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FRACTURE MECHANICS EVALUATION OF LOFT
LOWER PLENUM INJECTION NOZZLE

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FUELS AND MATERIALS DIVISION
EG&G IDAHO, INC.

MATERIALS ENGINEERING BRANCH
TECHNICAL REPORT

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LOWER PLENUM INJECTION NOZZLE

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LOFT TECHNICAL REPORT
LOFT PROGRAM

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ABSTRACT

Fuels and Materials Division was asked to perform an analysis to establish whether or not a leak-before-break concept would apply to the LOFT lower plenum injection nozzle. The analysis encompassed the structure from the inlet side of valve V-2170 to the lower plenum nozzle-to-reactor vessel weld on the left side of the emergency core cooling system (ECCS). The defect that was assumed to exist was of such a size that the probability of its being missed by the applicable inspection technique was near zero. Crack growth rates of axially and circumferentially oriented defects with Loss of Coolant Experiment (LOCE) plus Design Basis Earthquake (DBE) stresses applied to them were evaluated using analytical approaches developed at Battelle - Columbus.

The Inconel 600 nozzle forging with an initial assumed defect size of 0.64 cm (0.25 in.) deep would behave as follows: (1) the axially oriented defect would result in leak before rupture (the number of cycles to rupture was 11,000), (2) the circumferentially oriented defect would result in a rupture before leak. The number of cycles to failure would be in excess of 14,000.

Based on the conservative assumption that the thermal stresses were membrane stresses as opposed to a bending stress, the following were found. For the Inconel 82 weld metal (thickness of 1.3 cm [0.53 in.]) and AISI 316 SST valve body, with an initial assumed defect of 0.25 cm (0.1 in.), the crack would grow through the thickness in a minimum of 3950 cycles and to a critical rupture crack length of 5.1 cm (2.0 in.) in an additional 80 cycles.

The Inconel 82 weld metal at the shell body (thickness of 9.7 cm or 3.8 in.) with an assumed defect 1.3 cm (0.5 in.) deep would fail in 334 cycles. Calculations made assuming a linear stress gradient instead of the above-mentioned flat distribution through the wall indicated that the number of stress cycles increased to 2200.

SUMMARY

Fuels and Materials Division was asked to perform a crack propagation analysis on the LOFT lower plenum injection nozzle. The analysis encompassed the structure from the inlet side of valve V-2170 to the lower plenum nozzle-to-reactor-vessel weld (Fig. 1) on the left side of the emergency core cooling system (ECCS). The largest load is applied during the experimental blowdown in the loss-of-coolant experiment (LOCE) and design basis earthquake (DBE) where the internal pressure is 15.44 MPa (2237.7psi) and the thermal gradient is 221 K (398°F). The purpose of this analysis was to establish whether or not a leak-before-break concept would apply to the section shown in Figure 1 and, if the leak-before-break concept would prevail, then identify the critical defect size of a through-the-wall crack. Both axially and circumferentially oriented defects were evaluated in this analysis.

The approach used in this analysis was to assume a defect existed of a size for which the probability of being missed, by the applicable inspection technique, was near zero. The analytical approaches used were developed by Battelle for conditions of elastic-plastic stresses. The results are as follows:

1. The Inconel 82 weld metal between the Inconel 600 and 316SS plus the 316SS valve body. These structures are a nominal 1.3 cm (0.53 in.) thick and the assumed defect size was crack depth (a) = 0.25 cm (0.10 in.) and crack length (2c) = 0.84 cm (0.33 in.). Both axial and circumferential oriented defects would result in leak-before-break when the assumed defect was exposed to the highest stresses. The minimum number of cycles required to grow the potential defect from a = 0.25 cm (0.1 in.) to through-the-thickness was 3980 cycles.

The minimum number of cycles required to grow the through-thickness defect to the size required to cause catastrophic failure [4.5 cm (1.77 in.)] was 80 cycles.

2. Inconel 600 nozzle forging (cut 4 of Figure 4)

This structure is a nominal 7.4 cm (2.91 in.) thick and the assumed defect size was crack depth $a = 0.64$ cm (0.25 in.) and crack length ($2c$) = 2.1 cm (0.83 in.). The axially oriented defect would result in a leak-before-break when the assumed defect was exposed to the highest stresses. It required 11,100 cycles to grow the initial defect from $a = 0.64$ cm (0.25 in.) deep to through-thickness. The number of cycles needed to grow the axial crack to rupture length is not known. The circumferential crack will rupture before it leaks. The number of cycles required to grow the initial circumferential defect from $a = 0.64$ cm (0.25 in.) deep to rupture was calculated to be about 14,200 cycles.

3. Inconel 82 weld metal (cut 15 of Figure 4)

This structure is a nominal 9.7 cm (3.82 in.) thick and the assumed defect size was crack depth $a = 1.3$ cm (0.50 in.) and crack length ($2c$) = 4.2 cm (1.67 in.). The axially oriented defect would result in a leak-before-break when the assumed defect was exposed to the highest stresses. It requires 362 cycles to grow the crack from $a = 1.3$ cm (0.50 in.) to through-the-thickness. But, it only required a single cycle to grow the through-the-thickness defect to a length (19.3 cm or 7.59 in.) required to cause catastrophic failure. The circumferentially oriented defect of crack depth (a) = 1.3 cm (0.50 in.) would result in failure occurring before the defect penetrated the wall thickness, although, it would require 334 cycles to grow the potential defect ($a = 1.3$ cm or 0.50 in.) to a critical size (14.1 cm or 5.57 in. long).

