar{\sigma}$$

$$M_T (10.7 \text{ ksi}) = 42.24 \text{ ksi}$$

$$M_T = 3.95$$

1.5 Calculation of Critical Defect Length ("Rupture Length"), $2c$, from Fig. 3 for $M_T = 3.95$

$$\frac{2c}{(Rt)^{1/2}} = 7.4 \text{ (See fig. 3 which shows } M_T \text{ vs. } \frac{2c}{(Rt)^{1/2}})$$

$$R = 13.7 \text{ cm (5.375 in.)}$$

$$t = 2.5 \text{ cm (1.0 in)}$$

$$2c = 43.6 \text{ cm (17.16 in.)}$$

2. CALCULATIONS FOR RUPTURE CRACK SIZE USING BATTELLE APPROACH FOR CIRCUMFERENTIALLY ORIENTED DEFECT

The diagram of a pipe section containing a crack, shown in Fig. 4, is used as follows:

$$\text{Area of half region excluding the defect} = \alpha(Rt - t^2)$$

$$Y = R(1 - \frac{\sin \alpha}{\alpha})$$

$$Y_i = R - Y = R \frac{\sin \alpha}{\alpha}$$

where Y = Distance from outside diameter to pipe center of gravity.

Y_i = Distance from pipe center of gravity to geometrical center of pipe.

R = Radius to pipe outside diameter.

$$a = b + Y_i = R \cos(\pi - \alpha) + R \frac{\sin \alpha}{\alpha}$$

$$= R \left(\frac{\sin \alpha}{\alpha} - \cos \alpha \right)$$

where a = Distance from the pipe center of gravity to the outer edge of the crack.

b = Distance from outer edge of crack to pipe geometric center.

M = Bending moment applied to pipe due to pipe's center of gravity not coinciding with the geometric pipe center because of the crack's presence.

$$M = P\pi (R-t)^2 Y_i$$

where P = Fluid pressure in pipe.

$$I = R^3 t \left(\alpha + \sin \alpha \cos \alpha - \frac{2 \sin^2 \alpha}{\alpha} \right)$$

$$\sigma^* = \frac{Ma}{I} + \frac{Pr}{2t_{net}}$$

where σ^* = highest tensile stress on pipe due to bending and pressure.

t_{net} = the wall thickness for a partially through-wall crack.

So now

$$\sigma^* = \frac{P\pi(R-t)^2 Y_i R \left(\frac{\sin \alpha}{\alpha} - \cos \alpha \right)}{R^3 t \left(\alpha + \sin \alpha \cos \alpha - \frac{2 \sin^2 \alpha}{\alpha} \right)} + \frac{Pr}{2t_{net}}$$

However, there is no actual fluid pressure stress, but rather a mechanical stress. Substitutions will now be made to eliminate P from the equations. The membrane stress, σ_{app} or σ_T , in sections III, 1.2 and III, 1.3 respectively, is applied to the pipe as if the pipe were being pulled at its geometric center (see Fig. 5) by a load equal to

$$\sigma_{app} \pi (2Rt - t^2).$$

This load is being carried by an area $\alpha(2Rt - t^2)$ so the pressure stress is now $\sigma_{app}(\pi/\alpha)$ and so $\frac{Pr}{2t_{net}}$ is replaced by $\sigma_{app}(\pi/\alpha)$.

Furthermore, the cracked portion of the pipe cannot support any load. The load exerted by the pressure in the pipe-- if all the applied stress, σ_{app} , were made into a pressure load-- is given by

$$\sigma_{app} \pi [R^2 - (R-t)^2] = P \pi (R-t)^2.$$

So now the equation becomes

$$\sigma^* = \frac{\sigma_{app} \pi (2Rt - t^2) R \frac{\sin \alpha}{\alpha} (R) \left(\frac{\sin \alpha}{\alpha} - \cos \alpha \right) + \frac{\sigma_{app} \pi}{\alpha}}{R^3 t \left(\alpha + \sin \alpha \cos \alpha - \frac{2 \sin^2 \alpha}{\alpha} \right)}$$

where $\sigma^* = 57.8$ ksi ($\sigma^* = \sigma$)

$$\sigma_{app} = 10.7 \text{ ksi}$$

$$R = 5.375 \text{ in.}$$

$$t = 1.0 \text{ in.}$$

Solving the above equation graphically, it is found that the rupture crack length is 34.2 cm (13.45 in.).

3. CRACK GROWTH

3.1 Crack Growth Through the Wall for Both Axially and Circumferentially Oriented Cracks

It is assumed that a crack 0.51 cm (0.2 in.) deep exists in the pipe wall perpendicular to the pipe axis. This crack would have a high probability of detection since the ultrasonic test standard for 2.5 cm (1.0 in.) wall thickness is set at 0.25 cm (0.1 in.)^[9]. Further, it is assumed that a/l (or $a/2c$) = 0.3.

Therefore,

$$2c = 1.7 \text{ cm (0.67 in.)}$$

$$c \text{ (half crack length)} = 0.84 \text{ cm (0.33 in.)}$$

$$a/t = \frac{0.2}{1.0} = 0.2.$$

From ASME Section XI, Appendix A-3000^[10]

$$Q = 1.6 \text{ (for } a/\ell = 0.3)$$

M_m varies with a/t .

