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U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555-0001

Docket No. 50-323, OL-DPR-82
Diablo Canyon Unit 2
Flaw Evaluation of Unit 2, ASME Code Class 2 Charging Pump Discharge Lines: Welds WIC-45A and RB-46-7

Dear Commissioners and Staff:

In accordance with the requirements of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Section XI, 2007 Edition through 2008 Addenda, Paragraphs IWC-3132.3, IWC-3134(b), and IWC-3640, Pacific Gas & Electric Company (PG&E) is submitting the results of the analytical evaluation of the flaws found in Diablo Canyon Power Plant (DCPP) Unit 2, on the 4-inch diameter ASME Code Class 2 Charging Pump Discharge Lines: Welds WIC-45A and RB-46-7. IWC-3134(b) states, "Analytical evaluation of examination results as required by IWC-3132.3 shall be submitted to the regulatory authority having jurisdiction at the plant site."

PG&E identified circumferential indications at welds WIC-45A and RB-46-7 (i.e., one circumferential flaw in each weld) in the charging pump discharge lines using ultrasonic examination techniques during a DCPP routine scheduled risk-informed inservice inspection (RI-ISI) performed during Unit 2 twentieth refueling outage. Additional examinations required in accordance with IWC-2430 were completed and no other indications were detected.

The indications in WIC-45A and RB-46-7 were found to have exceeded the acceptance standards of ASME Section XI, 2007 Edition with 2008 addenda, Table IWB-3514-2 (as referenced by IWC-3514). The flaws were initially dispositioned as unacceptable. Subsequently, an analytical evaluation was performed based on the rules of ASME Code, Section IWC–3640, to demonstrate that the welds containing the flaw are acceptable for continued service for the life of the plant.

The results of the analysis show that, using the conservative bounding flaw size, the conservative bounding loads, and a conservative transient loading, the flaw does not exceed the ASME Code, Section XI allowable flaw size assuming an additional

40-year operating period. Therefore, the flaws are acceptable for the remainder of the Unit 2 plant life through the end of the operating license on August 26, 2025. The analysis, methodology, and results are shown in the Enclosure.

PG&E makes no new or revised regulatory commitments (as defined by NEI 99-04) in this letter. If you have any questions or require additional information, please contact Mr. Hossein Hamzehee at (805) 545-4720.

Sincerely,

James M. Welsch
*Vice President, Nuclear Generation and Chief Nuclear Officer*

rntt/4231/SAPN 50965613-04
Enclosure

| | |
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# Diablo Canyon Power Plant, Unit 2

## Evaluation of the Flaw in the 4-inch Charging Pump Discharge Line: Welds WIC-45A & RB-46-7

**Structural Integrity Associates, Inc.®**

# CALCULATION PACKAGE

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**CLIENT:**
Pacific Gas & Electric

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## 1.0 INTRODUCTION

During routine inservice inspection of the ASME Code, Class 2 Charging Pump discharge line welds at Diablo Canyon Power Plant (DCPP), Unit 2 in the Spring 2018 2R20 outage, a circumferential flaw was identified at two weldments: Weld WIC-45A and RB-46-7 [1, 2]. The location of weld WIC-45A is shown in Figure 1 (isometric drawing of the charging line) and weld RB-46-7 is shown in Figure 2. As can be seen from these figures, the welds are located a short distance from the charging pump. The possible cause of cracking is discussed in Section 3.6.

This calculation documents an evaluation to determine the acceptability of the circumferential flaws identified in the charging line welds WIC-45A and RB-46-7 at DCPP Unit 2 for continued operation. Included in the calculation is documentation of loadings, calculation of stresses and stress intensity factors, determination of fatigue crack growth, and the allowable flaw size. Based on the evaluation contained herein, the flawed component is acceptable for continued operation. The crack will not exceed the ASME Code, Section XI allowable flaw size for the life of the plant (assuming an additional 40-year operating life).

## 2.0 TECHNICAL APPROACH

The subject DCPP piping systems are classified as ASME Class 2 piping, with Class 1 requirements for seismic. The calculation documents the evaluation of existing flaws in a Class 2 piping system that remains in service. Therefore, the requirements for evaluation and acceptance criteria of ASME Code, Section XI, Subsection IWC apply. The current applicable Section XI Edition and Addenda for these systems at DCPP is the 2007 Edition with 2008 Addenda [3].

The technical approach used for the flaw evaluation consists of using the ASME Code, Section XI, Subarticle IWC-3600 and Appendix C requirements summarized in the following steps:

1. The characterization of the identified flaws are planar flaws located within the austenitic stainless steel piping butt welds, and are ID-connected [1, 2]. The flaws are first evaluated using the Acceptance Standards of Subarticle IWC-3500, specifically IWC-3514, for flaws in austenitic piping. IWC-3514 states that these standards "*are in the course of preparation*" and directs that "*the standards of IWB-3514 may be applied.*" IWB-3514, specifically IWB-3514.3(a) for austenitic piping, states that "*the size of allowable flaws shall not exceed the limits specified in Table IWB-3514-2.*" This determination has been performed by PG&E and the as-found flaws did not pass the rules of IWC-3500, implemented as IWB-3500 (Table IWB-3514-2).

   It is noted that these butt welds are in stainless steel piping in a pressurized water reactor (PWR), which are not susceptible to stress corrosion cracking, and therefore the requirements of IWB-3514 are applicable.

2. Subsubarticle IWC-3640 states that piping containing flaws that exceed the acceptance standards of IWC-3514 (implemented as IWB-3514) may be evaluated by analytical procedures to determine acceptability for continued service, and references use of Section XI, Appendix C. Therefore, a more detailed flaw evaluation using the rules of Appendix C is required. The specific steps in the evaluation involved are listed below.

   a. Determine the stresses at the flaw locations. Since the flaws are oriented in the circumferential direction, the stresses required are the axial stresses. The loadings considered in this evaluation include pressure, deadweight, thermal expansion, seismic (inertial and anchor movements), residual, and thermal transient stresses.

   b. Determine the ASME Code, Section XI allowable flaw size for austenitic stainless steel piping in Appendix C [3] {Past Operability}.

   c. Determine thermal transients applicable to flawed piping location.

   d. Calculate stress intensity factors for the thermal transients and other loadings.

   e. Perform a crack growth evaluation to determine how long it will take the as-found flaws to reach the ASME Code, Section XI allowable flaw size determined in Step b.

   f. Compare the end of the evaluation period flaw (after fatigue crack growth) to the ASME Code, Section XI allowable flaw size in Appendix C to determine acceptability for operation through the evaluation period {Continued Operability}.

The current version of ASME Code, Section XI used at DCPP [15] is the 2007 Edition with Addenda through 2008 [3].

Two computer programs verified under Structural Integrity Associates (SI) Quality Assurance (QA) program are used to facilitate the calculations in this evaluation. These computer programs are **SI-TIFFANY** [10] and **pc-CRACK** [11].

The software **SI-TIFFANY** [10] performs time history thermal stress and stress intensity factor analysis of a pipe with a specified temperature/flow history of the fluid inside the pipe. The end result (output) of the software is tables of the maximum and minimum stress intensity factor for ID part-through wall circumferential or axial flaws for selected crack sizes.

In this calculation, **SI-TIFFANY** is used to calculate the thermal transient stress and minimum and maximum stress intensity factor distributions for the bounding thermal transient(s). These maximum and minimum stress intensity factors are used for the fatigue crack growth evaluation.

The fatigue crack growth evaluation is performed using **pc-CRACK** [11]. **pc-CRACK** [11] is a Windows-based software for the fracture mechanics analysis of cracks in materials. Analysis procedures performed are based on linear elastic fracture mechanics (LEFM) or elastic-plastic fracture mechanics (EPFM). The code can be used for a very wide range of crack geometries subjected to a variety of stress states. Some 35 LEFM and 15 EPFM crack configurations are included, several with influence functions that allow consideration of arbitrary stress distributions. **pc-CRACK** can compute critical crack size, allowable flaw size based on the ASME Code, and the life of a component subjected to sub-critical crack growth such as fatigue, stress corrosion cracking (SCC) or primary water stress corrosion cracking (PWSCC).

In this calculation, **pc-CRACK** is used to calculate the fatigue crack growth and to determine the flaw acceptability (stability) using the rules of ASME Code, Section XI, Appendix C [3].

## 3.0 DESIGN INPUTS

### 3.1 Geometry

Nominal pipe size (NPS) = 4 inch [1, 2]
Pipe outside diameter (OD) = 4.5 inches [1, 2]
Nominal pipe thickness = 0.437 inches [1, 2]
Actual measured pipe thicknesses are all thicker than 0.48 inches [5]

In this evaluation, the nominal thickness (0.437 inches) will be conservatively used as it results in a larger a/t and larger stresses.

### 3.2 Loads

All piping loads for this analysis are taken from References 1 and 2. The locations of the flaws are shown in Figure 1 (WIC-45A) and Figure 2 (RB-46-7). The representative nodes in the piping analysis [1 and 2] are node 15 E for weld WIC-45A, and 348-380 for weld RB-46-7. Multiple load cases are provided in References 1 and 2. All the load cases in References 1 and 2 are contained in Table 2. To account for any future updates of the piping loads due to changes in the piping analysis, the loads (other than pressure) are conservatively increased by a 50% factor. The loads are further explained in the calculation of stresses.

