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CALCULATION TITLE PAGE

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Project: Hope Creek Decontamination Port	Task No. 1108-0502-0002-00
Title: Fatigue Crack Growth Evaluation	Calculation No. 1108-0002-08

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QUALITY ASSURANCE DOCUMENT
This document has been prepared, checked, and reviewed/approved in accordance with the Quality Assurance requirements of 10CFR50 Appendix B, as specified in the MPR Quality Assurance Manual.

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RECORD OF REVISIONS

Calculation No.	Prepared By	Checked By	Page: 2
1108-0002-08	J Hibbard	M. Hering	

Revision	Affected Pages	Description
0	All	Initial Issue

Note: *The revision number found on each individual page of the calculation carries the revision level of the calculation in effect at the time that page was last revised.*

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1.0 PURPOSE

The two purposes of this calculation are:

- Determine the acceleration that could cause a fatigue crack to initiate. Three cases are considered corresponding to the three design endurance limit stresses from the ASME Code (ASME Code Curves A, B, and C for different mean stress conditions).
- Determine the approximate number of cycles to propagate a crack through the wall thickness of the pipe. The three cases considered are for pipe accelerations that correspond to the results for crack initiation as discussed in the previous bullet.

2.0 SUMMARY

The acceleration that produces an alternating stress equal to the design value from the ASME Code at 10^{11} cycles is provided in the following table. The table provides the acceleration for crack initiation for the three fatigue design curves in the ASME Code (labeled A through C).

$$T1 = \begin{pmatrix} \text{"ASME"} & \text{"Endurance Limit Alternating Stress"} & \text{"Acceleration"} \\ \text{"Curve"} & \text{"ksi"} & \text{"g"} \\ \text{"A"} & 23.8 & 0.72 \\ \text{"B"} & 16.5 & 0.5 \\ \text{"C"} & 13.7 & 0.41 \end{pmatrix}$$

The minimum acceleration that gives a stress intensity factor at the crack tip greater than the threshold stress intensity factor for crack growth at the pipe OD is $a_{min} = 0.29\,g$. This is based on a threshold stress intensity factor for crack growth assumed to be $\Delta K_{min} = 5\ ksi\cdot\sqrt{in}$ and a defect initial depth of $a_{o.1} = 0.021\ in$. The defect size is based on the metalographic examination.

The crack growth rate at the threshold stress intensity factor for crack growth is $dadn_{min} = 3.73 \times 10^{-8} \frac{in}{cycle}$. At a frequency of $f_n = 123\ Hz$, this crack growth rate will go through the pipe wall thickness in $t_{max} = 0.85\ day$.

The number of cycles to propagate a crack through the pipe wall (defined as 70% though the pipe wall) is provided in Table T2 below for each of the accelerations in Table T1 above. The approximate time for the crack to propagate through the pipe wall is based on a frequency of $f_n = 123\ Hz$.

These are approximate results based on a simplified model for the crack growth. The results show the crack grows through the pipe wall in less than one day. This is consistent with the maximum time to grow the crack through the pipe wall discussed on the previous page.

$$T2 = \begin{pmatrix} \text{"Acceleration"} & \text{"Cycles for"} & \text{"Approximate Time"} \\ \text{"g"} & \text{"Through-wall Crack"} & \text{"hr"} \\ 0.72 & 170000 & 0.4 \\ 0.5 & 550000 & 1.3 \\ 0.41 & 1.02 \times 10^{6} & 2.3 \end{pmatrix}$$

3.0 APPROACH

This calculation is a simplified fatigue crack growth calculation. The actual defect location is a subsurface elliptical flaw in the circumferential direction as described in Reference 2. The defect is near the pipe OD, so that after some initial crack growth, the defect becomes a surface defect similar to that shown in Figure 1.