A linear elastic fracture mechanics approach was used and it was assumed that a/ℓ remained constant throughout crack growth. The crack growth was carried out in increments of 0.25 cm (0.1 in.) and the value for M_m was taken for the middle of that range. Thus, for the increment from 0.51 to 0.76 cm (0.2 to 0.3 in.), the M_m value for 0.64 cm (0.25 in.) was used. It was assumed that no bending moments were present. The equation in A-3300 in Ref. 10 becomes

$$\begin{aligned} K_I &= \sigma_m M_m \left(\frac{\pi a}{Q} \right)^{1/2} \\ &= (10.7) (M_m) \left(\frac{\pi a}{1.6} \right)^{1/2} \\ &= 14.99 (M_m) (a)^{1/2}. \end{aligned}$$

It was assumed that no compressive load was placed on the pipes. Therefore, $K_I = \Delta K$.

The da/dN vs ΔK curve is obtained from the Nuclear Systems Materials Handbook, Property Code 2431, p 1.0^{[11]*}.

$$da/dN = C(\Delta K)^{5.4925}$$

$$\text{where } \Delta K = 14.99 (M_m) (a)^{1/2}$$

*This is a preliminary curve but it is the best available.

$$C = 2.08 \times 10^{-13}$$

$$da/dN = \text{crack growth/cycle (in.)}$$

This curve can be used for AISI 304 and 316 SS base metal and weld metal.

Integrating the da/dN equation gives

$$da/dN = C [14.99 (a)^{1/2}]$$

$$\frac{da}{a^{n/2}} = C (14.99)^n dN$$

$$\frac{a_f^{(-n/2 + 1)} - a_o^{(-n/2 + 1)}}{(-n/2 + 1)} = C (14.99)^n (N_f - N_o)$$

where a_f = Final crack depth

a_o = Original crack depth

$N_f - N_o$ = Number of cycles needed to grow crack
from a_o to a_f^* .

Substituting

$$C = 2.08 \times 10^{-13}$$

$$n = 5.4925$$

and growing the crack by 2.5×10^{-3} m (0.1 in.) increments** from 5.1 to

*In Tables I-VI $g = -n/2 + 1$, therefore,

$$\frac{a_f^g - a_o^g}{g} = \frac{a_f^{(-n/2 + 1)} - a_o^{(-n/2 + 1)}}{(-n/2 + 1)}$$

**The results were presented in this manner so that the reader would be able to see the effect of assuming an initial crack depth greater than 0.5 cm (0.2 in.). This was done because the ultrasonic test results have not yet been interpreted.

$17.8 \times 10^{-3} \text{ m}$ (0.2 to 0.7 in.) (see Table I) gives

$$N_f - N_o = 6.95 \times 10^6 \text{ cycles.}$$

It is assumed that after this, the crack "pops" through the remaining 0.76 cm (0.3 in.) and becomes a through-wall crack of 2.5 x 5.92 cm (1.0 x 2.33 in.). This is quite conservative since calculations show that the crack will not "pop" through, but will keep growing until it grows through to the surface.

3.2 Crack Growth from "Pop"-Through Length to Rupture Length for Axially Oriented Cracks

Calculations in Section III, 1.5 indicate that the rupture length is 43.6 cm (17.16 in.). To calculate the number of cycles needed to grow the crack from a half length of 2.9 cm to 21.8 cm (1.16 in. to 8.58 in.), the formulae for a uniformly stressed panel with a central through-thickness crack can be used^[12]. The formula giving the highest value for K is

$$K = \sigma (\pi c)^{1/2} \left(\sec \frac{\pi c}{2b} \right)^{1/2}$$

where c = Half crack length (1.16 in. to 8.58 in.)

σ = Applied stress (10.7 ksi)

b = Half panel width.

However, the value of b must be known. If $b \gg c$, (say $10c$) then $\left(\sec \frac{\pi c}{2b} \right)^{1/2}$ is small and K is small, and a large value for $N_f - N_o$ results. If b is smaller (say $4c$), then $\left(\sec \frac{\pi c}{2b} \right)^{1/2}$ is larger, K is larger, and $N_f - N_o$ is smaller. Furthermore $N_f - N_o$ is a very sensitive function of K because of the crack growth exponent $n (=5.4925)$. An increase by a factor of 2 in K results in a decrease by a factor of 45 in $N_f - N_o$. Since a value of b cannot be readily ascertained for axially oriented cracks, calculations of $N_f - N_o$ for crack lengths from "pop"-through to rupture cannot be made. However, these calculations may not be necessary because (a) the calculated number of cycles for

crack propagation from $a_0 = 0.51 \times 10^{-3} \text{ m}$ (0.2 in.) to "pop"-through is 6.95×10^6 and (b) the rupture length is so much greater than the "pop"-through length and the stress so low that considerably more than 10 cycles will be needed to propagate the "pop"-through crack to rupture.