### 3.3 Operating Conditions

References 1 and 2 define the operating conditions for the charging pump discharge line. The discharge line is line 2-S6-45-4 [1] for weld WIC-45A, and line 2-S6-46-4 [2] for weld RB-46-7. Operating conditions are defined [1]. Pages 9 and 15 of Reference 1 define the temperatures and pressures to be used. Discussion of the thermal transients applicable to this location is contained in Section 3.7.

Internal Pressure = 2800 psig [1, pg. 9, Based on pipe specification S6]
Temperature = 130°F [1, pg. 15, Mode 1NN]

### 3.4 Material

The material of the piping is A-376 TP 316 [1, pg. 14] austenitic stainless steel and the elbow and tee are A-403 Type 316 [8]. Reference 7 identifies the weld as being stainless steel (Type 308 and 316) and using both GTAW and SMAW welding processes. As a flux type weld is used, the elastic plastic fracture mechanics method of the ASME Code, Section XI, Appendix C will be required for the allowable flaw size determination.

For the flaw evaluation, the flow stress of the material is required. At a temperature of 150°F, the stainless steel material properties are as follows (SA-376 TP 316 properties used):

$S_y$ = 27.4 ksi [4]
$S_u$ = 75.0 ksi [4]
$\sigma_f$ = 51.2 ksi (average of $S_y$ and $S_u$)

### 3.5 Indication Characterization

The two flaws are described below, and a bounding flaw is then defined. The bounding flaw will be evaluated using bounding loads from the two piping systems.

Weld WIC-45A: One circumferential indication was identified in the weld [1]. The NDE report is contained in Appendix A of this calculation, and the indication is shown in Figure 3.

Length = 0.40 inch [1]
Maximum flaw depth = 0.075 inch [1]
Flaw depth-to-thickness ratio (a/t) = 0.172 (based on nominal thickness)

Weld RB-46-7: One circumferential indication was identified in the weld [2]. The NDE report is contained in Appendix A of this calculation, and the indication is shown in Figure 4.

Length = 0.45 inch [2]
Maximum flaw depth = 0.067 inch [2]
Flaw depth-to-thickness ratio (a/t) = 0.153 (based on nominal thickness)

BOUNDING FLAW:

Length = 0.45 inch [Greater of 1 and 2]
Maximum flaw depth = 0.075 inch [Greater of 1 and 2]
Flaw depth-to-thickness ratio (a/t) = 0.172 (based on nominal thickness)

### 3.6 Cause of Cracking

A thorough root cause of the cracking cannot be undertaken since the flawed components were not removed from service. Possible causes of the cracking include:

- Thermal fatigue from thermal transients and thermal stratification
- Stress corrosion cracking
- Vibration
- Fabrication defect

The crack like indications identified in References 1 and 2 are noted as being ID connected. Given the significant rate of flow, and resulting velocity, in these discharge piping runs, it is unlikely that any thermal stratification is present. Most importantly, these systems are run without voids, that is, there is no water/steam interface within the line. Also, the RB-46-7 weldment is on a vertical run, making stratification unlikely. Therefore, thermal stratification as a cause for the cracking can be eliminated.

One other possible apparent cause could be stress corrosion cracking. However, as the Reactor Coolant System (RCS) is in constant operation and there is very little oxygen in the system, the risk of stress corrosion cracking is small. DCPP has also performed other evaluations that has eliminated stress corrosion cracking as a plausible degradation mechanism in the reactor coolant system. Additionally, the operating temperature of the piping system is low (<200°F). At these temperatures SCC is not significant [14].

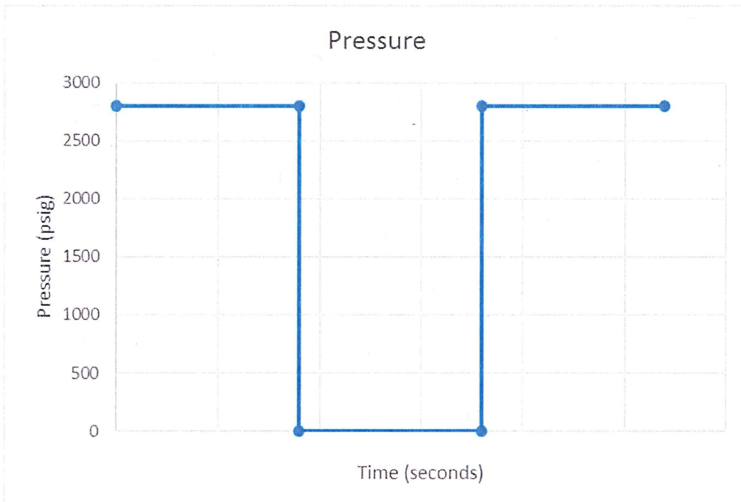
It is not necessary to include vibration as a mechanism to grow the flaw. The basis for this is that currently the flaws have not grown through wall but have "initiated". Given the extremely high number of cycles that would have been generated by the operation of the pump (cycles » $10^7$), if the vibration-induced stress were greater than the K threshold stress value for flaw growth, then the flaw would already have grown through wall. As the flaw is still small, the stress due to vibration is by default below the threshold K stress value, and therefore fatigue growth, due to vibration, is not an issue.

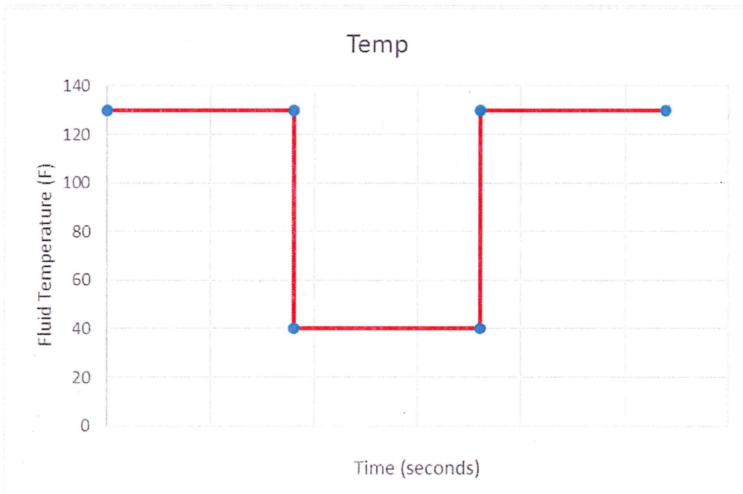
As thermal stratification and SCC are not likely causes, and the defect could be associated with a lack of fusion (weld root), the only mechanism that will lead to flaw growth is due to thermal transients and thermal cycling. As such, the fatigue crack growth evaluation is appropriate as the thermal transient cycles are considered.

### 3.7 Thermal Transients

The charging system delivers RCS water back to the RCS (cold leg) after it has been processed ("cleaned") through the ion exchange system. As such, the 2-1 and 2-2 charging pumps (there are three (3) at each unit of DCPP) are either on or off. The feed for the charging pumps is low temperature RCS water from the regenerative heat exchangers and is nominally 130°F [1, pg. 15, Mode 1NN].

A set of design transients for the charging pump discharge piping is not defined as part of the design basis. Therefore, in order to perform a fatigue crack growth evaluation, SI developed a conservative pressure and temperature transient for these two sections of piping that contain the flawed weldments. The bounding transient is shown schematically below. See Table 8 for an explanation of time steps.



The specifics of the transient are:

1. The discharge piping line is pressurized at 2800 psig and the fluid temperature is 130°F.
2. It then instantaneously drops pressure to zero, and fluid temperature to 40°F. It is acknowledged that RCS water cooled to 40°F will create crystallization of dissolved boron, but this temperature, although unrealistic, is conservatively selected to maximize the thermal transient.
3. After 3600 seconds (long enough for the pipe to reach 40°F thru-wall), the pressure is instantaneously ramped to 2800 psig and the fluid temperature goes to 130°F. The selection of 3600 seconds for this portion of the transient is an academic one and is not a realistic value for any actual charging pump transient. It is only intended to conservatively assure steady state behavior prior to the temperature upshock.
4. Then another period of time sufficient to reach steady state at the 2800 psig and 130°F.

This transient conservatively bounds the maximum pressure change (2800 psig to 0 psig [1]) and the maximum operating temperature range (130°F to 40°F) [1, Pg. 15, Mode 1NN].

Relative to the number of cycles to be evaluated, SI referenced SI Calculation FP-PGE-305, Rev. 3 [9]. The objective of this calculation, performed as part of SI's FatiguePro implementation, is to determine transient cycle counts and fatigue usage factors (at selected monitored locations) that accurately reflect the operating history of Diablo Canyon Power Plant (DCPP) Units 1 and 2 from initial startup to year-end 2008. These results constitute a 'baseline' of cycle counts and cumulative usage factor (CUF) on which future monitoring efforts will be based.

Table 1 from [9] lists all the identified transients, and those transients applicable (for which a cycle will be assigned) are highlighted in yellow. These include all charging transients, both prompt and delayed, and delayed letdown transients (that would potentially result in stopping of the charging pump). Lp3 and Lp4 refer to different loops, but the cycles from each are conservatively combined to develop a number of cycles for either of the flawed weldments. Heatup and Cooldown are also included.

The number of cycles for each listed transient in Table 1 is taken as the greater of the design cycles or the projected cycles (based on monitoring). The number of cycles chosen is marked with yellow highlight.

Based on the selected transients listed in Table 1, a total of (75 + 25 + 25 +25 +75 + 25 + 118 + 25 + 200 + 200), equals **793 total cycles for 60 years, or conservatively 14 cycles per year.** This yearly cycle count (14) is then applied in this flaw evaluation for a period of 40 years (14 * 40 =560 cycles) to justify <u>an additional 40 years of operation</u> (starting from the present) for this bounding flaw.