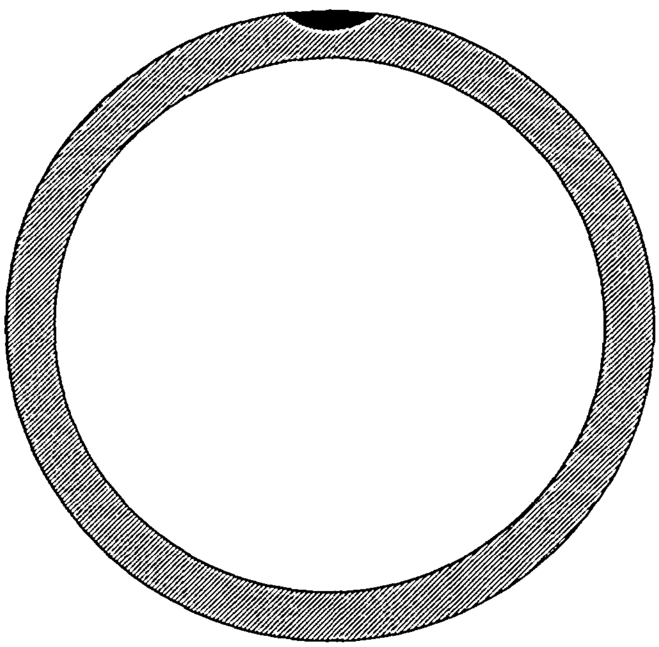


Figure 1. Approximate Crack Configuration after Defect Grows to Pipe OD

The growth of the defect from cyclic loads is predicted using the Paris equation.

$$\frac{da}{dN} = C_I \cdot \Delta K_I^{\,n}$$

where $\frac{da}{dN}$ = defect growth per cycle

ΔK_I = cyclic range of stress intensity factor

C_1, n = crack growth constants

The cyclic range of stress intensity factor is calculated with the following equation:

$$\Delta K_I = M \cdot \Delta\sigma \cdot \sqrt{\pi \cdot a}$$

where $\Delta\sigma$ = effective stress range
M = magnification factor
a = crack depth

The magnification factor is based on an edge crack in a semi-infinite plate. The crack configuration for the magnification factor is shown in Figure 2. The magnification factor is a constant that does not change with crack depth. This model for the crack in the pipe is approximate. At small crack depths, the flat plate model will give good results, but at larger crack depths the magnification factor will vary. The approach used in this calculation is sufficient for evaluating the propagation of shallow cracks as well as showing the crack propagation occurs in a short time as discussed in Section 2.0.

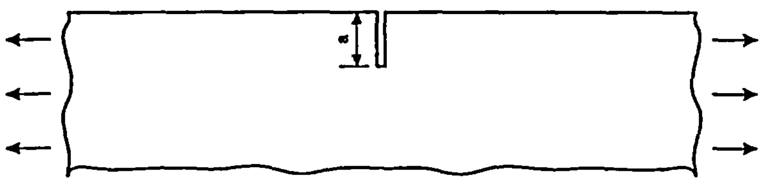


Figure 2. Model for Crack Magnification Factor

Section 4.1 below shows that stress varies significantly through the thickness of the pipe. The maximum stress occurs at the pipe OD and the minimum occurs at the pipe ID. The stress used to grow the crack at each cycle is the stress range at the crack depth.

The initial defect size is based on the metalographic examination. The defect that was identified was a sub-surface elliptical defect with minor radius of $a_{o.I} = 0.021\ in.$ For this calculation, it was assumed that a defect with this depth is at the surface. It is noted that this initial defect size is one-half the size of the sub-surface defect. Using this initial defect overestimates the number of cycles for the crack to grow through the pipe wall.

4.0 CALCULATION

4.1 Data

$T_{op} := 550 \cdot F$ — approximate operating temperature; assumption

$t_{wt} := 0.337 \cdot in$ — pipe wall thickness; assumption

$a_{o.1} \equiv \frac{0.042}{2} \cdot in$ — defect initial depth; scaled from Ref. 2, Figure 8

$f_n := 123 \cdot Hz$ — frequency for approximate conversion of cycles into time

$E_{hot.304SS} := 25.55 \cdot 10^{6} \cdot psi$ — modulus of elasticity of 304 SS at the operating temperature, Ref. 4, Table I-6.0

Fatigue Crack Growth Equations (Reference 3, C-8410; austenitic stainless steel in air)

$n_{304SS} := 3.3$ — crack growth exponent; Ref. 3, C-8410

$S := 1$ — scaling parameter; based on R=-1 and Ref. 3, C-8410

$$C_{304SS} := 10^{-10.009 + 8.12 \cdot 10^{-4} \cdot \frac{T_{op}}{F} - 1.13 \cdot 10^{-6} \cdot \left(\frac{T_{op}}{F}\right)^{2} + 1.02 \cdot 10^{-9} \cdot \left(\frac{T_{op}}{F}\right)^{3}} \cdot \frac{in}{\left(ksi \cdot \sqrt{in}\right)^{n_{304SS}}}$$

$C_{304SS} = 1.84 \times 10^{-10} \frac{in}{\left(ksi \cdot \sqrt{in}\right)^{n_{304SS}}}$ — temperature corrected proportionality constant for crack growth; Ref. 3, C-8410