3.3 Crack Growth from "Pop"-Through Length to Rupture Length for Circumferentially Oriented Cracks

From Section III, 2 it is seen that ℓ (or $2c$) = 34.2 cm (13.45 in.) at fracture. This means that the crack will leak before it ruptures. To determine the number of cycles necessary to grow the crack from 5.9 cm (2.33 in.) to 34.2 cm (13.45 in.), the formula in Section III, 2.3 will be used.

$$K = \sigma(\pi c)^{1/2} \left(\sec \frac{\pi c}{2b} \right)^{1/2}$$

where c = Half crack length (1.16 to 6.22 in.)

σ = Applied stress (10.7 ksi)

b = Half panel width (it is now assumed that the pipe is a flat panel whose width is πD)

$$K = 18.97 (c)^{1/2}$$

The number of cycles to grow the crack from $c_0 = 2.95 \text{ cm}$ (1.16 in.) to $c_f = 17.1 \text{ cm}$ (6.72 in.) is 179,000. This means that for a circumferentially oriented crack with $\sigma_{app} = 68.9 \text{ MPa}$ (10.0 ksi), $a/2c = 0.3$, and $a_0 = 0.51 \text{ cm}$ (0.2 in.), it takes 6.95×10^6 cycles to propagate the crack through the wall ("pop"-through) and 179,000 more cycles to propagate it to rupture length. This is a total of greater than 7.1×10^6 cycles.

4. CYCLES TO FAILURE FOR PARAMETER VALUES

Since the imposed stresses have not yet been calculated, it was decided that σ_{app} should be varied as well as $a/2c$ because either raising σ_{app} or lowering $a/2c$ increases ΔK and thereby decreases $N_f - N_0$. The larger value of σ_{app} was chosen as 345 MPa (50 ksi) and the lower value of $a/2c$ as 0.1. The result is a 2 x 2 x 2 matrix (see Tables I-V). The calculations are essentially the same as in Section III, 1.

4.1 Axial Defects

The only departure from the methodology in Section III, 1 came when the "pop"-through crack length was greater than the rupture length for axially oriented cracks. Calculations were then made to determine what the crack depth should be, such that one application of σ_{app} on a crack having the appropriate $a/2c$ ratio would result in the crack propagating through to the surface. This then became the new "pop"-through length, which was compared to the rupture length. If the latter were greater than the former, leak before rupture occurred, and if vice versa, then rupture before leak.

Rough calculations indicate that if σ_{app} was decreased from 344.8 MPa (50 ksi) to 227.5 MPa (33 ksi), $N_f - N_0$ would increase tenfold. At this point there would still be no leak before rupture.

Axial defects will propagate into the base metal, so that base metal properties must be used. In the case of an applied stress, σ_{app} , greater than the yield stress, 129.4 MPa (18.76 ksi), the applied stress was used in the equation for the stress intensity factor:

$$K = \sigma_m M_m \left(\frac{\pi a}{Q} \right)^{1/2}$$

If the applied stress, σ_{app} , was larger than the hoop stress, $\bar{\sigma}$ (=291.2 MPa or 42.24 ksi), the pipe was assumed to rupture upon the first application of the stress.

4.2 Circumferential Cracks

The technique used was identical to that used in Section III, 2 except, that stress values higher than 68.9 MPa (10.7 ksi) were used.

IV. DISCUSSION

The results are tabulated in Tables I-IV, and summarized in Table V. Four factors affect the number of cycles to failure - two decrease the cycles to failure and two increase them.

One factor which tends to decrease the number of cycles to failure is the water in the pipe. Aqueous environments have been known to increase the crack growth rate, da/dN ^[13]. The other factor tending to decrease the number of cycles to failure is the frequency effect^[14]. It is not known precisely how much the above factors affect the number of cycles to failure. An estimate would be about an order of magnitude so that the numbers in Tables I-VII would need to be divided by 10.

A factor which tends to increase the number of cycles to failure is the assumption that the stresses are uniform through the pipe wall thickness. If this were not true and the actual case were that a stress gradient existed, then the number of cycles to failure, $N_f - N_0$, would increase because ΔK would decrease. With n , the crack growth exponent, having such a large value, 5.49, each decrease of about 12 percent in ΔK doubles $N_f - N_0$. Calculations in Reference 15 indicate that these factors more than compensate for those tending to decrease the number of cycles. The 73.8 MPa (10.7 ksi) stress on the pipe is all mechanical in origin. It is not known what the relative proportions of the thermal and mechanical contributions to the total stress will be^[16].

Also, it was assumed that the crack dimensions after "pop"-through were of the configuration in Fig. 6b. Actually, if there were a stress gradient, the configuration would be more like that in Fig. 6c because the stress is lower at the outside diameter. This means that to grow the through-thickness crack from Fig. 6c to Fig. 6b would require some number of additional cycles.

Another thing that could increase the number of cycles to failure is to reduce the size of the assumed defect by increasing the defect detection capabilities of the nondestructive testing (NDT) techniques.