### 3.8 Residual Stress

The residual stresses in the weld are required for the crack growth evaluation. For this evaluation, a constant tensile residual stress will be assumed. The value assumed is the operating temperature yield strength of the material, which is 27.4 ksi [4] for Type 316 stainless steel (@ 150°F). The yield stress is taken at 150°F, as it is a stated value from the Code (no interpolation required). Use of a lower yield stress value (< 10%) for the uniform through-wall residual stress, is bounded by the assumption of uniform tensile residual stresses through the thickness. Using this value is conservative as the axial residual stresses in piping are required to balance through the wall thickness to remain in equilibrium. Assuming a constant tensile stress is not realistic, but it is conservative as it gives a higher mean stress for the evaluation which leads to higher crack growth rates.

## 4.0 CALCULATIONS

### 4.1 Flaw Characterization

Since only one circumferential flaw was identified in each weldment, the flaw combination rules of ASME Code, Section XI, IWA-3330 do not apply. The bounding characterized flaw length is 0.45 inch and the flaw depth is 0.075 inch [1 and 2] (see Section 3.5). The actual measured thickness at the flaw location varies, but is greater than 0.48 inches, therefore, the nominal pipe wall thickness of 0.437 inches is conservatively used for a flaw-depth to-thickness ratio of 0.172 and an aspect ratio (flaw depth, a (0.075 inch), divided by flaw length, l (0.45 inch)) of 0.167. Using Table IWB-3514-2 of ASME Code Section XI, this flaw does not meet the Acceptance Standards and, therefore, will need to be evaluated per the flaw evaluation procedures of IWC-3600.

### 4.2 Determination of Stresses and Load Combinations

The stresses are calculated based on the piping loads from References 1 and 2 and the loads are contained in Table 2. Table 3 performs the load combinations for both weldments and Table 4 determines the resulting membrane and secondary stresses from the load combinations. Table 5 lists the resulting bounding membrane stresses that include the 50% increase for margin. Table 6 lists the resulting bounding secondary stresses that include the 50% increase for margin.

A description of the individual loads is given below. Following the description of the individual loads, the load combinations for all service levels are defined and listed.

Deadweight (DW) - Deadweight of piping system (Listed as **WT01**)

THRMN1 through THRMN5 – Five normal thermal expansion conditions described in References 1 and 2. These loads include thermal anchor movement. The bounding thermal load, **TM**, is determined based on the maximum SRSS value of the three moments for each thermal load case.

**THRMA1** – Accident thermal load (includes thermal anchor movement).

SEISDX – DE (similar to OBE) inertial seismic loading for X & Y directions. Seismic anchor movements are zero.
SEISDZ – DE (similar to OBE) inertial seismic loading for Z & Y directions. Seismic anchor movements are zero.

**SEISDE** – Maximum of SEISDX and SEISDZ (Based on the maximum SRSS value of the three moments for each seismic load case

**SEISDD** - DD (similar to SSE) inertial seismic loading. Seismic anchor movements are zero. This is 2 times **SEISDE**.

SEISHX – Hosgri (Faulted seismic condition specific to DCPP) inertial seismic loading for X & Y directions. Seismic anchor movements are zero.
SEISHZ – Hosgri (Faulted seismic condition specific to DCPP) inertial seismic loading for Z & Y directions. Seismic anchor movements are zero.

**SEISH** – Maximum of SEISHX and SEISHZ (Based on the maximum SRSS value of the three moments for each seismic load case

With the definition of the piping loadings, the load combinations for each service level are defined as:

**Primary Loads:**

| | | |
|---|---|---|
| Service Level A | DW01 | + Pressure (P) |
| Service Level B | DW01 | + P + SEISDE |
| Service Level C | DW01 | + P + SEISDD |
| Service Level D | DW01 | + P + SEISH |

**Secondary Loads**

| | |
|---|---|
| Service Level A | TM |
| Service Level B | TM |
| Service Level C | THRMA1 (Conservatively added as Service Level C) |
| Service Level D | THRMA1 |

The load combinations are performed and shown in Table 4. The piping stresses are calculated based on pressure and external bending moments using equations from Appendix C, Section C-2500 [3] as described as follows.

Primary membrane stress ($\sigma_m$) is given by:

$\sigma_m = PD/(4t) + F/A$, where:

| | | |
|---|---|---|
| $P$ | = | operating pressure for the service level being considered |
| $D$ | = | outside diameter of the component |
| $t$ | = | thickness, consistent with the location at which the outside diameter is taken |
| $F$ | = | resultant force for the appropriate primary load combination for each Service Level |
| $A$ | = | cross sectional area of the pipe |

Primary bending stress ($\sigma_b$) is given by:

$\sigma_b = DM_b/(2I)$, where:

| | | |
|---|---|---|
| $D$ | = | outside diameter of the component |
| $d$ | = | inside diameter, consistent with the point at which the outside diameter is taken |
| $M_b$ | = | resultant moment for the appropriate primary load combination for each Service Level |
| $I$ | = | moment of inertia, $(\pi/64)(D^4 - d^4)$ |

Secondary membrane stress ($\sigma_{msec}$) is given by:

$\sigma_{msec} = F_{sec}/A$, where:

| | | |
|---|---|---|
| $F_{sec}$ | = | resultant force for the appropriate secondary load combination for each Service Level |
| $A$ | = | cross sectional area of the pipe |

Secondary bending stress ($\sigma_e$) is given by:

$\sigma_e = DM_e/(2I)$, where:

| | | |
|---|---|---|
| $D$ | = | outside diameter of the component |
| $d$ | = | inside diameter, consistent with the point at which the outside diameter is taken |
| $M_e$ | = | resultant moment for the appropriate secondary load combination for each Service Level (includes seismic anchor loads and thermal expansion) |
| $I$ | = | moment of inertia, $(\pi/64)(D^4 - d^4)$ |

For this evaluation, all the primary forces are combined (SRSS) and are conservatively considered a membrane stress and added to the pressure component. In **pc-CRACK**, all secondary forces are also combined and added to the secondary bending stress term for conservatism. In **SI-TIFFANY**, the secondary membrane and secondary bending stresses are input separately. The stress for the secondary forces are calculated as F/A, where F is the resultant force (SRSS of 3 directions) and A is the area of the piping. The bounding stresses are shown in Table 5 (membrane) and Table 6 (bending), and both Tables include the 50% margin.

## 4.3 Thermal Transient Stress Analyses and Stress Intensity Factors Determination

Table 7 and Table 8 list the transients that are evaluated for the flawed location. The transient in Table 8 is evaluated with **SI-TIFFANY** to determine the transient stresses and stress intensity factors. Construction of the input file for the transient involves inserting the transient time history into an input file. A time step of 0.1 seconds is used in all **SI-TIFFANY** runs. All material properties used for the **SI-TIFFANY** runs are contained in Table 9.

Each **SI-TIFFANY** run with the corresponding filename has the following relevant files, which are included as supporting files to this calculation:

- *.dat **SI-TIFFANY** input file
- *.rpt **SI-TIFFANY** output file, which echoes the inputs.
- *.mnn **SI-TIFFANY** output file with tabulated $K_{min}$ values.
- *.mxn **SI-TIFFANY** output file with tabulated $K_{max}$ values.

The tabulated values of the minimum and maximum stress intensity factors, $K_{min}$ and $K_{max}$, for specific crack sizes are used for fatigue crack growth analysis. All **SI-TIFFANY** files are listed in Appendix B.

**SI-TIFFANY** uses temperature history of the transient to compute the thermal stress due to the radial gradient of the temperature in the pipe wall. At the beginning of the transient, the piping location is taken to be at a uniform temperature equal to the first line in the transient history. The radial gradient thermal stress is then combined with the pressure stress and thermal expansion stresses due to tensile and bending loads (restraint of thermal expansion) to provide stresses that are used to calculate stress intensity factors. The thermal expansion tension and bending stress at the beginning of the transient is taken to be the stress due to the resultant force and moment of the restraint of thermal expansion, which are obtained from the loads in Table 3, scaled up or down from the normal operating temperature using the following relation:

$$\sigma(T_{ave}) = \frac{T_{ave} - 40}{T_{no} - 40}\sigma_{no}$$

This relation is applied to tension and bending thermal expansion stresses to scale the values during the transient. $T_{no}$ is 130.0°F (normal operation temperature). $T_{ave}$ is the average wall temperature, which is evaluated in **SI-TIFFANY**. The values of $\sigma_{no}$ (nominal stress) for tension and bending were calculated using the equations from Section 4.2 and the loads from Table 2.

The values of $\sigma_{no\ tension}$ and $\sigma_{no\ bending}$ from thermal expansion input to **SI-TIFFANY** are 0.031 ksi and 1.165 ksi, respectively. Stresses due to deadweight, residual stress, and seismic are input separately in the subsequent crack growth calculation. Pressure stresses do not need to be input to **SI-TIFFANY** separately. Only the pressure term is included as **SI-TIFFANY** calculates the stresses due to pressure.

**SI-TIFFANY** treats the piping conservatively as insulated and the insulation is considered perfect which means that no heat transfer is considered to the surrounding environment. The piping is not insulated as noted in References 1 and 2.