I. INTRODUCTION

Fuels and Materials Division was asked to perform a crack propagation analysis on the LOFT lower plenum injection nozzle. The analysis encompassed the structure from the inlet side of valve V-2170 to the lower plenum nozzle-to-reactor-vessel weld (Fig. 1) on the left side of the emergency core cooling system (ECCS) ^[1]. The nozzle is an Inconel 600 (ASME SB-166) forging, welded at both ends with Inconel 82 (ASME SB-304) filler wire ^[2]. The largest load is applied during the experimental blowdown in the Loss-of-Coolant-Experiment (LOCE) and design basis earthquake (DBE) where the internal pressure is 15.44 MPa (2237.7 psi) ^[3] and the thermal gradient is 221K (398°F) ^[4]. The LOFT system will operate at 555K (540°F) ^[5]. A stress cycle is defined as one excursion in stress from the nominal stress before LOCE + DBE to the peak experienced during LOCE + DBE and back down to the nominal stress.*

The purpose of this analysis was to establish whether or not a leak-before-break concept would apply to the section shown in Figure 2 and, if the leak-before-break concept would prevail, then identify the critical defect size of a through-the-wall crack. Both axially and circumferentially oriented defects were evaluated in the analysis because the crack orientation was not known.

The approach used in this analysis was to assume a defect existed of a size for which the probability of being missed, by the applicable inspection techniques, was near zero. Calculations were made to determine the number of stress cycles necessary to propagate the crack through-the-wall-thickness. Calculations were also made to determine the crack size at rupture. If the latter was larger than the former, then calculations were made to see how many cycles were necessary to propagate the initial through-wall crack size to rupture size.

* Heat-up and cool-down stresses are so low (36.5 MPa or 5.3 ksi) they can be ignored ^[5].

II. CONCLUSIONS

The fracture mechanics evaluation of the LOFT lower plenum injection nozzle are tabulated below. Calculations made using conservative assumptions indicate that a defect initially 1.3 cm (0.5 in.) deep in the injection nozzle to reactor shell weld will withstand 334 cycles before rupture. Calculations utilizing more realistic, less conservative assumptions and the same initial and final crack depths indicate that the number of stress cycles increased to 2200.* Two other conservative assumptions** are listed below. First the critical crack lengths were calculated assuming that membrane stresses were being applied. Actually, the pipe is being subjected to bending stresses. Second, the bending stress distribution is not linear as was assumed, but nonlinear, the peak stress decreasing to near zero at the midwall. The effect of the above conservative assumptions cannot be assessed at this time.

The results are tabulated below.

	Axial Defects	Circumferential Defects
1. Weld between nozzle and valve body		
Initial defect size	0.25 cm x 0.85 cm (0.10 in. x 0.33 in.)	
Leak before rupture	yes	yes
Suggested cycles to failure	4030	4150
2. Valve body		
Initial defect size	0.25 cm x 0.85 cm (0.10 in. x 0.33 in.)	
Leak before rupture	yes	yes
Suggested cycles to failure	532,000	529,900
3. Nozzle body		
Initial defect size	0.64 cm x 2.1 cm (0.25 in. x 0.83 in.)	
Leak before rupture	yes	no
Suggested cycles to failure	>11,100	14,200
4. Weld metal		
Initial defect size	1.3 cm x 4.2 cm (0.50 in. x 1.67 in.)	
Leak before rupture	yes	no
Suggested cycles to failure	2900	2200

Based on the above table and conservative assumptions, it is felt that the LOFT lower plenum injection nozzle region can withstand at least 2200 LOCE + DBE's.

* The conservative and more realistic, less conservative assumptions are listed in Table II. **Both assumptions were used in the Battelle axial and circumferential analyses.

III. ANALYTICAL PROCEDURE AND RESULTS

1. INCONEL 82 WELD (BETWEEN INCONEL 600 AND AISI 316 VALVE BODY)

Linear elastic fracture mechanics (LEFM) concepts may be appropriate for this analysis but values of the stress intensity factor (K_c) for the critical plane stress are not available for Inconel 82 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_c . 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 nozzle containing a through-the-wall defect.

1.1 Calculating for Crack Size at Rupture Using Axially Oriented Defects

The first method^{*} was developed by Battelle - Columbus for axially oriented cracks in a pipe.

1.1.1 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

1.1.2 Calculation of σ_T

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

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

* 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.

For this particular problem $\sigma_{app} = 627.4$ MPa (91 ksi) and was developed from an elastic analysis.^[8]

σ_T is determined by true stress - true strain relationship

$$\sigma_T = K \epsilon_T^n$$

where σ_T = true stress

K = constant

ϵ_T = true strain

n = strain hardening exponent

At 588K (600°F) the engineering strain, ϵ is 30.0% and is related to ϵ_T by

$$\epsilon_T = \ln(1 + \epsilon) = \ln 1.30 = 0.262. \text{ The true stress - true strain}$$

equation is subject to the following conditions:

$$\sigma_{ys}(T) \approx \sigma_{ys} = K \left(\frac{\sigma_{ys}}{E} + 0.002 \right)^n$$

and

$$\sigma_{uts}(T) = \sigma_{uts} (1 + \epsilon_{uniform})^n = K [\epsilon_{uniform}(T)]^n$$

Solving the two equations simultaneously yields $n = 0.204$ and

$K = 135.9$. The subscript in parentheses, (T), applies only to situations where true stress and/or true strain apply. The absence of a subscript denotes engineering stress and/or strain. As the purpose of this effort is to relate σ_T as a function of σ_{app} where $\sigma_{app} = 627.4$ MPa (91 ksi) it is necessary to determine ϵ corresponding to 91 ksi.

$$\epsilon = \frac{91 \times 10^3}{26.6 \times 10^6} = 0.0034$$

Substituting $\epsilon = 0.0034$, $n = 0.204$ and $K = 135.9$ in the flow curve equation and assuming that $\sigma_T \approx \sigma$, to obtain $\sigma_T = 293.7$ MPa (42.6 ksi).