Better defect detection capabilities would enable the inspectors to determine crack sizes more effectively so that such large initial defects would not have to be assumed to be present in the structure. The smaller the initial crack size, the greater the number of cycles to failure. Crack growth rate (da/dN) at a constant stress increases with increasing crack depth (a) because the stress intensity factor (K) increases as the square root of a . However,

$$da/dN \propto K^n.$$

Therefore

$$da/dN \propto a^{n/2}$$

$$\text{if } n > 4, da/dN \propto a^{2+}.$$

It can be seen, then, that da/dN is small at first, increasing greatly as the crack depth, a , increases. Thus, it is important that the initial crack size be kept as small as possible.

Fig. 1 Drawing 204270
(Drawing is too large to be placed here;
only the section of interest is reproduced)

Fig. 2 Drawing 204318
(Drawing is too large to be placed here; only the section of interest is reproduced).

Fig. 3 M_T vs $2c/(Rt)^{1/2}$.

Fig. 4. Circumferential through-wall crack geometry.

Fig. 5 Diagram of Pipe Loading

FIG. 6a CRITICAL CRACK CONFIGURATION
BEFORE "POP" THROUGH

FIG. 6b ASSUMED CRACK CONFIGURATION
AFTER "POP" THROUGH

FIG. 6c MORE REALISTIC CRACK
CONFIGURATION AFTER
"POP" THROUGH.

Fig. 6 Configuration for "Pop"-Through Cracks

TABLE I

INCREMENTAL CRACK GROWTH FOR SPECIFIED CONDITIONS*
(Axial and Circumferential Cracks)

a_o		a_f		M_m	$\sigma_m M_m \left(\frac{\pi}{1.6}\right)^{1/2}$	$a_f^g - a_o^g$	$[(\Delta K)^n C]^{-1}$	$N_f - N_o$
cm	(in.)	cm	(in.)			g		
0.51	(0.2)	0.76	(0.3)	1.11	6.53	4.82	1,344,700	6.48×10^6
0.76	(0.3)	1.02	(0.4)	1.14	16.04	1.85	1,156,000	2.15×10^6
1.02	(0.4)	1.27	(0.5)	1.18	16.60	0.92	957,000	0.88×10^6
1.27	(0.5)	1.52	(0.6)	1.24	17.35	0.52	751,400	0.39×10^6
1.52	(0.6)	1.78	(0.7)	1.32	18.47	0.33	532,600	0.18×10^6
							TOTAL CYCLES = 10.08×10^6	

*Specified conditions are:

1. $a = 0.5$ cm (0.2 in.) to $a = 1.8$ cm (0.7 in.)
2. $\sigma_{app} = 68.9$ MPa (10.0 ksi)
3. $a/2c = 0.3$
4. All calculations were done in the English system.

TABLE II

INCREMENTAL AXIAL CRACK GROWTH FOR SPECIFIED CONDITIONS*

a_o		a_f		M_m	$\sigma_m M_m \left(\frac{\pi}{Q}\right)^{1/2}$	$\frac{a_f^g - a_o^g}{g}$	$(\Delta K^{n_c})^{-1}$	$N_f - N_o$
cm	(in.)	cm	(in.)					
0.51	(0.2)	0.76	(0.3)	1.11	30.40	4.83	34,429.84	166,296
0.76	(0.3)	1.02	(0.4)	1.14	31.23	1.85	29,738.67	55,016
1.02	(0.4)	1.27	(0.5)	1.18	32.32	0.93	24,607.05	22,884
1.27	(0.5)	1.52	(0.6)	1.24	33.96	0.53	18,739.28	9,931
1.52	(0.6)	1.78	(0.7)	1.32	36.23	0.33	13,144.80	4,423
							TOTAL CYCLES = 258,550	

*Specified conditions:

1. M_m was not defined for $a/t > 0.7$
2. $a = 0.5$ cm (0.2 in.) to $a = 1.8$ cm (0.7 in.)
3. $\sigma_{app} = 344.8$ MPa (50 ksi)
4. $a/2c = 0.3$
5. All calculations were done in the English system.

TABLE III

INCREMENTAL AXIAL AND CIRCUMFERENTIAL CRACK GROWTH FOR SPECIFIED CONDITIONS*

a_o		a_f		M_m	$\sigma_m M_m \left(\frac{\pi}{1.4}\right)^{1/2}$	$\frac{a_f^g - a_o^g}{g}$	$(\Delta K^n C)^{-1}$	$N_f - N_o$
cm	(in.)	cm	(in.)					
0.51	(0.2)	0.76	(0.3)	1.27	23.31	4.83	148,204	715,769
0.76	(0.3)	1.02	(0.4)	1.44	26.40	1.85	74,784	138,464
1.02	(0.4)	1.27	(0.5)	1.67	29.64	0.93	33,377	31,005
1.27	(0.5)	1.52	(0.6)	1.96	36.03	0.53	13,562	7,105
TOTAL CYCLES = 892,343								

* Specified conditions:

1. M_m is not defined for $a/t > 0.6$ at $a/2c = 0.1$.
2. $a = 0.5$ cm (0.2 in.) to $a = 1.8$ cm (0.7 in.)
3. $\sigma_{app} = 68.9$ MPa (10.0 ksi)
4. $a/2c = 0.1$
5. All calculations were done in the English system.