## 4.4 Crack Growth Evaluation

### *4.4.1 Stress Intensity Factors*

**SI-TIFFANY** calculated stress intensity factors (K) and determined maximum applied K ($K_{max}$) and minimum applied K ($K_{min}$) for a semi-elliptical inside-surface circumferential flaw in a cylinder for various flaw depths and aspect ratios. The $K_{max}$ and $K_{min}$ values include the effects of internal pressure, thermal expansion piping loads, and thermal transient stresses. $K_{max}$ and $K_{min}$ represent the range of applied K for each transient whose difference, $\Delta K = K_{max} - K_{min}$, are used by **pc-CRACK** for the fatigue crack growth (FCG) calculations.

The constant stress intensity values for deadweight and residual stress were not included in **SI-TIFFANY**. As such, they are input as constant stress values for each load cycle. Seismic is input as a reversible stress. Additionally, the crack face pressure of 2.8 ksi (conservative operating pressure) is added to the $K_{max}$ term. The semi-elliptical flaw model with variable aspect ratio is used in **pc-CRACK** to determine the fatigue crack growth. The flaw model is shown in Figure 5.

### 4.4.2 *Austenitic Stainless Steel Fatigue Crack Growth Law*

The ASME Code has developed new fatigue crack growth laws for austenitic stainless steels in PWR water environments. The fatigue crack growth law for stainless steels in PWR environment has been approved by the ASME Code, Section XI Committee through Code Case N-809 [12, 13]. This crack growth law (provided below) is used for the present analysis.

$da/dN = C_0 \cdot \Delta K^n$, units of inch/cycle

where:

$C_0$ = scaling parameter that accounts for the effect of loading rate and environment on fatigue crack growth rate

= $C\ S_T\ S_R\ S_{ENV}$

$n$ = slope of the log (da/dN) versus log ($\Delta K$) curve = 2.25

$C$ = nominal fatigue crack growth rate constant
= $4.43 \times 10^{-7}$ for $\Delta K \geq \Delta K_{th}$
= 0 for $\Delta K < \Delta K_{th}$

$\Delta K$ = stress intensity factor range, ksi√in

$\Delta K_{th}$ = 1.10 ksi√in

$S_T$ = parameter defining effect of temperature on FCG rate
= $e^{-2516/T_K}$ for 300°F ≤ T ≤ 650°F
= $3.39 \times 10^5\ e^{[(-2516/T_K)-0.0301 T_K]}$ for 70°F ≤ T < 300°F

$T$ = metal temperature, °F

$S_R$ = parameter defining the effect of R-ratio on FCG rate
= 1.0 for R < 0
= $1 + e^{8.02(R-0.748)}$ for $0 \leq R < 1.0$

$R$ = $K_{min}/K_{max}$ = R ratio (Conservative value of 0.9 is used, and bounds the case of $K_{min}$ <0)

$S_{ENV}$ = parameter defining the environmental effects on FCG rate
= $T_R^{0.3}$

$T_R$ = loading rise time, sec

$T_K$ = [(T-32)/1.8+273.15], K

The following parameters were used:

- T = 130°F (metal temperature)
- R = 0.9 (Conservative value)
- $T_R$ = 1000 seconds (Conservatively long rise time results in greater flaw growth)

The crack growth evaluation is performed with a variable aspect ratio, which uses the K values at the deepest and surface points of the flaw, while allowing the flaw aspect ratio (depth, a, divided by length, l) to vary.

### *4.4.3 Loading Combinations and Stresses*

**SI-TIFFANY** was used to obtain tables of maximum applied K ($K_{max}$) and minimum applied K ($K_{min}$) for various flaw depths and aspect ratios due to system transients. The $K_{max}$ values are contained in the filename with MXN file extension and the $K_{min}$ values are contained in the filename with MNN file extension.

The maximum and minimum K for crack growth cycles are the combined total of the $K_{max}$ and $K_{min}$ tables output from **SI-TIFFANY**, combined with deadweight and weld residual stress added to both the max and min of the cycle. Seismic is added to $K_{max}$ as a plus value and added to $K_{min}$ as a minus value. Deadweight stresses are calculated from the loads given in Table 3. Deadweight and residual stress loads do not cycle but are present in both the maximum and minimum of the cycle. The fatigue crack growth also needs to include Service Level B seismic (SEISDE). Therefore, SEISDE was considered to occur with the bounding transient. Seven hundred and ninety-three (793) SEISDE cycles are assumed over a 60 year plant life. This is a conservative value for seismic cycles and exceeds the design basis value [9]. Therefore, fourteen (14) seismic cycles are considered each year. Table 10 defines the loading combinations used for each event evaluated in **pc-CRACK**. A crack growth period of an additional 40 years was evaluated.

### *4.4.4 Allowable Flaw Size Determination*

After the fatigue crack growth is performed, the final flaw size has to be checked against the allowable flaw sizes in the ASME Code, Section XI, Appendix C. **pc-CRACK** is used to determine the allowable flaw sizes. As stated earlier, the weld was manufactured partly with a SMAW process and, therefore, requires the use of elastic plastic fracture mechanics (EPFM). The EPFM rules are contained in Article C-6000 of Section XI [3].

The specific equations from Appendix C, including the appropriate safety factors, used to determine allowable flaw size are listed below.

The allowable bending stress for EPFM under combined membrane plus bending loads is given by the equation:

$$S_c = \frac{1}{SF_b}\left[\frac{\sigma_b^c}{Z} - \sigma_e\right] - \sigma_m\left[1 - \frac{1}{ZSF_m}\right]$$ Reference 3, C-6321,

where, $$\sigma_b^c = \frac{2\sigma_f}{\pi}\left[2\sin\beta - \frac{a}{t}\sin\theta\right], for\ (\theta + \beta) \le \pi$$ Reference 3, C-5321,

$$\beta = \frac{1}{2}\left(\pi - \frac{a}{t}\theta - \pi\frac{\sigma_m}{\sigma_f}\right)$$ Reference 3, C-5321,

The allowable membrane stress is given by the equation:

$$S_t = \frac{\sigma_m^c}{ZSF_m}$$ Reference 3, C-6322,

where, $$\sigma_m^c = \sigma_f\left[1 - \left(\frac{a}{t}\right)\left(\frac{\theta}{\pi}\right) - \frac{2\varphi}{\pi}\right],$$ Reference 3, C-5322,

$$\varphi = \arcsin\left[0.5\left(\frac{a}{t}\right)\sin\theta\right],$$

and

$S_c$ = allowable bending stress for a circumferentially flawed pipe
$\sigma^c_b$ = bending stress at incipient plastic collapse
$SF_m$ = safety factor for membrane stress based on Service Level as shown in the Table below [3, C-2621]
$SF_b$ = safety factor for bending stress based on Service Level as shown in the Table below [3, C-2621]
$a$ = flaw depth
$t$ = total wall thickness
$S_t$ = allowable membrane stress for a circumferentially flawed pipe
$\sigma^c_m$ = membrane stress at incipient plastic collapse
$\theta$ = half flaw angle [3, Figure C-4310-1], 180° or π for a 100% full circumferential flaw
$\beta$ = angle to neutral axis of flawed pipe in radians
$\sigma_m$ = unintensified primary membrane stress at the flaw location
$\sigma_f$ = flow stress = $(S_y + S_u)/2$ [3, C-8200(a)]
$S_y$ = specified value for material yield strength at the evaluation (operating) temperature from Reference 4
$S_u$ = specified value for material ultimate strength at the evaluation (operating) temperature from Reference 4

$\sigma_e$ = Secondary bending stress

For austenitic weldments fabricated by SMAW,

$$Z = 1.30[1 + 0.010(NPS - 4)],$$ Reference 3, C-6330

Where: NPS = Nominal pipe size

Safety factors are provided in Appendix C of Section XI for evaluation of flaws in austenitic stainless steel piping. The safety factors used are shown below and are taken from C-2621 [3].

**Safety Factors for Sizing – Circumferential Flaw [3, C-2621]**

| Service Level | Membrane Stress Safety Factor, $SF_m$ | Bending Stress Safety Factor, $SF_b$ |
|---|---|---|
| A | 2.7 | 2.3 |
| B | 2.4 | 2.0 |
| C | 1.8 | 1.6 |
| D | 1.3 | 1.4 |

Each service level is checked by inputting pipe geometry, crack parameters, and stresses appropriate for the service level. For this calculation, the initial flaw size is input into the program. Based on the stress ratios, it gives the allowable flaw size tables (a/t (flaw depth/pipe thickness) and l/c (flaw length/pipe circumference) values). The **pc-CRACK** output files for the allowable flaw sizes are contained in Appendix C.

## 5.0 RESULTS

The results of the evaluation are contained in Table 11. Table 11 contains the initial flaw size and the final flaw sizes using the variable aspect ratio assumption. Table 12 contains the bounding limiting allowable flaw size from all service levels, for both combined stress and membrane stress. For the loadings, all Service Levels, A through D (see Appendix C), show that the allowable flaw depth is relatively large (75% of pipe wall thickness which is the maximum allowed by the ASME Code, Section XI).

For the fatigue crack growth evaluation, the flaw was grown with a variable aspect ratio. The results show that using the conservative bounding flaw size, the conservative bounding loads, and a conservative transient loading, the flaw does not exceed the ASME Code, Section XI allowable flaw size for the remainder of the plant life (assuming an additional 40-year operating period). Figure 6 shows a plot of crack growth (depth) per year and the allowable flaw size for the 40 year period. All files used in the analysis are listed in Appendix B.

## 6.0 CONCLUSIONS

The evaluation presented in this report has shown that the flawed welds in the 2-1 and 2-2 pump discharge piping weldments (WIC-45A and RB-46-7) at DCPP, Unit 2 are acceptable for continued operation. Using the bounding loads assumption, the flaws are acceptable for the remainder of the plant life (assuming an additional 40-year operating period from the present day).