$M := 1.1215$ — magnification factor for an edge crack in a semi-infinite plate; Ref. 5, p. 8.1a

$\Delta K_{min} := 5 \cdot ksi \cdot \sqrt{in}$ — approximate minimum stress intensity factor threshold for crack growth; assumption; see Ref. 3, Figure C-8410-1

Fatigue Crack Initiation Data

$S_a := \begin{pmatrix} 23.8 \\ 16.5 \\ 13.7 \end{pmatrix} \cdot ksi \qquad c := \begin{pmatrix} "A" \\ "B" \\ "C" \end{pmatrix}$ — ASME Code alternating stress at 10^{11} cycles from design fatigue curve for austenitic stainless steel; Ref. 4, Figure I-9.2.2

$E_{fatigue} := 28.3 \cdot 10^{6} \cdot psi$ — modulus of elasticity for fatigue data; Ref. 4, Figure I-9.2.2

Stress and Stress Distribution Function

$S1_{max} := 29.967 \cdot \frac{ksi}{g}$ maximum axial stress at pipe OD for reference case with 1 g acceleration; Ref. 1

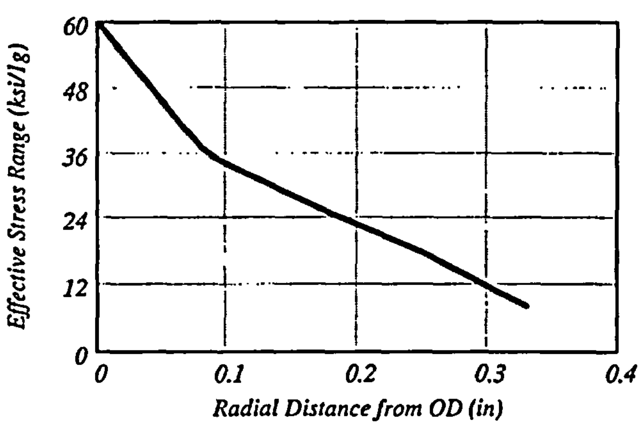
$S3_{min} := -S1_{max}$ $S3_{min} = -29.97 \frac{ksi}{g}$ minimum axial stress at pipe OD for reference case with 1 g acceleration; Ref. 1

$SI := (S1_{max} - S3_{min})$ $SI = 59.93 \frac{ksi}{g}$ stress range at pipe OD

Define a function for the stress range distribution through the pipe wall. The stress range is twice the alternating stress from Reference 1. Data for the stress vs. distance from the pipe OD are in Reference 1. The stress distribution is based on a 1g pipe acceleration.

$$t := t_{wt} - \begin{pmatrix} 0.337 \\ 0.2528 \\ 0.1685 \\ 0.0842 \\ 0 \end{pmatrix} \cdot in \qquad \sigma := \begin{pmatrix} 29.967 \\ 18.016 \\ 13.106 \\ 8.7483 \\ 3.6388 \end{pmatrix} \cdot \frac{ksi}{g}$$

$$\Delta\sigma(x) := 2 \cdot linterp(t, \sigma, x)$$



Pipe OD

Pipe ID

Notes:

The depth dimension in figure is based on the distance from the pipe OD.

The effective stress range is twice the alternating stress.

The stress profile from Reference 1 varies significantly through the pipe wall. The reason for the variation is the close proximity of the weld to the weldolet. Further away from the weldolet in the axial direction, there is little variation is stress through the wall thickness, which is the expected result for a pipe with an applied bending moment.

4.2 Acceleration for Fatigue Crack Initiation

Calculate the acceleration for fatigue crack initiation. No stress concentration factor is required in this calculation since the finite element results in Reference 1 captured the effects of stress concentration.

$$a_{init} := \overrightarrow{\frac{S_a \cdot \left(\frac{E_{hot.304SS}}{E_{fatigue}} \right)}{SI_{max}}}$$

$$a_{init} = \begin{pmatrix} 0.72 \\ 0.5 \\ 0.41 \end{pmatrix} g$$

4.3 Minimum Acceleration for Crack Growth

Calculate the minimum acceleration that gives a stress intensity factor at the crack greater than the threshold stress intensity factor for crack growth.