TABLE IV
INCREMENTAL CIRCUMFERENTIAL CRACK GROWTH FOR SPECIFIED CONDITIONS*

a_o		a_f		M_m	$\sigma_m M_m \left(\frac{\pi}{Q}\right)^{1/2}$	$\frac{a_f^g - a_o^g}{g'}$	$(\Delta K^n C)^{-1}$	$N_f - N_o$
cm	(in.)	cm	(in.)					
0.51	(0.20)	0.76	(0.30)	1.27	116.36	4.83	21.66	104
0.76	(0.30)	1.02	(0.40)	1.44	131.79	1.85	10.93	20
1.02	(0.40)	1.27	(0.50)	1.67	152.64	0.9284	4.80	4
1.27	(0.50)	1.52	(0.60)**	1.96	179.83	0.5239	1.98	1
TOTAL CYCLES = 129								

*Specified conditions:

- 26
1. M_m is not defined for $a/t > 0.6$ or for $a/2c = 0.1$.
  2. $a = 0.5$ cm (0.2 in.) to $a = 1.5$ cm (0.6 in.)
  3. $\sigma_{app} = 344.8$ MPa (50 ksi)
  4. $a/2c = 0.1$
  5. All calculations were done in the English system.

**The partial through-wall crack length which will rupture on one application of 344.8 MPa (50 ksi) stress with $a/2c = 0.1$ is greater than the rupture length 4.1 cm (1.63 in.). The pipe will not leak before it ruptures.

TABLE V
SUMMARY OF TABLES I-IV

$$a/2c = 0.3$$

	<u>Axially Oriented Defect</u>	<u>Circumferentially Oriented Defect</u>
Stress	68.9 MPa (10.0 ksi)	68.9 MPa (10.0 ksi)
"Pop"-through Crack Size	2.54 x 8.46 cm (1.0 x 3.33 in.)	2.54 x 8.46 cm (1.0 x 3.33 in.)
Cycles to "Pop"-through	6.95×10^6	6.95×10^6
Rupture Crack Size	2.54 x 43.6 cm (1.0 x 17.16 in.)	2.54 x 34.2 cm (1.0 x 13.45 in.)
Leak Before Rupture	Yes	Yes
Cycles from "Pop"-through to Rupture	Not determined	0.17×10^6
Total Cycles	$< 10.08 \times 10^6$	10.25×10^6
Stress	344.8 MPa (50 ksi)	344.8 MPa (50 ksi)
"Pop"-through Crack Size	0.51 x 1.7 cm (0.2 x 0.667 in.)	2.54 x 4.14 cm (1.0 x 1.63 in.)
Cycles to "Pop"-through	None	967
Rupture Crack Size	0.51 x 1.7 cm (0.2 x 0.667 in.)	2.54 x 4.14 cm (1.0 x 1.63 in.)
Leak Before Rupture	No	Yes
Cycles from "Pop"-through to Rupture	determined	None
Total Cycles	None	967

TABLE V (Cont'd)

	<u>Axially Oriented Defect</u>	<u>Circumferentially Oriented Defect</u>
Stress	63.9 MPa (10.0 ksi)	68.9 MPa (10.0 ksi)
"Pop"-through Crack Size	2.54 x 25.4 cm. (1.0 x 10.0 in.)	2.54 x 25.4 cm (1.0 x 10.0 in.)
Cycles to "Pop"-through	6.15×10^5	6.15×10^5
Rupture Crack Size	2.54 x 43.6 cm (1.0 x 17.16 in.)	2.54 x 34.2 cm (1.0 x 13.45 in.)
Leak Before Rupture	Yes	Yes
Cycles from "Pop"-through to Rupture	Not determined	3941
Total Cycles	$< 8.92 \times 10^5$	8.96×10^5
Stress	344.8 MPa (50 ksi)	344.8 MPa (50 ksi)
"Pop"-through Crack Size	0.51 x 5.1 cm (0.2 x 2.0 in.)	2.54 x 15.2 cm (1.0 x 6.0 in.)
Cycles to "Pop"-through	None	129
Rupture Crack Size	0.51 x 5.1 cm (0.2 x 2.0 in.)	2.54 x 8.56 cm (1.0 x 3.37 in.)
Leak Before Rupture	No	No
Cycles from "Pop"-through to Rupture	None	None
Total Cycles	None	129

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APPENDIX
FRACTURE MECHANICS EVALUATION OF DEFECTS
FOUND IN BS 249

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FRACTURE MECHANICS EVALUATION OF DEFECTS
FOUND IN BS 249

I. INTRODUCTION

During analysis of the results of the nondestructive evaluation (NDE) engineering ultrasonic inspection of the LOFT bypass piping, four axial defects and a circumferential defect were found in BS 249 (Figs. A-1 and A-2 and Table I)^[17]. Fuels and Materials Division (F&MD) was asked to perform a fracture mechanics evaluation to determine how the defect would behave when subjected to faulted condition stresses (SSE and LOCA).