## 7.0 REFERENCES


1. DCPP Design Input Transmittal No. DIT-50966007-001-00, "Diablo Canyon Unit 2, CVCS Pump 2-1, 4" Discharge Line – Weld Indications WIC-45A," SI File No. 1800289.201.

2. DCPP Design Input Transmittal No. DIT-50966526-001-00, "Diablo Canyon Unit 2, CVCS Pump 2-2, 4" Discharge Line – Weld Indications RB-46-7," SI File No. 1800289.205.

3. ASME Boiler and Pressure Vessel Code, Section XI, 2007 Edition, with Addenda through 2008.

4. ASME Boiler and Pressure Vessel Code, Section II, Part D, 2007 Edition, with Addenda through 2008.

5. DCPP Design Input Transmittal No. DIT-50966007-005-00, "Diablo Canyon Unit 2, CVCS Pump 2-1 and 2-2, 4" Discharge Line – UT Reports from ISI, WIC-45A and RB-46-7, SI File No. 1800289.211.

6. DCPP Design Input Transmittal No. DIT-50966007-004-00, "Diablo Canyon Unit 2, CVCS Pump 2-1, 4" Discharge Line – Weld Indication WIC-45A, SI File No. 1800289.208.

7. DCPP Design Input Transmittal No. DIT-50966526-002-00, "Diablo Canyon Unit 2, CVCS Pump 2-2, 4" Discharge Line – Weld Indication RB-46-7, SI File No. 1800289.210.

8. DCPP Design Input Transmittal No. DIT-50966007-002-00, "DCPP Pipe Specification, Drawing 047288, Revision 12, S6," SI File No. 1800289.206.

9. SI Calculation FP-PGE-305, Revision 3, Cycle and Fatigue Baseline up through YE 2008, SI File No. 1800289.203.

10. **SI-TIFFANY** 3.0, Structural Integrity Associates, September 15, 2015.

11. **pc-CRACK** 4.1 CS, Version Control No. 4.1.0.0, Structural Integrity Associates, December 31, 2013.

12. R. C. Cipolla and W. H. Bamford, "Technical Basis for Code Case N-809 on Reference Fatigue Crack Growth Curves for Austenitic Stainless Steels in Pressurized Water Reactor Environments," Proceedings of PVP2015 ASME Pressure Vessels and Piping Division Conference, PVP2015-45884, July 19-23, 2015, Boston, Massachusetts, USA, **SI File No. 1800289.207**.

13. ASME Boiler and Pressure Vessel Code, Section XI, Division 1, Code Case N-809, "Reference Fatigue Crack Growth Rate Curves for Austenitic Stainless Steels in Pressurized Water Reactor Environments," June 23, 2015.

14. a. P. L. Andresen, J. Hickling, K. S. Ahluwalia and J. A. Wilson, "Effects of Hydrogen on SCC Growth Rate of Ni Alloys in High Temperature Water", Corrosion, Vol. 64, No. 9, p. 707. Sept 2008.

b. P. L. Andresen, R. Reid and J. Wilson, "SCC Mitigation of Ni Alloys and Weld Metals by Optimizing Dissolved H2", Proc. 14th Int. Symp. on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors", American Nuclear Soc., August 2009.

15. DCPP Design Input Transmittal No. DIT-50966007-003-00, "Diablo Canyon Unit 2, CVCS Pump 2-1, 4" Discharge Line – Weld Indications WIC-45A, SI File No. 1800289.209.

## Table 1: Transient Cycles for Evaluation [9]

**Table 9: Baseline and 60-Year Projection of Cycles (Unit 2)**

| Transient | Startup thru 12/31/04 | 1/1/05 thru 12/31/08 | Startup thru 12/31/08 | 60 year projection | Design Cycles | % Used to-date (12/31/08) | 60 year projected % Used |
|---|---|---|---|---|---|---|---|
| 7.5M Hosgri Earthquake | 0 | 0 | 0 | 1 | 1 | 0% | 100% |
| Accumulator SI into CL | 0 | 0 | 0 | 4[1] | 1,000 | 0% | 0.4% |
| Aux. Spray during C/D | 54 | 0 | 54 | 102 | 500 | 11% | 20% |
| Charging SI into Cold Leg | 13 | 0 | 13 | 20 | 400 | 3.3% | 5.0% |
| Complete Loss of Normal FW | 0 | 0 | 0 | 1 | 20 | 0% | 5.0% |
| Complete Loss of RCS Flow | 0 | 0 | 0 | 1 | 20 | 0% | 5.0% |
| Control Rod Drop | 1 | 0 | 1 | 2 | 80 | 1.3% | 2.5% |
| Design Earthquake (OBE) | 0 | 0 | 0 | 1 | 20 | 0% | 5.0% |
| Double Design Earthquake | 0 | 0 | 0 | 1 | 1 | 0% | 100% |
| Excessive Feedwater Flow | 0 | 0 | 0 | 1 | 30 | 0% | 3.3% |
| Feedwater Cycling (S/G-1) | 0 | 0 | 0 | *[3] | 18,300 | N/A | N/A |
| Feedwater Cycling (S/G-2) | 0 | 0 | 0 | *[3] | 18,300 | N/A | N/A |
| Feedwater Cycling (S/G-3) | 0 | 0 | 0 | *[3] | 18,300 | N/A | N/A |
| Feedwater Cycling (S/G-4) | 0 | 0 | 0 | *[3] | 18,300 | N/A | N/A |
| High Head SI into CL | 0 | 0 | 0 | 4[1] | 97 | 0% | 4.1% |
| Hot Leg Safety Injection | 0 | 0 | 0 | 4[1] | 500 | 0% | 0.8% |
| Inadv. Accumulator Blowdn. | 0 | 0 | 0 | 1 | 5 | 0% | 20% |
| Inadv. Aux. Spray Actuation | 5 | 0 | 5 | 7 | 10 | 50% | 70% |
| Inadv. ECCS Actuation | 0 | 0 | 0 | 5 | 60 | 0% | 8.3% |
| Inadv. RCS Depressurization | 0 | 0 | 0 | 3[5] | 20 | 0% | 15% |
| Large Steam Pipe Break | 0 | 0 | 0 | 1 | 1 | 0% | 100% |
| Large Step Load Decrease | 3 | 1 | 4 | 9 | 200 | 2.0% | 4.5% |
| Loss of All Offsite Power | 1 | 0 | 1 | 3 | 40 | 2.5% | 7.5% |
| Loss of Load (TT w/o RT) | 3 | 0 | 3 | 10 | 80 | 3.8% | 13% |
| Lp3 Chrg & Ltdn Shutoff | 0 | 0 | 0 | 8[4] | 75 | 0% | 11% |
| Lp3 Chrg Trip Delayed Rtn. | 0 | 0 | 0 | 3[4] | 25 | 0% | 12% |
| Lp3 Chrg Trip Prompt Rtn. | 0 | 0 | 0 | 3[4] | 25 | 0% | 12% |
| Lp3 Ltdn Trip Delayed Rtn. | 0 | 0 | 0 | 3[4] | 25 | 0% | 12% |
| Lp3 Ltdn Trip Prompt Rtn. | 0 | 0 | 0 | 25[4] | 250 | 0% | 10% |
| Lp4 Chrg & Ltdn Shutoff | 3 | 1 | 4 | 11 | 75 | 5.3% | 15% |
| Lp4 Chrg Trip Delayed Rtn. | 3 | 0 | 3 | 6 | 25 | 12% | 24% |
| Lp4 Chrg Trip Prompt Rtn. | 53 | 1 | 54 | 118 | 25 | 216% | 472% |
| Lp4 Ltdn Trip Delayed Rtn. | 5 | 1 | 6 | 14 | 25 | 24% | 56% |
| Lp4 Ltdn Trip Prompt Rtn. | 44 | 1 | 45 | 94 | 250 | 18% | 38% |
| Main RCS Pipe Break | 0 | 0 | 0 | 1 | 1 | 0% | 100% |
| Partial Loss of Flow | 2 | 1 | 3 | 8 | 80 | 3.8% | 10% |

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**Note: Selected transients and number of cycles are highlighted in yellow. Greater of design or projected cycles is used.**