Data from Oak Ridge National Laboratory^[9] indicates $\sigma_{ys} = 297.9$ MPa (43.2 ksi) for Inconel 82 at 588K (600°F) which means that $\sigma_T < \sigma_{ys}$.

1.1.3 Calculation of $\bar{\sigma}$. Data from reference 9 were used to obtain

$\sigma_{ys} = 297.9$ MPa (43.2 ksi).

$\sigma_{uts} = 550.2 \text{ MPa (79.6 ksi) at } 588\text{K (600}^\circ\text{F)}$. Therefore,

$$\bar{\sigma} = \frac{43.2 + 79.6}{2} = 423.3 \text{ MPa (61.4 ksi)}.$$

1.1.4 Calculation of M_T for a Through-Thickness Crack.

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

$$M_T (42.6) = 423.3 \text{ MPa (61.4 ksi)}$$

$$M_T = 1.44$$

1.1.5 Calculation of Critical Defect Length (2c) from Figure 3 for $M_T = 1.44$

$$\frac{2c}{Rt}^{\frac{1}{2}} = 1.85$$

$$R = 5.7 \text{ cm (2.25 in.)}$$

$$t = 1.3 \text{ cm (0.531 in.)}$$

1.2 Calculation of Critical Crack Size At Rupture Using Battelle Approach For a Circumferentially Oriented Defect

1.2.1 General Equation (Ref. 6). The schematic, shown in Figure 2, of a pipe section containing a crack is used as follows:

Area of half region excluding the defect = $2\alpha RT$

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

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

Where $\bar{Y}$ = Distance from outside diameter to center of gravity

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

R = Radius to pipe outside diameter.

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

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

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

b = Distance from crack to center of circle.

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

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

where P = pressure of fluid in pipe

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

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

where t_{net} = the wall thickness for a partially-through-wall crack (e.g. $t_{net} = R-t$).

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

$$S_o \pi [R^2 - (R-t)^2] = P \pi (R-t)^2$$

where $S_o = 293.7$ (42.6 ksi) (effective force in Pipe)

$$R = 5.7 \text{ cm (2.25 in.)}$$

$$t = 1.3 \text{ cm (0.531 in.)}$$

and solve for P = 209.5 MPa (30.38 ksi)

** This term should be $\frac{Pr}{2t_{net}}$. This is an oversight, but errs on the conservative side as it gives a higher stress.

Solving for $\underline{S}$, that stress in the pipe where the component associated with $2(\pi-\alpha)Rt$ has been eliminated;

$$S (2\alpha Rt) = S_0 (2\pi Rt)$$

$$S = S_0 \frac{\pi}{\alpha}$$

$$\text{Substituting for } \frac{Pr}{t_{\text{net}}} = \underline{S} = S_0 \frac{\pi}{\alpha}$$

$$\text{and } S_0 (2Rt - t^2) = P (R-t)^2$$

to get

$$\sigma^* = \frac{S_0 \pi (2Rt - t^2) (R \frac{\sin \alpha}{\alpha}) (R) (\frac{\sin \alpha}{\alpha} - \cos \alpha)}{R^3 t (\alpha + \sin \alpha \cos \alpha - \frac{2 \sin^2 \alpha}{\alpha})} + \frac{S_0 \pi}{\alpha}$$

substituting for

$$\sigma = 423.3 \text{ MPa (61.4 ksi),}$$

$$R = 5.7 \text{ cm (2.25 in.)}$$

$$S = 209.5 \text{ MPa (30.38 ksi)}$$

$$t = 1.3 \text{ cm (0.531 in.)}$$

Solving the above equation graphically, it was found that the critical crack length corresponds to $62^\circ 3'$ around the circumference or 6.2 cm (2.44 in.) long.

1.3 Crack Growth

It is assumed that a crack 0.1 in. deep exists in the pipe wall perpendicular to the pipe axis. This is the size crack that would be detected about 90% of the time^[10]. Further, it is assumed that a/ρ (or a/ρ_c) = 0.3.

Therefore

$$a/\rho = 0.3$$

$$a/t = \frac{0.1}{0.531} = 0.189.$$

From ASME Section XI Appendix A-3000^[11]

$$M_m \approx 1.3$$

$$Q \approx 1.2.$$

A linear elastic fracture mechanics approach was used and it was assumed that a/ρ remains constant throughout crack growth.

$$\begin{aligned} K_I &= \sigma_m M_m \sqrt{\frac{\pi a}{Q}} = 42.6 \quad (1.3) \sqrt{\frac{\pi a}{1.2}} \\ &= 89.6 \sqrt{a} \quad \text{ksi (in.)}^{\frac{1}{2}} \end{aligned}$$

The da/dN vs. ΔK curve^{*} is obtained from the Nuclear Systems Materials Handbook, Property Code 2431, p.1.0^[12].

$$da/dN = C (\Delta K)^{4.583}$$

$$\text{where } \Delta K = 89.6 \sqrt{a} \quad \text{ksi} \sqrt{\text{in}}$$

$$C = 3.8312 \times 10^{-12}.$$

Integrating the above gives

$$\frac{da}{dN} = C (89.6 \sqrt{a})^n \quad \text{and}$$

$$\frac{da}{a^{n/2}} = C (89.6)^n dN.$$

$$\frac{a_f^{(-n/2 + 1)} - a_0^{(-n/2 + 1)}}{(-n/2 + 1)} = C(89.6)^n (N_f - N_0).$$

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

Substituting

$$C = 3.83 \times 10^{-12}$$

$$n = 4.583$$

$$a_o = 0.1 \text{ in.}^*$$

$$a_f = 0.531 \text{ in.}$$

gives

$$N_f - N_o = 3947 \text{ cycles.}$$

Therefore, it takes 3947 cycles to propagate a crack 0.25 cm (0.1 in.) deep through the 1.3 cm (0.531 in.) wall.