The evaluation method previously outlined in this report was used. The distance of the circumferential defect from the inside diameter (ID) of the pipe could vary $\pm 50\%$ ^[18] so that the defect could be as close as 0.35 cm (0.14 in.) from the pipe ID or as far away as 1.04 cm (0.41 in.). Results of a linear elastic finite element thermal stress analysis for LOCE^[19] and a mechanical stresses for OBE, LOCE, and heat up and cooldown^[20] (Table II) were used to determine the stresses. These analyses indicated that the highest elastic stresses were from the LOCE thermal stress plus the heat up and cooldown stresses^[21], and that these stresses were highest near the pipe ID (Fig. A-3).

II. ANALYTICAL PROCEDURE

The circumferential crack (Figure A-2) is subsurface. Since the crack could be as close as 0.35 cm (0.14 in.) from the pipe ID (worst case) the crack was assumed to be 0.37 cm (0.15 in.) from the pipe ID and extend to 1.02 cm (0.40 in.) (0.63 cm or 0.25 in. deep). The length was assumed to be 5.1 cm (2.0 in.). This configuration (Figure A-3) gave the highest stresses, which were LOCE thermal plus heat up and cooldown stresses, and thus the highest growth rate. The crack front closer to the ID (hereafter, ID crack front) grew faster than the crack front closer to the OD (hereafter, OD crack front). In fact, calculations show that the OD crack front hardly grew at all, so the crack depth increased only by the movement of the ID crack front.* The number of cycles to crack "pop"-through on the pipe ID was calculated using techniques outlined in reference 10. "Pop"-through occurred at about 1300 cycles, and at that point the crack was 1.02 x 8.1 cm (0.40 x 3.2 in.).

Crack growth rates were also calculated for the OBE and LOCE stresses in Table A-II. Unlike the LOCE thermal plus heatup and cooldown stresses, the OBE and the LOCE stresses in Table II are all tensile membrane stresses, so that cracks will grow when they are applied. The stresses are also tension and compression, so the OBE stress is ± 12.24 ksi (± 84.4 MPa). This value of $R = -1$ ** has been found to increase the fatigue crack growth rate^[22] in the following way:

$$K_{\text{eff}} = K_{\text{max}} (1-R)^m$$

where $m = 0.65$ for $0.50 < R < 0.65$.

---

* All calculations were performed in English units.

** $R = \frac{K_{\text{min}}}{K_{\text{max}}}$, so

that a fully reversed fatigue test has $R = -1$.

$$K_{\max} = \sigma_{\max} M_m \sqrt{\frac{\pi a}{Q}} \text{ (Reference 10).}$$

Now if this applies to $R = -1$, then

$$K_{\text{eff}} = 1.57 K_{\max}$$

K_{eff} was substituted into the equations in Section III.3.1 of the main text and the distance the crack would propagate during the previously calculated 1300 cycles was obtained.

The largest axial defect is shown in Figure A-1. Since there was a small ligament between the defect and the pipe outside diameter, it was assumed to be surface rather than a subsurface crack. This is conservative since the correction factor for membrane stresses, M_m , is higher for surface cracks than subsurface cracks, all other things being equal^[10].

The LOCE thermal plus heat up and cooldown stresses vs pipe wall thickness are shown in Fig. A-4. It can be seen that the stresses in the vicinity of the axial defect are all compressive. Therefore the crack will not grow under these stresses. The OBE and LOCE membrane stresses are handled in the same way as they were for the circumferential defect, and the number of cycles necessary to propagate the defect to a through-wall crack is calculated.

III. RESULTS AND DISCUSSION

The results of the calculations for the circumferential crack subjected to the LOCE thermal plus heatup and cooldown stresses are presented in Table A-III. They show that the crack will not "pop"-through to the ID until 1300 or more test cycles have passed. This is approximately five times the expected life of the LOFT system (260 cycles).

Growth of the circumferential crack under 1300 cycles of either OBE or LOCE stresses (whichever is greater) is shown in Table A-IV; there is negligible growth from these stresses.

Growth of the largest axial crack under 1300 cycles of either OBE or LOCE stresses is shown in Table A-V. Again, there is negligible growth in 1300 cycles.

Two conservative assumptions were made in the above calculations. First, it was assumed that the crack depth-to-length ratio ($a/2c$ for surface cracks; $2a/2c$ for subsurface cracks) remained constant. Fatigue cracks propagating under bending or membrane stresses tend to have depth-to-length ratios greater than 0.3^[23]. As a consequence, Q , the flaw shape parameter, is increased and K is reduced, resulting in a lower da/dN and a larger value of $N_f - N_0$.

The second conservative assumption involved "moving" the circumferential crack closer to the pipe ID. This assumption has the effect of moving the crack into a higher stress field. If the crack were "returned" to its original position so that the distance from its closest edge to the pipe ID was 0.70 cm (0.275 in.) rather than 0.37 cm (0.15 in.), the crack would not have propagated.

A calculation conforming to the requirements of Section XI (Article A-3000) of the ASME Code indicates that ΔK , the stress intensity factor

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*The yield stress, ultimate stress, and uniform elongation data were obtained from reference 24.

range, is in the vicinity of $46.56 \text{ MPa (m)}^{1/2}$ [$42.4 \text{ ksi (in.)}^{1/2}$] when the circumferential crack "pops" through to the pipe ID. This value is far below that of the critical stress intensity factor, which is at least $200 \text{ MPa (m)}^{1/2}$. At this point the crack is $1.0 \times 8.1 \text{ cm}$ ($0.4 \times 3.2 \text{ in.}$). A summary of the results is presented, in Table A-VI.