**Table 1 (Concluded) [9]**

| Transient | Startup thru 12/31/04 | 1/1/05 thru 12/31/08 | Startup thru 12/31/08 | 60 year projection | Design Cycles | % Used to-date (12/31/08) | 60 year projected % Used |
|---|---|---|---|---|---|---|---|
| Plant (RCS) Cooldown | 27 | 3 | 30 | 63 | 200 | 15% | 32% |
| Plant (RCS) Heatup | 28 | 3 | 31 | 65 | 200 | 16% | 33% |
| Pressurizer Cooldown | 28 | 4 | 32 | 72 | 250 | 13% | 29% |
| Pressurizer Heatup | 29 | 4 | 33 | 73 | 250 | 13% | 29% |
| Primary Hydrostatic Test | 1 | 0 | 1 | 2(5) | 5 | 20% | 40% |
| Primary Side Leak Test | 0 | 0 | 0 | 5 | 50 | 0% | 10% |
| RHR Operation (Train A) | 27 | 2 | 29 | 59 | 250 | 12% | 24% |
| RHR Operation (Train B) | 27 | 2 | 29 | 59 | 250 | 12% | 24% |
| Reactor Trip - C/D & SI | 0 | 0 | 0 | 4(2) | 10 | 0% | 40% |
| Reactor Trip - C/D no SI | 11 | 0 | 11 | 17 | 160 | 6.9% | 11% |
| Reactor Trip - no C/D | 36 | 1 | 37 | 61 | 230 | 16% | 27% |
| Refueling | 12 | 2 | 14 | 36 | 80 | 18% | 45% |
| Secndry Hydrotest (S/G-1) | 0 | 0 | 0 | 1 | 10 | 0% | 10% |
| Secndry Hydrotest (S/G-2) | 0 | 0 | 0 | 1 | 10 | 0% | 10% |
| Secndry Hydrotest (S/G-3) | 0 | 0 | 0 | 1 | 10 | 0% | 10% |
| Secndry Hydrotest (S/G-4) | 0 | 0 | 0 | 1 | 10 | 0% | 10% |
| Secndry Leak Test (S/G-1) | 0 | 0 | 0 | 1 | 10 | 0% | 10% |
| Secndry Leak Test (S/G-2) | 0 | 0 | 0 | 1 | 10 | 0% | 10% |
| Secndry Leak Test (S/G-3) | 0 | 0 | 0 | 1 | 10 | 0% | 10% |
| Secndry Leak Test (S/G-4) | 0 | 0 | 0 | 1 | 10 | 0% | 10% |
| Step Load Decrease 10% | 4 | 1 | 5 | 13 | 2,000 | 0.3% | 0.7% |
| Step Load Increase 10% | 25 | 0 | 25 | 48 | 2,000 | 1.3% | 2.4% |
| Switchover from Norm/Alt Charg. | 0 | 0 | 0 | 4(7) | 120 | 0% | 3.3% |
| Tavg Coastdn to Red. Temp. | 4 | 0 | 4 | 9 | 50 | 8.0% | 18% |
| Turbine Roll Test | 6 | 0 | 6 | 9(5) | 10 | 60% | 90% |

Table Notes:

(1) These SI events were specified to an unreasonably high # of cycles; the projected is reduced accordingly.
(2) This event, which includes an SI actuation, is conservatively projected to the same # of cycles as *High-Head SI*.
(3) This event is not monitored – the design number of cycles should be used as the projection.
(4) Because DCPP never uses the alternate charging, 10% × (design cycles) is used as the projection.
(5) These events are startup tests, unlikely to be repeated; project at 50% above current (round up).
(6) This event is considered more likely than other events with <40 design cycles, so the projection was increased.
(7) The design assumption is very high for this event; the Unit 1 projection is considered good for Unit 2 also.

**Note: Selected transients and number of cycles are highlighted in yellow. Greater of design or projected cycles is used.**

**Table 2: Piping Loads for Weldment WIC-45A (Node 15 E) and RB-46-7 (348-380)**

| Forces & Moments for WIC-45A [1, Pg. 17-27] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Load Case | Node/ Notation | Forces (lb) | | | Moments (ft-lb) | | | **FINAL LOAD CASE** | SRSS of Moment |
| | | FA | FB | FC | MA | MB | MC | | |
| | | | | | | | | | |
| WT01 | 15 E | 21 | 108 | 9 | 13 | -13 | 68 | **WT01** | |
| | | | | | | | | | |
| THRMN1 | 15 E | 13 | 76 | 87 | 235 | -154 | 182 | **TM** | 334.8 |
| THRMN2 | 15 E | 99 | 184 | -118 | -148 | 192 | 132 | | 276.0 |
| THRMN3 | 15 E | 41 | 112 | 17 | 104 | -36 | 164 | | 197.5 |
| THRMN4 | 15 E | 99 | 184 | -118 | -148 | 192 | 132 | | 276.0 |
| THRMN5 | 15 E | 33 | 106 | 42 | 150 | -78 | 177 | | 244.8 |
| | | | | | | | | | |
| THRMA1 | 15 E | -121 | -101 | 411 | 839 | -698 | 240 | **THRMA1** | |
| | | | | | | | | | |
| SEISDX | 15 E | 152 | 54 | 5 | 7 | 21 | 45 | | 50.1 |
| SEISDZ | 15 E | 76 | 48 | 45 | 54 | 68 | 42 | **SEISDE** | 96.5 |
| | | | | | | | | | |
| | | 152 | 96 | 90 | 108 | 136 | 84 | **SEISDD** | 192.9 |
| | | | | | | | | | |
| SEISHX | 15 E | 397 | 153 | 13 | 19 | 54 | 122 | | 134.8 |
| SEISHZ | 15 E | 212 | 122 | 111 | 131 | 167 | 109 | **SEISH** | 238.6 |

Notes:

1. The bounding case is determined from the largest square root of the sum of the squares of the moments and is shown in bold. These are shown in grey.
2. These piping loads are given in the local coordinate system. A is the axial direction, so FA is the axial force and MB and MC are the bending moments.

**Table 2 Concluded - Piping Loads for Weldment WIC-45A and RB-46-7 (Node 348-380)**

| Forces & Moments for RB-46-7 [2, Pg. 19-43] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Load Case | Node/ Notation | Forces (lb) | | | Moments (ft-lb) | | | **FINAL LOAD CASE** | SRSS of Moment |
| | | FA | FB | FC | MA | MB | MC | | |
| | | | | | | | | | |
| WT01 | 348-380 | -20 | 37 | 35 | -2 | -90 | -147 | **WT01** | |
| | | | | | | | | | |
| THRMN1 | 348-380 | 103 | 54 | 6 | -19 | 2 | 87 | | 89.1 |
| THRMN2 | 348-380 | -69 | -127 | 13 | 8 | -42 | -249 | **TM** | 252.6 |
| THRMN3 | 348-380 | 45 | -8 | 8 | -10 | -13 | -29 | | 33.3 |
| THRMN4 | 348-380 | -69 | -127 | 13 | 8 | -41 | -249 | | 252.5 |
| THRMN5 | 348-380 | 65 | 15 | 8 | -13 | -10 | 16 | | 22.9 |
| | | | | | | | | | |
| THRMA1 | 348-380 | 148 | 256 | -43 | -63 | 123 | 525 | **THRMA1** | |
| | | | | | | | | | |
| SEISDX | 348-380 | 2 | 12 | 17 | 8 | 89 | 32 | | 94.9 |
| SEISDZ | 348-380 | 22 | 81 | 11 | 6 | 42 | 169 | **SEISDE** | 174.2 |
| | | | | | | | | | |
| | | 44 | 162 | 22 | 12 | 84 | 338 | **SEISDD** | 348.5 |
| | | | | | | | | | |
| SEISHX | 348-380 | 45 | 84 | 79 | 20 | 263 | 185 | | 322.2 |
| SEISHZ | 348-380 | 66 | 218 | 41 | 15 | 154 | 458 | **SEISH** | 483.4 |

Notes:

1. The bounding case is determined from the largest square root of the sum of the squares of the moments and is shown in bold. These are shown in grey.
2. These piping loads are given in the local coordinate system. A is the axial direction, so FA is the axial force and MB and MC are the bending moments.

**Table 3: Piping Loads for Load Combinations – Weldment WIC-45A & RB-46-7**

| **PRIMARY RESULTANT Forces & Moments - Weldment WIC-45A** | | | Forces (lb) | | | Moments (ft-lb) | | |
|---|---|---|---|---|---|---|---|---|
| | | | FA | FB | FC | MA | MB | MC |
| | **Service Level A** | **WT01** | 21 | 108 | 9 | 13 | -13 | 68 |
| LEVEL A | Summary Force/Moment | | | **110.4** | | | **70.4** | |
| | **Service Level B** | **WT01** | 21 | 108 | 9 | 13 | -13 | 68 |
| | | **SEISDE** | 76 | 48 | 45 | 54 | 68 | 42 |
| | | Abs Sum | 97 | 156 | 54 | 67 | 81 | 110 |
| LEVEL B | Summary Force/Moment | | | **191.5** | | | **152.2** | |
| | **Service Level C** | **WT01** | 21 | 108 | 9 | 13 | -13 | 68 |
| | | **SEISDD** | 152 | 96 | 90 | 108 | 136 | 84 |
| | | Abs Sum | 173 | 204 | 99 | 121 | 149 | 152 |
| LEVEL C | Summary Force/Moment | | | **285.2** | | | **244.8** | |
| | **Service Level D** | **WT01** | 21 | 108 | 9 | 13 | -13 | 68 |
| | | **SEISH** | 212 | 122 | 111 | 131 | 167 | 109 |
| | | Abs Sum | 233 | 230 | 120 | 144 | 180 | 177 |
| LEVEL D | Summary Force/Moment | | | **348.7** | | | **290.6** | |

| **SECONDARY RESULTANT Forces & Moments - Weldment WIC-45A** | | | Forces (lb) | | | Moments (ft-lb) | | |
|---|---|---|---|---|---|---|---|---|
| | | | FA | FB | FC | MA | MB | MC |
| | **Service Level A** | **TM** | 13 | 76 | 87 | 235 | -154 | 182 |
| LEVEL A | Summary Force/Moment | | | **116.2** | | | **334.8** | |
| | **Service Level B** | **TM** | 13 | 76 | 87 | 235 | -154 | 182 |
| LEVEL B | Summary Force/Moment | | | **116.2** | | | **334.8** | |
| | **Service Level C** | **THRMA1** | -121 | -101 | 411 | 839 | -698 | 240 |
| LEVEL C | Summary Force/Moment | | | **440.2** | | | **1117.5** | |
| | **Service Level D** | **THRMA1** | -121 | -101 | 411 | 839 | -698 | 240 |
| LEVEL D | Summary Force/Moment | | | **440.2** | | | **1117.5** | |