At this point the crack is 0.531 in. deep and 1.77 in. long ($a/\ell = 0.3$).

From the preceding, it is seen that $\ell = 2.02$ in. at rupture. To determine the number of cycles to grow the crack from 1.77 to 2.02 in., the formulae for a uniformly stressed panel with a central through-thickness crack are used to determine the stress-intensity factor, K [13].

The formula which gives the largest value for K is

$$K = \sigma \sqrt{\pi c} \sqrt{\sec \frac{\pi c}{2b}}$$

where c = half crack length (= 1.01 in.)

b = half panel width

σ = applied stress

$$\begin{aligned} K &= 42.6 \sqrt{\pi c} \sqrt{\sec \left(\frac{\pi (1.01)}{2b} \right)} \\ &= 75.47 (c)^{\frac{1}{2}} \text{ ksi (in.)}^{\frac{1}{2}}. \end{aligned}$$

Using the above integrated equation for crack growth,

$$\frac{c_f^{(-n/2 + 1)} - c_o^{(-n/2 + 1)}}{(-n/2 + 1)} = C(75.47)^n (N_f - N_o)$$

* All input data are not in SI units because the calculations were made in the English system. If the metric equivalence of these are desired, see Table I.

and substituting

$$c_f = 1.01 \text{ in.}$$

$$c_o = 0.885 \text{ in.}$$

$$n = 4.932$$

$$C = 3.83 \times 10^{-12}$$

it is found that

$$N_f - N_o \approx 85 \text{ cycles.}$$

If the results of $c_f = 1.22 \text{ in.}$ of the Circumferential Axial Battelle Method are used, then

$$N_f - N_o \approx 199 \text{ cycles.}$$

Combining the above number of cycles with that needed to propagate a 0.1 in.-deep crack through the wall (3947 cycles), it is seen that the total number of cycles to rupture in the Axial Battelle Method is 4032 and that for the Circumferential Battelle Method is 4146 cycles.

2. VALVE BODY

According to Fig. 1 the valve body is AISI 316 stainless steel. The wall thickness is 1.3 cm (0.531 in.). The rupture crack sizes for both the Axial and Circumferential Battelle Approaches require the calculation of the flow stress, $\bar{\sigma}$, and the stress corresponding to the strain imposed by the LOCE's. From the Nuclear Systems Handbook^[14] and ASME code case 1592^[15], the following are the mechanical tensile properties for AISI 316 stainless steel at 600°F:

$$\sigma_{uts} = 423.9 \text{ MPa (61.48 ksi)}$$

$$\sigma_{ys} = 125.5 \text{ MPa (18.20 ksi)}$$

$$\% \text{ Elongation} = 22.08\% (\text{min.})$$

$$E = 175.4 \text{ GPa (25.44} \times 10^6 \text{ psi)}$$

The valve body was analyzed to undergo an elastically calculated stress of 573.0 MPa (83.1 ksi) ^[16]. The elastic strain associated with this stress is $\frac{83.1}{25.44 \times 10^3} = 0.00327$.

Using the mechanical data above, the coefficient, K, and exponential, n, for the Flow Curve equation are found. The equation was found to take the form

$$\sigma_{(T)} = 127.8 \epsilon_{(T)}^{0.3299}$$

where $\epsilon_{(T)}$ = True Strain
 $\sigma_{(T)}$ = True Stress

Substituting

$$\epsilon_{(T)} = 0.00327$$

it is found that

$$\sigma_{(T)} = 133.3 \text{ MPa (19.34 ksi)}$$

Since the above 133.3 MPa (19.34 ksi) is not very much higher than the 125.5 MPa (18.2 ksi) σ_{ys} , linear elastic fracture calculations were used. *

The flow stress, $\bar{\sigma}$, was found to be 274.4 MPa (39.8 ksi).

2.1. Battelle Approach for Axially Oriented Defect Initially 0.1 in. Deep

2.1.1. Rupture Crack Size for Through Wall Crack, Substituting

$$\sigma_T = 133.3 \text{ MPa (19.34 ksi)}$$

$$\bar{\sigma} = 274.4 \text{ MPa (39.8 ksi)}$$

* This is not an overly unconservative assumption because strain hardening will cause σ_{ys} to increase as the number of cycles increases.

into $M_T (\sigma_t) = \bar{\sigma}$

gives $M_T = 2.06$.

Using Fig. 3

$$\frac{2c}{(Rt)^{\frac{1}{2}}} = 3.26$$

and $2c = 9.0$ cm (3.55 in.)

2.1.2 Cycles Required to Grow a Crack 0.1 in. Deep to Through Thickness.

From the literature^[17] comes the following relation for da/dN vs. ΔK :

$$da/dN = 2.09 \times 10^{-13} (\Delta K)^{5.4925}$$

where $da/dN = \text{in/cycle}$

$$\Delta K = \text{ksi} \cdot (\text{in})^{\frac{1}{2}}$$

Substituting

$$C = 2.09 \times 10^{-13}$$

$$n = 5.4925$$

into the integrated crack growth equation in Section III., page 9, and using

$$a_f = 0.531 \text{ in.}$$

$$a_o = 0.1 \text{ in.},$$

it is found that $N_f - N_o = 523,363$. The crack is now assumed to be 0.531 in. deep and 1.77 in. long (half length = 0.885 in.).