The ASME Code, Section XI, requires that the critical crack size be at least ten times the final crack size after all the stress cycles have been applied. In this case, the original crack was 0.63 cm (0.25 in.) deep and the wall thickness was 2.54 cm (1.0 in.), and the ASME Section XI criterion could not be met.

The problem was handled in the manner shown in Fig. A-5. The highest elastic thermal LOCE stress was obtained from the Applied Mechanics calculations^[19]. This elastic stress, 586.1 MPa (85 ksi), was divided by Young's Modulus to obtain the strain corresponding to that stress. This strain, 0.0033 , was related to an equivalent stress on a stress-strain curve calculated by means of the Hollomon equation*:

$$\sigma_T = K\epsilon^n$$

where

ϵ = True strain

σ_T = True stress

K, n = Material constants.

The boundary conditions are given below:

1. At yield $\sigma_T = \sigma_{ys}$, and $\epsilon = \frac{\sigma_{ys}}{E} + 0.002$.

where σ_{ys} = Yield Stress

E = Young's Modulus.

2. At the ultimate stress

$$\sigma_T = \sigma_E \text{ UTS} (1 + e_{\text{uniform}})$$

$$\epsilon = \ln(1 + e_{\text{uniform}})$$

where $\sigma_E \text{ UTS}$ = Engineering Ultimate Tensile Stress

e_{uniform} = Uniform elongation

By substituting the above values into the Hollomon equation, one obtains two equations with two unknowns which can be solved for n and K.

The elastic-plastic stress was calculated to be slightly less than the yield stress, 310.3 MPa (45 ksi), so it was rounded off to 310.3 MPa (45 ksi).

The Battelle technique for handling circumferential defects is found in reference 7. The results indicate that the flow stress, $\bar{\sigma}$, is not exceeded even for a circumferential defect 1.0 cm (0.4 in.) deep and 8.1 cm (3.2 in.) long.

Next, crack growth under 260 LOCE thermal cycles and 3600 OBE cycles was calculated. 3600 OBE cycles were chosen because this is ten times the sum of the OBE and LOCE cycles, and the OBE stresses are higher than the LOCE mechanical stresses (101.4 MPa vs 68.6 MPa or 14.7 ksi vs 9.95 ksi). The size of the crack after the 260 LOCE thermal cycles was calculated in the same manner as the crack growth data in Table A-III. It was found that the amount of crack propagation toward the ID was 0.02 cm (0.0069 in.). The crack did not propagate toward the OD. The crack size after the application of 260 LOCE thermal cycles was 0.65 x 5.2 cm (0.26 x 2.06 in.).

This crack size was then subjected to 3600 OBE cycles. The final crack size was calculated to be 0.67 x 5.3 cm (0.26 x 2.10 in.). Thus, the defect will not propagate through to the ID after 260 LOCE thermal

cycles and 3600 OBE cycles. Also, the crack that has propagated through to the ID (1.0 x 8.1 cm or 0.4 x 3.2 in.) will not then extend enough to sever the pipe on one application of the highest elastic-plastic LOCE thermal stress.

FIG. A-1 SKETCH OF AXIAL DEFECT

FIG. A-2 SKETCH OF CIRCUMFERENTIAL DEFECT

FIG A-3 STRESS VS PIPE WALL

THICKNESS FOR FINITE

STRESS ELEMENTS 155 TO 165

FIG. A-4 STRESS VS. PIPE WALL

THICKNESS FOR FINITE

STRESS ELEMENTS 46 TO 55

Fig. A-5a Procedure for determining whether a 1.0 x 3.2 cm circumferential crack will rupture on the application of one LOCE stress cycle.

Fig. A-5b Procedure for determining whether 260 LOCE stress cycles + 3600 OBE stress cycles will cause the original circumferential defect to grow larger than 1.0 x 8.1 cm.

TABLE A-I

DESCRIPTION OF DEFECTS IN BS 249

Circumferential Defect

Circumferential Position: 54.6 - 59.7 cm
(21.5 - 23.5 in.)

(Complete circumference =
 $\pi d = 85.8 \text{ cm} = 33.77 \text{ in.}$)

Crack Depth (2a) = 0.64 cm (0.25 in.)

Crack Length (2c) = 5.1 cm (2.0 in.)

Distance from pipe ID = 0.70 cm (0.275 in.) $\pm$ 50%

Distance downstream from weld centerline $\approx$ 1.14 cm
(0.45 in.)

Axial Defects

Circumferential Position*	83.8 cm (33.0 in.)	1.91 cm (0.75 in.)	8.9 cm (3.5 in.)	12.7 cm (5.0 in.)
Crack Depth (a)	0.37 cm (0.15 in.)	0.37 cm (0.15 in.)	0.33 cm (0.13 in.)	0.33 cm (0.13 in.)
Crack Length (2c)	4.6 cm (1.8 in.)	4.1 cm (1.6 in.)	3.1 cm (1.2 in.)	3.7 cm (1.5 in.)
Distance from weld centerline	3.7 cm (1.2 in.)	3.3 cm (1.3 in.)	4.1 cm (1.6 in.)	3.7 cm (1.5 in.)