Note: Summary forces and moments are resultant SRSS of three directions

**Table 3 Concluded: Piping Loads for Load Combinations – Weldment WIC-45A & RB-46-7**

| PRIMARY RESULTANT Forces & Moments - Weldment RB-46-7 | | | Forces (lb) | | | Moments (ft-lb) | | |
|---|---|---|---|---|---|---|---|---|
| | | | FA | FB | FC | MA | MB | MC |
| | **Service Level A** | **WT01** | -20 | 37 | 35 | -2 | -90 | -147 |
| LEVEL A | Summary Force/Moment | | | **54.7** | | | **172.4** | |
| | **Service Level B** | **WT01** | -20 | 37 | 35 | -2 | -90 | -147 |
| | | **SEISDE** | 22 | 81 | 11 | 6 | 42 | 169 |
| | | Abs Sum | 42 | 118 | 46 | 8 | 132 | 316 |
| LEVEL B | Summary Force/Moment | | | **133.4** | | | **342.6** | |
| | **Service Level C** | **WT01** | -20 | 37 | 35 | -2 | -90 | -147 |
| | | **SEISDD** | 44 | 162 | 22 | 12 | 84 | 338 |
| | | Abs Sum | 64 | 199 | 57 | 14 | 174 | 485 |
| LEVEL C | Summary Force/Moment | | | **216.7** | | | **515.5** | |
| | **Service Level D** | **WT01** | -20 | 37 | 35 | -2 | -90 | -147 |
| | | **SEISH** | 66 | 218 | 41 | 15 | 154 | 458 |
| | | Sum | 86 | 255 | 76 | 17 | 244 | 605 |
| LEVEL D | Summary Force/Moment | | | **279.6** | | | **652.6** | |

| SECONDARY RESULTANT Forces & Moments - Weldment RB-46-7 | | | Forces (lb) | | | Moments (ft-lb) | | |
|---|---|---|---|---|---|---|---|---|
| | | | FA | FB | FC | MA | MB | MC |
| | **Service Level A** | **TM** | -69 | -127 | 13 | 8 | -42 | -249 |
| LEVEL A | Summary Force/Moment | | | **145.1** | | | **252.6** | |
| | **Service Level B** | **TM** | -69 | -127 | 13 | 8 | -42 | -249 |
| LEVEL B | Summary Force/Moment | | | **145.1** | | | **252.6** | |
| | **Service Level C** | **THRMA1** | 148 | 256 | -43 | -63 | 123 | 525 |
| LEVEL C | Summary Force/Moment | | | **298.8** | | | **542.9** | |
| | **Service Level D** | **THRMA1** | 148 | 256 | -43 | -63 | 123 | 525 |
| LEVEL D | Summary Force/Moment | | | **298.8** | | | **542.9** | |

Note: Summary forces and moments are resultant SRSS of three directions

## Table 4: Primary/Secondary Stresses

### STRESS Calculation WIC-45A

| | | | |
|---|---|---|---|
| Pipe OD | 4.5 | | |
| tnom | 0.437 | | |
| Pipe ID | 3.626 | | |
| Pipe Metal Cross-sectional area | | (π/4)(Do^2-Di^2) | 5.578 in2 |
| Pipe Section Modulus | | (π/(32*Do)*(Do^4-Di^4) | 5.175 in3 |

Membrane Stress = $F_{SRSS}/A_{pipe}$

Bending Stress = $Moment_{SRSS}$/Section Modulus

| Primary Membrane Stress | DCPP Charging Nozzle WIC-45A Nozzle | |
|---|---|---|
| | Summary Force (SRSS) (lb) | Stress (psi) |
| **Service Level A** | 110.4 | 19.8 |
| **Service Level B** | 191.5 | 34.3 |
| **Service Level C** | 285.2 | 51.1 |
| **Service Level D** | 348.7 | 62.5 |

| Primary Bending Stress | DCPP Charging Nozzle WIC-45A Nozzle | |
|---|---|---|
| | Summary Moment(SRSS)ft-lb | Stress (psi) |
| **Service Level A** | 70.4 | 163.3 |
| **Service Level B** | 152.2 | 352.8 |
| **Service Level C** | 244.8 | 567.8 |
| **Service Level D** | 290.6 | 673.9 |

| Secondary Membrane Stress | | |
|---|---|---|
| | Summary Force (SRSS) (lb) | Stress (psi) |
| **Service Level A** | 116.2 | 20.8 |
| **Service Level B** | 116.2 | 20.8 |
| **Service Level C** | 440.2 | 78.9 |
| **Service Level D** | 440.2 | 78.9 |

| Secondary Bending Stress | | |
|---|---|---|
| | Summary Moment(SRSS)ft-lb | Stress (psi) |
| **Service Level A** | 334.8 | 776.3 |
| **Service Level B** | 334.8 | 776.3 |
| **Service Level C** | 1117.5 | 2591.3 |
| **Service Level D** | 1117.5 | 2591.3 |

Secondary Stresses are conservatively added (both membrane and bending)

| Secondary Stress | DCPP Charging Nozzle WIC-45A Nozzle |
|---|---|
| | Stress (psi) |
| **Service Level A** | 797.1 |
| **Service Level B** | 797.1 |
| **Service Level C** | 2670.2 |
| **Service Level D** | 2670.2 |

## Table 4 (Concluded): Primary/Secondary Stresses

### STRESS Calculation - RB-46-7

| | | | |
|---|---|---|---|
| Pipe OD | 4.5 | | |
| tnom | 0.437 | | |
| Pipe ID | 3.626 | | |
| Pipe Metal Cross-sectional area | | (π/4)(Do^2-Di^2) | 5.578 in2 |
| Pipe Section Modulus | | (π/(32*Do)*(Do^4-Di^4) | 5.175 in3 |

Membrane Stress = $F_{SRSS}/A_{pipe}$

Bending Stress = $Moment_{SRSS}$/Section Modulus

| Primary Membrane Stress | DCPP Charging Nozzle RB-46-7 Nozzle | |
|---|---|---|
| | Summary Force (SRSS) (lb) | Stress (psi) |
| **Service Level A** | 54.7 | 9.8 |
| **Service Level B** | 133.4 | 23.9 |
| **Service Level C** | 216.7 | 38.8 |
| **Service Level D** | 279.6 | 50.1 |

| Primary Bending Stress | DCPP Charging Nozzle RB-46-7 Nozzle | |
|---|---|---|
| | Summary Moment(SRSS)ft-lb | Stress (psi) |
| **Service Level A** | 172.4 | 399.7 |
| **Service Level B** | 342.6 | 794.4 |
| **Service Level C** | 515.5 | 1195.3 |
| **Service Level D** | 652.6 | 1513.3 |

| Secondary Membrane Stress | | |
|---|---|---|
| | Summary Force (SRSS) (lb) | Stress (psi) |
| **Service Level A** | 145.1 | 26.0 |
| **Service Level B** | 145.1 | 26.0 |
| **Service Level C** | 298.8 | 53.6 |
| **Service Level D** | 298.8 | 53.6 |

| Secondary Bending Stress | | |
|---|---|---|
| | Summary Moment(SRSS)ft-lb | Stress (psi) |
| **Service Level A** | 252.6 | 585.9 |
| **Service Level B** | 252.6 | 585.9 |
| **Service Level C** | 542.9 | 1258.9 |
| **Service Level D** | 542.9 | 1258.9 |

Secondary Stresses are conservatively added (both membrane and bending)

| Secondary Stress | DCPP Charging Nozzle RB-46-7 Nozzle |
|---|---|
| | Stress (psi) |
| **Service Level A** | 611.9 |
| **Service Level B** | 611.9 |
| **Service Level C** | 1312.5 |
| **Service Level D** | 1312.5 |

**Table 5: Bounding Primary Piping Stresses**

| Primary Membrane Stress | DCPP Charging Nozzle | | BOUNDING |
|---|---|---|---|
| | Summary Force (SRSS) (lb) | Stress (psi) | **Stress (psi)** |
| **Service Level A** | 110.4 | 19.8 | **29.7** |
| **Service Level B** | 191.5 | 34.3 | **51.5** |
| **Service Level C** | 285.2 | 51.1 | **76.7** |
| **Service Level D** | 348.7 | 62.5 | **93.8** |

| Primary Bending Stress | DCPP Charging Nozzle | | BOUNDING |
|---|---|---|---|
| | Summary Moment(SRSS)ft-lb | Stress (psi) | **Stress (psi)** |
| **Service Level A** | 172.4 | 399.7 | **599.6** |
| **Service Level B** | 342.6 | 794.4 | **1191.5** |
| **Service Level C** | 515.5 | 1195.3 | **1793.0** |
| **Service Level D** | 652.6 | 1513.3 | **2269.9** |

Note: Bounding stress column includes 50% increase. Input membrane stress to **pc-CRACK** and **SI-TIFFANY** includes pressure stress.

**Table 6: Bounding Secondary Piping Stresses**

| Secondary Stress | DCPP Charging Nozzle | BOUNDING |
|---|---|---|
| | Stress (psi) | **Stress (psi)** |
| **Service Level A** | 797.1 | **1195.7** |
| **Service Level B** | 797.1 | **1195.7** |
| **Service Level C** | 2670.2 | **4005.3** |
| **Service Level D** | 2670.2 | **4005.3** |

Note: Bounding stress column includes 50% increase. Stresses listed above do not include thermal transient stress.