2.1.3 Cycles Required to Grow a Crack of $c = 0.885$ in to $c = 1.78$ in.

Substituting

$$c_f = 1.78 \text{ in.}$$

$$c_o = 0.885 \text{ in.}$$

$$C = 2.09 \times 10^{-13}$$

$$n = 5.4925$$

into the crack growth equations in Section III, 1.3, it is found that

$N_f - N_o = 864$. The total number of cycles is therefore 532,007.

2.2 Circumferential Battelle Approach

2.2.1 Rupture Crack Size for Through-Thickness Defects. Substituting

$$S_o = 19.34 \text{ ksi}$$

$$\bar{\sigma} = 39.8 \text{ ksi}$$

into the equation in Section III, 1.2.1, it is found that

$$\alpha = 2.49 \text{ radians}$$

and

$$2c = 2.49 \text{ in.}$$

2.2.2 Cycles Required to Grow a Crack 0.1 in. Deep to Through Thickness.

This was calculated before as being 523,363.

2.2.3 Cycles Required to Grow a Crack of $c = 0.885$ in. to $c = 1.24$ in.

Using the technique outlined in the section on the Axial Battelle Approach, it is found that $N_f - N_o = 5467$. The total number of cycles is 528,830 cycles.

3. INCONEL 600 NOZZLE FORGING (CUT 4 in FIG. 4)

The nozzle body is Inconel 600 alloy ^[8]. The mechanical properties at 600°F are below ^[19]:

$$\sigma_{uts} = 543.2 \text{ MPa (78.79 ksi)}$$

$$\sigma_{ys} = 192.2 \text{ MPa (27.87 ksi)}$$

$$\% \text{ Elongation (total)} = 31$$

$$\text{Young's Modulus} = 199.3 \text{ GPa} (28.9 \times 10^6 \text{ psi})$$

From other data [20], the uniform elongation at 588 K (600°F) is expected to be 96.8% of the total elongation. This makes the minimum uniform elongation about 30%. The flow curve is now

$$\text{The flow stress is } \frac{\sigma(T) 143.82 \epsilon(T)^{0.2819} + 78.79}{2} = 53.33 \text{ ksi} = \bar{\sigma}$$

The highest elastic stress 899.8 MPa or 130,500 psi is found at cut 4 in Fig. 4 [21]. This corresponds to an elastic strain of 0.00452. Substituting this into the Flow Curve Equation gives a stress of 216.4 MPa (31.38 ksi). At this point the nozzle has a 7.4 cm (2.91 in.) wall thickness [21].

3.1 Rupture Crack Size for Through Thickness Defects

3.1.1 Axial Battelle Approach. From the above it is found that

$$\sigma = 216.4 \text{ MPa (31.38 ksi)}$$

$$\bar{\sigma} = 367.7 \text{ MPa (53.33 ksi)}$$

The equation for a through-thickness crack in Section III, 1.1.4, indicates that the crack length, $2c$, at rupture is 23.7 cm (9.35 in.).

It is now necessary to determine what size crack with $a/2c = 0.3$ will propagate through the wall thickness with one application of the 216.4 MPa (31.38 ksi) stress. The equation used is

$$\sigma = \bar{\sigma} \left(\frac{t/a - 1}{t/a - 1/M_T} \right)$$

from Ref. 6. Using Figure 3, repeated iterations indicate that the crack size will be 5.0 cm x 16.7 cm (1.96 in. x 6.56 in.). This crack will propagate through the wall thickness in one application of the 31.38 ksi stress. The crack will be through-the-thickness

and 16.6 cm (6.56 in.) long. It will need to grow to a length of 9.35 in. before rupture would occur at the applied stress of 2.6.8 MPa (31.4 ksi).

3.1.2 Circumferential Battelle Approach. Substituting

$$\bar{\sigma} = 53.33 \text{ ksi}$$

$$S_0 = 31.38 \text{ ksi}$$

into the equation in Section III, 1.2.1, it is found that a through-thickness crack would have to be 13.7 cm (5.4 in.) long before rupture occurs. However, this would make $a/2c = \frac{2.91}{5.4} = 0.54$, a value greater than the 0.3

first assumed. This means that rupture will occur before the crack penetrates the nozzle wall. Taking $a/2c = 0.3$ and $2c = 13.7 \text{ cm (5.4 in.)}$, $a = 4.1 \text{ cm (1.62 in.)}$ for rupture. This means that one application of the 216.4 MPa

(31.38 ksi) stress on a pipe with a 4.1 cm x 13.7 cm (1.62 in. x 5.4 in.) crack will result in rupture. This is a conservative assumption; the crack will grow deeper (and longer) than that before "pop-through" occurs.

3.2 Crack Growth to Critical Size

3.2.1 Axial Battelle Approach. The crack growth rates of Inconel 82 and 600 are assumed to be the same in the literature^[14]. Using the equations in Section III, 1.3 for stress intensity factor and crack growth respectively, and substituting

$$\sigma_m = 31.38 \text{ ksi}$$

$$a_f = 1.97 \text{ in.}$$

$$a_0 = 0.25 \text{ in.}^*$$

it is found that $N_f - N_0 = 11,096$ cycles. On the application of one more stress cycle the crack will propagate through the wall thickness. It will, however, be less than the 23.5 cm (9.35 in.) rupture length and so will leak before rupturing.

* It is estimated that this size crack (0.63 cm or 0.25 in. deep) can be detected by ultrasonic techniques with about the same confidence as a defect 0.25 cm (0.1 in.) deep in 1.3 cm (0.531 in.) wall^[24].