* Referenced to an arbitrary zero position.

TABLE A-II

MEMBRANE STRESSES ON BS 249

	OBE	LOCE	Heat Up and Cooldown
Tangential	84.4 MPa (122.24 ksi)	83.8 MPa (12.16 ksi)	83.4 MPa (12.1 ksi)
Circumferential	101.4 MPa (14.7 ksi)	68.6 MPa (9.95 ksi)	50.3 MPa (7.3 ksi)

TABLE A-III

CRACK GROWTH CALCULATIONS UNDER SPECIFIED CONDITIONS*

a_o		a_f		M_b	M_m	σ_m		σ_b		$(\sigma_b M_b + \sigma_m M_m) \left(\frac{\pi}{Q}\right)^{1/2}$	$a_f^g - a_o^g$	$[(\Delta K)^m C]^{-1}$	$N_f - N_o$
cm	(in.)	cm	(in.)			MPa	(ksi)	MPa	(ksi)		g		
0.32	(0.125)	0.44	(0.175)	0.713	1.146	-129.6	(-18.8)	653.0	(94.7)	83.52	9.6075	133.8	1285
0.44	(0.175)	0.51	(0.20)	0.838	0.838	-156.5	(-22.7)	781.2	(113.3)	119.76	2.4491	18.5	46
												TOTALS CYCLES	1331

*Specified Conditions:

1. 594 K (610°F)
2. Initial crack size: 0.63 x 5.1 cm (0.25 x 2.0 in.) (See Fig. A-2)
3. Final crack size: 1.02 x 8.1 cm (0.4 x 3.2 in.)
4. Circumferential cracks
5. All calculations were performed in English units.

TABLE A-IV

CRACK GROWTH CALCULATIONS UNDER SPECIFIED CONDITIONS*

	$2 a_o$		M_m	σ		$\sigma M_m (1-R)^{0.65} \left(\frac{\pi}{Q}\right)^{1/2}$	a_f	
	cm	(in.)		MPa	(ksi)	(ksi)	cm	(in.)
OBE stresses	0.63	(0.25)	1.146	+101.4	(+14.7)	44.67	0.64	(0.252)
LOCE stresses	0.63	(0.25)	1.146	+ 68.6	(+ 9.95)	30.24	0.63	(0.250)

*Specified Conditions:

1. 594 K (610°F)
2. Initial crack size: 0.63 x 5.1 cm (0.25 x 2.0 in.) (see Fig. A-2)
3. Circumferential cracks
4. Number of cycles = 1300
5. All calculations were performed in English units.
6. $2a/2c = 0.125$.

TABLE A-V
CRACK GROWTH CALCULATIONS UNDER SPECIFIED
CONDITIONS*

	a_o		M_m	σ		$\sigma M_m (1-R)^{0.65} (\pi/a)^{1/2}$	a_f	
	cm	(in.)		MPa	(ksi)	(ksi)	cm	(in.)
OBE stresses	0.57	(0.225)	1.2	± 84.4	(± 12.24)	38.59	0.58	(0.227)
LOCE stresses	0.57	(0.225)	1.2	± 83.8	(± 12.16)	38.34	0.58	(0.227)

*Specified Conditions:

1. 594 K (610°F)
2. Initial crack size: 0.57 x 4.57 cm (0.225 x 1.8 in.) (See Fig. A-1)
3. Axial cracks
4. Number of cycles = 1300
5. All calculations were performed in English units
6. $a/2c = 0.125$.

TABLE A-VI
SUMMARY OF RESULTS

50

Stress Source	Number of Cycles	Stress Range		Initial Crack Size		Final Crack Size		Rupture at this Point
		MPa	(ksi)	cm	(in.)	cm.	(in.)	
<u>Circumferential</u>								
LOCE Thermal (Elastic) + Heat Up and Down	1300	+511.3 to - 67.6	(+74.15 to - 9.80)	0.64 x 5.1	(0.25 x 2.0)	1.0 x 8.1	(0.4 x 3.2)	No
OBE	1300	+101.4	(+14.7)	0.64 x 5.1	(0.25 x 2.0)	0.64 x 5.1	(0.25 x 2.0)	No
LOCE	1300	+ 68.6	(+ 9.95)	0.64 x 5.1	(0.25 x 2.0)	0.64 x 5.1	(0.25 x 2.0)	No
<u>Axial</u>								
LOCE Thermal (Elastic) & Heat Up and Cool Down	1300	+606.0 to - 93.4	(+87.89 to -13.54)	0.57 x 4.6	(0.225 x 1.8)	0.57 x 4.6	(0.225 x 1.8)	No
OBE	1300	+ 84.4	(+12.24)	0.57 x 4.6	(0.225 x 1.8)	0.58 x 4.6	(0.227 x 1.8)	No
LOCE	1300	+ 83.8	(+12.16)	0.57 x 4.6	(0.225 x 1.8)	0.58 x 4.6	(0.227 x 1.8)	No

55