$$a_{min} := \left| \begin{array}{l} a_{guess} \leftarrow 1 \cdot g \\ root\left(\Delta K_{min} - a_{guess} \cdot M \cdot SI \cdot \sqrt{a_{0.1} \cdot \pi}, a_{guess}\right) \end{array} \right.$$

$$a_{min} = 0.29\,g$$

The crack growth rate at the threshold stress intensity factor for crack growth is:

$$dadn_{min} := S \cdot C_{304SS} \cdot \Delta K_{min}{}^{n_{304SS}}$$

$$dadn_{min} = 3.73 \times 10^{-8}\,\frac{in}{cycle}$$

The maximum time to grow the crack through the pipe wall at the minimum crack growth rate is (frequency of $f_n = 123\,Hz$):

$$t_{max} := \frac{t_{wt}}{dadn_{min} \cdot f_n}$$

$$t_{max} = 0.85\,day$$

4.4 Crack Growth Functions

The crack growth for an application of a single cycle is:

$$a_g(a,SI) := \left| \begin{array}{l} \Delta K \leftarrow M \cdot SI \cdot \sqrt{a \cdot \pi} \\ dadn \leftarrow \left| \begin{array}{ll} S \cdot C_{304SS} \cdot \Delta K^{n_{304SS}} & \text{if } \Delta K > \Delta K_{min} \\ 0 \cdot in & \text{otherwise} \end{array} \right. \end{array} \right.$$

A function for calculating crack growth for multiple applications of a single transient is provided below. The parameters passed to the function are as follows:

a	=	initial crack depth
t	=	component thickness
acc	=	accuracy criterion (see discussion below)
accel	=	acceleration to apply to 1 g stress distribution

At the start of the crack growth calculation, the membrane stress, bending stress, and magnification factors are updated after each transient, i.e., N=1. As the calculation progresses, N is increased to reduce the calculation time provided the accuracy criterion is met and N is less than the total cycles divided by 10. The accuracy criterion "min" is the total projected crack growth in the transient at the current value of N divided by the initial flaw size.

The accuracy criterion used is:

$$acc := 0.01\%$$

The number of cycles per iteration, N, is allowed to increase if the total crack growth in the transient is projected to be less than $acc = 0.01\,\%$ of the initial crack size. Using values smaller than $acc = 0.01\,\%$ did not significantly change the answer.

The following function determines the number of cycles for the crack to propagate through 70% of the wall thickness. For the purpose of this calculation, this is considered a through-wall crack.

$$a_{end} := 70 \cdot \%$$

$$Crk_1(a, t, acc, accel) := \left| \begin{array}{l} count \leftarrow 1 \\ test \leftarrow 1 \\ N \leftarrow 1 \\ \text{while } test \\ \quad \left| \begin{array}{l} \sigma \leftarrow accel \cdot \Delta\sigma(a) \\ a_{old} \leftarrow a \\ a \leftarrow a_{old} + N \cdot a_g(a, \sigma) \\ N \leftarrow 2 \cdot N \ \text{ if } \dfrac{a - a_{old}}{a_{old}} < acc \\ test \leftarrow 0 \ \text{ if } a > a_{end} \cdot t \vee count > 10^9 \\ count \leftarrow count + N \end{array} \right. \\ count \end{array} \right.$$

4.5 Crack Growth Calculations

Calculate the number of cycles to grow the crack through the wall thickness of the pipe for the accelerations calculated in Section 4.2.

$$n_{cyc} := \overrightarrow{Crk_I(a_{o.1}, t_{wt}, acc, a_{init})}$$

$$n_{cyc} = \begin{pmatrix} 1.65 \times 10^5 \\ 5.54 \times 10^5 \\ 1.02 \times 10^6 \end{pmatrix}$$

The approximate time to accumulate this number of cycles at a frequency of $f_n = 123\,Hz$ is:

$$t := \overrightarrow{\frac{n_{cyc}}{f_n}}$$

$$t = \begin{pmatrix} 0.37 \\ 1.25 \\ 2.31 \end{pmatrix} hr$$

5.0 REFERENCES

1. MPR Calculation No. Attachment 17 to C-0142, "Harmonic Stress Analysis of Loop 'B' Port," Revision 0.

2. Hope Creek "B" Loop Decontamination Port Cracking Preliminary Results, attachment to e-mail from A. Roberts (PSE&G) to R. Keating (MPR), 4-1-05, Subject: Areva Report.

3. 2004 ASME B&PV Code, Section XI.

4. 1989 ASME B&PV Code, Section III, Division 1, Appendices.

5. Hiroshi Tada, "The Stress Analysis of Cracks Handbook, Second Edition," Paris Productions Incorporated, St. Louis, MO, 1985.