3.2.2 Circumferential Battelle Approach. Using the same equations as above, except that $a_f = 1.62$ in., $N_f - N_0 = 37,884$ cycles. With $a_0 = 1.3$ cm (0.25 in.) instead of 0.25 cm (0.1 in.), $N_f - N_0 = 14,176$ cycles.

4. INCONEL 82 WELD AT SHELL (NOZZLE OUTLET, Cut 15 in Fig. 3)

The highest 336.3 MPa (121,300 psi) elastic stress near the shell-to-nozzle weld is found at cut 15. Using the data for Inconel 82, it is found that the strain is 0.00456 and the stress from the true stress-true strain is 312 MPa (45.25 ksi). At this point the wall thickness is 9.7 cm (3.82 in.).

4.1 Rupture Crack Size for Through-Thickness Defects

4.1.1 Axial Battelle Approach. Using the Flow Curve Equation, it was found that $\sigma = 312$ MPa (45.25 ksi). The flow stress remained the same, $\sigma = 423.3$ MPa (61.4 ksi). Using Fig. 3, it was found that $2c = 19.3$ cm (7.59 in.). Using the same technique as that used on the rupture crack size for the Inconel 600 (cut 4 in Fig. 4), it was found that the crack depth for $a/2c = 0.3$ that would propagate through (or "pop" through) the wall on one application of the 312 MPa (45.25 ksi) stress was 6.7 cm x 19.0 cm (2.24 in. x 7.36 in.). Since the crack rupture length was 19.3 cm (7.59 in.), the weld will leak before it ruptures.

4.1.2 Circumferential Battelle Approach. Using

$$S_0 = 312 \text{ MPa (45.25 ksi)}$$

$$\bar{\sigma} = 423.3 \text{ MPa (61.4 ksi)}$$

and substituting them in the equation in Section III, 1.2.1, the crack length at rupture for a through-wall defect was 14.1 cm (5.57 in.). This makes $a/2c = 0.69$ for a through-wall crack of 9.7 cm (3.82 in.). For $a/2c = 0.3$, $a = 4.2 \text{ cm (1.67 in.)}$ for $2c = 14.1 \text{ cm (5.57 in.)}$. This means that upon one application of 312 MPa (45.25 ksi) stress the 4.2 cm x 14.1 cm (1.67 in. x 5.57 in.) defect will "pop"-through the wall thickness. Rupture will occur before leaking.

4.2 Crack Growth

4.2.1 Axial Battelle Approach. Using the stress intensity and crack growth equations in Section III, 1.3, and $a_f = 6.7 \text{ cm (2.24 in.)}$, $a_0 = 0.25 \text{ cm (0.1 in.)}$ $N_f - N_0 = 3323 \text{ cycles}$. If the same conditions hold, except $a_0 = 1.3 \text{ cm (0.5 in.)}$, $N_f - N_0 = 362 \text{ cycles}$. The through-thickness crack will propagate to rupture crack length in one cycle.

4.2.2 Circumferential Battelle Approach. Similar calculations using $a_f = 4.2 \text{ cm (1.67 in.)}$ and $a_0 = 0.25 \text{ cm (0.1 in.)}$ give $N_f - N_0 = 3295 \text{ cycles}$. With $a_f = 4.2 \text{ cm (1.67 in.)}$ and $a_0 = 1.3 \text{ cm (0.5 in.)}$, $N_f - N_0 = 334 \text{ cycles}$.

* This is an estimate by the writer of the crack depth that can be detected by ultrasonic techniques about 90% of the time.

IV DISCUSSION

The results of the calculations are presented in Table I. Four factors affect the number of cycles to failure - two decrease the cycles to failure and two increase them.

One factor tending to decrease the number of cycles to failure is the water environment inside the pipe. Aqueous environments have been known to increase crack growth rate, da/dN ^[15]. The other factor is the frequency effect^[23]. A lower frequency tends to increase crack growth rate. It is not known precisely how much the above factors affect the number of cycles to failure. An educated guess would be by a factor of 10, so that the number of cycles to failure in Table I would need to be divided by 10.

A factor tending to increase the number of cycles to failure is the assumption that the stress is uniform through the pipe wall thickness. This is not true - over 75% of the elastically calculated stress is due to the thermal gradient^[24]. If the thermal gradient stress were reduced to one-third its original value at half the pipe wall thickness, a crack half the pipe wall thickness in the 1.3 cm (0.531 in.) thick Inconel 82 weld would need over 17,900 cycles to grow through the wall thickness, as opposed to about 750 cycles for crack growth over the same distance but assuming that the thermal stresses were membrane stresses. This occurs because the crack growth exponent, n , for the Inconel 82 weld metal is sufficiently large so that any decrease in ΔK has a large effect on da/dN or $N_f - N_0$. The above separation of the thermal gradient from the pressure stress is treated in Section A-3000 of the ASME Code (Ref.11). A second illustration of the conservatism introduced by this assumption is found in the Appendix for the Inconel 82 weld at cut 15 (Fig.4). An axially oriented, 1.3 cm (0.5 in.) deep crack required 363 cycles to grow to failure. Making the assumptions

that 689.5 MPa (100 ksi) of the stress is tensile (the other 146.9 MPa (21.3 ksi) is compressive) and that the stress gradient was linear through the wall thickness (a conservative assumption ^[25]), it was calculated that 2944 cycles would be needed to grow the crack from 1.3 cm (0.5 in.) deep to rupture. This is more than an eightfold increase in cycles to failure. Similar calculations for a circumferentially oriented 1.3 cm (0.5 in.) deep crack indicate that 2211 cycles are required for sufficient crack growth to cause rupture. This is more than a sixfold increase in life from the originally calculated 334 cycles. The rupture crack depths used in the Appendix were the ones originally calculated in the main body of this report. These values are also conservative because the whole stress was considered to be a membrane stress, whereas the stress is really the sum of membrane and thermal bending stresses. There are no known methods to handle this problem.

Furthermore, the tensile stress on the pipe outer diameter (O.D.) is actually much lower than the stress on the inside diameter (I.D.). This means that the crack will initially grow at a high rate, slowing down as it penetrates the wall. When (if) it penetrates the wall, it will be traveling very slowly. This slowly growing part of the crack on the pipe O.D. will put a drag on the part of the crack at the pipe I.D. Therefore, the crack will grow to its critical size more slowly than the numbers in Table I indicate. At this time, the effect of these cannot be evaluated.

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

The above indicates that the factors tending to increase the number of cycles to failure more than compensate for those tending to decrease the cycles to failure.

* A configuration such as Fig. 5b may never occur because of the compressive stress at the outer diameter.

Another item 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.

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APPENDIX

FURTHER CALCULATIONS ON INCONEL 82 WELD AT CUT 15

This appendix contains the calculations which determine the number of stress cycles necessary to propagate a defect from an assumed initial size to rupture with a linear stress gradient through the wall i.e., a bending stress. The previous treatment in Section III. 1.2 assumed no stress gradient through the wall, i.e., that the pipe was being subjected only to a membrane stress.

1. ASSUMPTIONS

- (1) 689.5 MPa (100 ksi) of the 836.3 MPa (121.3 ksi) thermal stress in the McPherson Associates report is tensile; the balance is compressive.
- (2) The stress gradient is linear through the wall thickness.
- (3) The originally calculated critical crack depths for both the Axial and Circumferential Battelle Approaches can be used for this evaluation.

2. STRESS CONVERSION BY FLOW CURVE EQUATION

The Flow Curve Equation is

$$\sigma = K\epsilon^n$$

where $n = 0.204$

$$K = 135.9$$

ϵ = True Strain

σ = True Stress (ksi)

The above values come from section 1.2 of Analytical Procedure and Results.

The elastic modulus of Inconel 82 at 600°F is $E = 183.40 \text{ GPa}$ ($26.6 \times 10^6 \text{ psi}$).

The pressure (2237.7 psi or 15.4 MPa) exerts an additional stress on the pipe of 3244 psi ($\sim 3.2 \text{ ksi}$ or 22.1 ksi) resulting in an elastic tensile stress of 103.2 ksi or 711.5 MPa.

This 103.2 ksi is converted to a stress from the Flow Curve Equation by

$$\begin{aligned} \frac{103.2 \text{ ksi}}{26.6 \times 10^3 \text{ ksi}} &= 0.00388 = \epsilon \\ \sigma &= K\epsilon^n = 135.9 (0.00388)^{0.204} = 43.8 \text{ ksi.} \end{aligned}$$

This value is so close to the 297.7 MPa (43.2 ksi) yield stress that linear elastic fracture mechanics (LEFM) can be used. The -124.8 MPa (-18.1 ksi) compressive stress is within the elastic region and so remains the same.

3. CALCULATIONS OF σ_m AND σ_b BY ASME SECTION XI, ARTICLE A - 3000.

The Linearized Representation of Stresses in Fig. 5 is taken from Fig. A-3200-1 (Ref. 11). The bending stress, σ_b , is 30.95 ksi and the membrane stress, σ_m , is 12.85 ksi.

4. CALCULATION OF K_I BY ASME SECTION XI, ARTICLE A - 3000 (Ref. 11)

The equation in Ref. 11 is

$$K_I = \sigma_m M_m \left(\frac{\pi a}{Q}\right)^{\frac{1}{2}} + \sigma_b M_b \left(\frac{\pi a}{Q}\right)^{\frac{1}{2}}$$

where $\sigma_m = 12.85$ ksi

M_b, M_m = comes from Fig A-3300-3 and 5 respectively of Ref. 11

$Q = 1.2$

$\sigma_b = 30.95$ ksi

Since M_b and M_m are both functions of flaw depth to thickness (a/t), the evaluation will be done in steps, e.g., from $0.15 < a/t < 0.25$, the values of M_b and M_m for $a/t = 0.20$ will be used. This will be done till the crack attains the critical depth before "pop"-through.

5. CALCULATION OF NUMBER OF CYCLES BEFORE "POP"-THROUGH

The equation used will be

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

where a_f = Final crack size

a_o = Initial crack size

$C = 3.83 \times 10^{-12}$

$n = 4.583$

ΔK = Stress intensity factor amplitude with dependence on crack depth removed by integration.

5.1 Number of Cycles for a Circumferentially Oriented Defect

The crack depth at "pop"-through was 1.67 in. The steps taken were (1) "a" increasing from 0.573* in. to 0.955 in. (a/t from 0.15 to 0.25), (2) "a" increasing from 0.955 in. to 1.337 in. (a/t from 0.25 to 0.35), and (3) "a" increasing from 1.337 in. to 1.67 in. (a/t from 0.35 to 0.44) where "a" is crack depth. The results are tabulated below.

	M_m	M_b	$\frac{K_I}{(a)^{1/2}}$	$N_f - N_o$
$a_o = 0.573$ in. $a_f = 0.955$ in.	1.1	0.8	62.93	1142
$a_o = 0.955$ in. $a_f = 1.337$ in.	1.14	0.7	58.76	590
$a_o = 1.337$ in. $a_f = 1.67$ in.	1.17	0.55	51.87	479
TOTAL				2211 cycles

5.2 Axial Battelle Approach

The same procedure was followed as in the Circumferential Battelle Approach except that the crack depth at "pop"-through was 5.7 cm (2.24 in.) instead of 4.2 cm (1.67 in.). This required two more steps. The results are tabulated below.

* The value 0.573 in., as opposed to 0.50 in. was inadvertently used. As this was an error on the conservative side, no additional effort was deemed necessary.

	M_m	M_b	$\frac{K_I}{(a)^{1/2}}$	$N_f - N_o$
$a_o = 0.573$ in. $a_f = 0.955$ in.	1.1	0.8	62.93	1142
$a_o = 0.955$ in. $a_f = 1.337$ in.	1.14	0.7	58.76	590
$a_o = 1.337$ in. $a_f = 1.67$ in.	1.17	0.55	51.87	479
$a_o = 1.67$ in. $a_f = 2.101$ in.	1.22	0.43	28.99	586
$a_o = 2.101$ in. $a_f = 2.24$ in.	1.25	0.40	28.44	147
			TOTAL	<u>2944</u> cycles

Fig. 1 Dwg 204283 Rev. J

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so the appropriate portion is reproduced here.)

Fig. 2. Crack in Pipe

FIG. 3 M_T vs $\frac{2c}{(Rt)^{1/2}}$.

FIG. 4- SCHEMATIC OF NOZZLE.

FIG. 5
LINEARIZED REPRESENTATION OF
STRESSES.

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
RESULTS OF FRACTURE MECHANICS CALCULATIONS

1. Inconel 82 weld (between Inconel 600 nozzle and AISI 316 valve body) with an estimated initial maximum defect size of $a = 0.25$ cm (0.10 in.) and a nominal wall thickness of 1.3 cm (0.531 in.).

	<u>Axial Battelle Approach</u>	<u>Circumferential Battelle Approach</u>	<u>Suggested Number of Cycles</u>
Cycles to grow crack through wall	3947	3947	3950
Crack length at "pop"-through	4.5 cm (1.77 in.)	4.5 cm (1.77 in.)	
Critical crack length *	5.1 cm (2.02 in.)	6.2 cm (2.44 in.)	
Leak before rupture?	yes	yes	
Cycles to grow crack from "pop"-through to critical length	85	199	80; 200
Total cycles to failure	4032	4146	4030; 4150

2. AISI 316 Valve Body with an estimated initial maximum defect size of $a = 0.25$ cm (0.10 in.) and a nominal wall thickness of 1.3 cm (0.531 in.).

Cycles to grow crack through wall	523,363	523,363	523,400
Crack length at "pop"-through	4.5 cm (1.77 in.)	4.5 cm (1.77 in.)	
Critical crack length *	9.0 cm (3.55 in.)	4.5 cm (1.77 in.)	
Leak before rupture	yes	yes	
Cycles to grow crack from "pop"-through to critical length	8644	5467	8600; 5500
Total cycles to failure	532,007	528,830	532,000; 528,800

*Assumes $a/2c = 0.3$

TABLE I (continued)

3. Inconel 600 Forging Nozzle Body (cut 4 in Fig. 4) with an estimated maximum initial defect size of $a = 0.25$ in. and a nominal wall thickness of 2.91 in.

	<u>Axial Battelle Approach</u>	<u>Circumferential Battelle Approach</u>	<u>Suggested Number of Cycles</u>
Cycles to grow crack through wall	11,096	14,176	11,100; 14,200
Crack length at "pop"-through	16.7 cm (6.56 in.)	24.6 cm (9.7 in.)	
Critical crack length*	23.8 cm (9.35 in.)	13.7 cm (5.4 in.)	
Leak before rupture?	yes	no	
Cycles to grow crack from "pop" through to critical length	?	None	
Total cycles to failure	> 11,096	14,176	> 11,100; 14,200

4. Inconel 82 Weld Metal (cut 15 in Fig. 4) with an estimated maximum initial defect size of $a = 1.3$ cm (0.50 in.) and a nominal wall thickness of 9.7 cm (3.82 in.)

Cycles to grow crack through wall	362 (2944)**	334 (2211)**	2900; 2200
Crack length at "pop"-through	18.7 cm (7.36 in.)	32.3 cm (12.73 in.)	
Critical crack length*	19.3 cm (7.59 in.)	14.2 cm (5.57 in.)	
Leak before rupture?	yes	no	
Cycles to grow crack from "pop"-through to critical length	1	none	
Total cycles to failure	363 (2945)	334 (2211)	2900; 2200

*Assumes $a/2c = 0.3$

** See Appendix

TABLE II

CONSERVATIVE AND MORE REALISTIC ASSUMPTIONS

CONSERVATIVE ASSUMPTIONS

1. The design specification stress values (for the lower plenum injection nozzle) used here were supplied to the writers by C. A. Moore.
2. The thermal stresses are considered as exclusively membrane stresses.
3. LOCA stresses are not considered because a LOCA is a once-in-a-lifetime occurrence and damage tolerance levels are higher than for LOCA's.
4. The stresses are applied to the system as strains; therefore, the true stress - true strain curve can be used to obtain the stresses.
5. The defect grows by fatigue to a point where it will create a leak or rupture. Whether a leak or rupture occurs is determined by approaches developed by Battelle-Columbus^[6,7]. (Thus, defect growth is calculated by fracture mechanics equations; the point at which leak or rupture occurs is established by empirical means)

MORE REALISTIC ASSUMPTIONS

1. The McPherson Associates report stresses are used.^[21] In the above report, 689.5 MPa (100 ksi) of the 836.3 MPa (121.3 ksi) thermal is tensile; the balance is compressive.
2. The stress gradient is linear through the wall thickness. ASME Section XI^[11] was used to evaluate the crack growth in the presence of the stress gradient.
3. Conservative Assumptions 3, 4, and 5 apply.

* If the system will be subjected to conditions beyond those outlined in the design specification, additional thermal and mechanical analyses should be performed.