**Table 7: Transient Cycles Evaluated**

| Transients | Cycles for 60 years |
|---|---|
| **Normal** | |
| Lp3 Chrg & Ltdn Shutoff | 75 |
| Lp3 Chrg Trip Delayed Rtn. | 25 |
| Lp3 Chrg Trip Prompt Rtn. | 25 |
| Lp3 Ltdn Trip Delayed Rtn. | 25 |
| Lp4 Chrg & Ltdn Shutoff | 75 |
| Lp4 Chrg Trip Delayed Rtn. | 25 |
| Lp4 Chrg Trip Prompt Rtn | 118 |
| Lp4 Ltdn Trip Delayed Rtn. | 25 |
| | |
| Plant (RCS) Cooldown | 200 |
| Plant (RCS) Heatup | 200 |
| | |
| TOTAL Cycles | 793 |

Notes: 1. All information is obtained from Reference 9.

**Table 8: Transient Analyzed in SI-TIFFANY**

| Transient | Time (sec) | Temperature (°F) | Pressure (psig) | Flow Rate (gpm) |
|---|---|---|---|---|
| Charging | 0 | 130 | 2800 | 560 |
| | 0.1 | 40 | 0 | 560 |
| | 3600 | 40 | 0 | 560 |
| | 3600.1 | 130 | 2800 | 560 |
| | 7200 | 130 | 2800 | 560 |

Notes: 1. For information on transient development, see Section 3.7. The figure in Section 3.7 which shows the pressure and temperature transient is a schematic representation, as the actual time period between the start of the analysis input and the drop in pressure/temperature is only 0.1 seconds. However, the initial conditions of the system (2800 psig and 130°F) at time zero are consistent with steady state operation (the initial straight line of the trace). Actual SI-TIFFANY time step starts at 0.1 seconds for pressure/temperature change.

**Table 9: Material Properties for A-376 TP 316**

| Material Property | Units | Pump Discharge Line |
|---|---|---|
| Normal Operating Temperature | °F | 130 |
| Young's Modulus | ksi | 28,300 |
| Poisson's Ratio | -- | 0.3 |
| Density | $lb/in^3$ | 0.29 |
| Specific Heat | BTU/lb-°F | 0.11 |
| Coefficient of Thermal Expansion | in/in-°F | $8.5 \times 10^{-6}$ |
| Thermal Conductivity | BTU/sec-in-°F | $1.90 \times 10^{-4}$ |

Note: 1. Material properties are taken at a temperature of 70 °F from Reference [4].

**Table 10: Fatigue Crack Growth Loadings**

| Event | $K_{max}$ | $K_{min}$ |
|---|---|---|
| **Charging Transient** | $Thermal\ Expansion_{max}$, $Thermal\ Transient_{max}$, $Pressure_{max}$, Deadweight, Residual, $Seismic_{max}$ Crack Face Pressure | $Thermal\ Expansion_{min}$, $Thermal\ Transient_{min}$, $Pressure_{min}$, Deadweight, Residual, $Seismic_{min}$ |

**Table 11: Initial, Final, and Allowable Flaw Sizes**

| Flaw | Depth (in) | Length (in) | a/t(1) | l/circ(2) | Years |
|---|---|---|---|---|---|
| **Initial** | 0.075 | 0.45 | 0.175 | 0.032 | N/A |
| **Final** | 0.0917 | 0.48 | 0.21 | 0.034 | 40(3) |

Notes: 1. a/t is the ratio of the flaw depth to the pipe wall thickness.
2. l/circ is the ratio of the flaw length to the pipe circumference.
3. Flaw growth was evaluated for an additional 40 years.

## Table 12: Allowable Flaw Sizes

**For Combined Loading**

| | Allowable flaw depth (a/t) | | | |
|---|---|---|---|---|
| | Level A | Level B | Level C | Level D |
| l/Cir. | SR=0.2112 | SR=0.2298 | SR=0.2941 | SR=0.3157 |
| 0 | 0.75 | 0.75 | 0.75 | 0.75 |
| 0.1 | **0.75** | **0.75** | **0.75** | **0.75** |
| 0.2 | 0.75 | 0.75 | 0.75 | 0.75 |
| 0.3 | 0.75 | 0.75 | 0.75 | 0.75 |
| 0.4 | 0.75 | 0.75 | 0.75 | 0.75 |
| 0.5 | 0.7343 | 0.7381 | 0.703 | 0.7328 |
| 0.6 | 0.6843 | 0.6983 | 0.6465 | 0.6912 |
| 0.75 | 0.6366 | 0.6502 | 0.5983 | 0.6328 |

SR= Stress Ratio, L/Cir. = 0.034

**For Membrane Loading**

| | Allowable flaw depth (a/t) | | | |
|---|---|---|---|---|
| | Level A | Level B | Level C | Level D |
| l/Cir. | SR=0.4962 | SR=0.4424 | SR=0.3329 | SR=0.2410 |
| 0 | 0.75 | 0.75 | 0.75 | 0.75 |
| 0.1 | **0.75** | **0.75** | **0.75** | **0.75** |
| 0.2 | 0.75 | 0.75 | 0.75 | 0.75 |
| 0.3 | 0.75 | 0.75 | 0.75 | 0.75 |
| 0.4 | 0.7115 | 0.733 | 0.75 | 0.75 |
| 0.5 | 0.6146 | 0.6791 | 0.7434 | 0.75 |
| 0.6 | 0.5542 | 0.6134 | 0.7203 | 0.75 |
| 0.75 | 0.5038 | 0.5576 | 0.6671 | 0.7295 |

SR= Stress Ratio, L/Cir. = 0.034

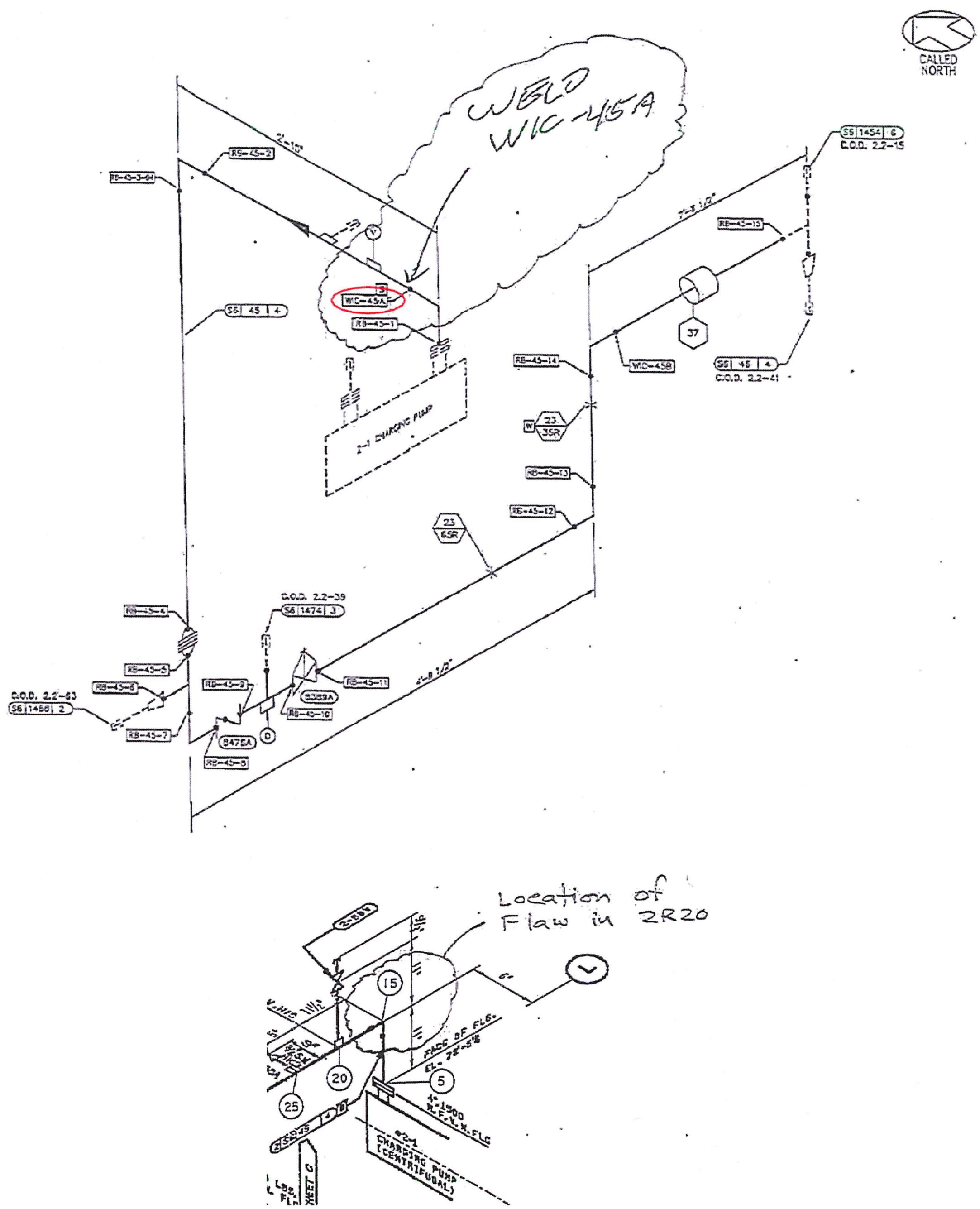



**Figure 1. Isometric Drawing of the Charging Pump 2-1 Line**
Weldment WIC-45A

Note: Location of the flaw is circled in the picture. The node of interest is #15 E. Drawing is from Reference 1.

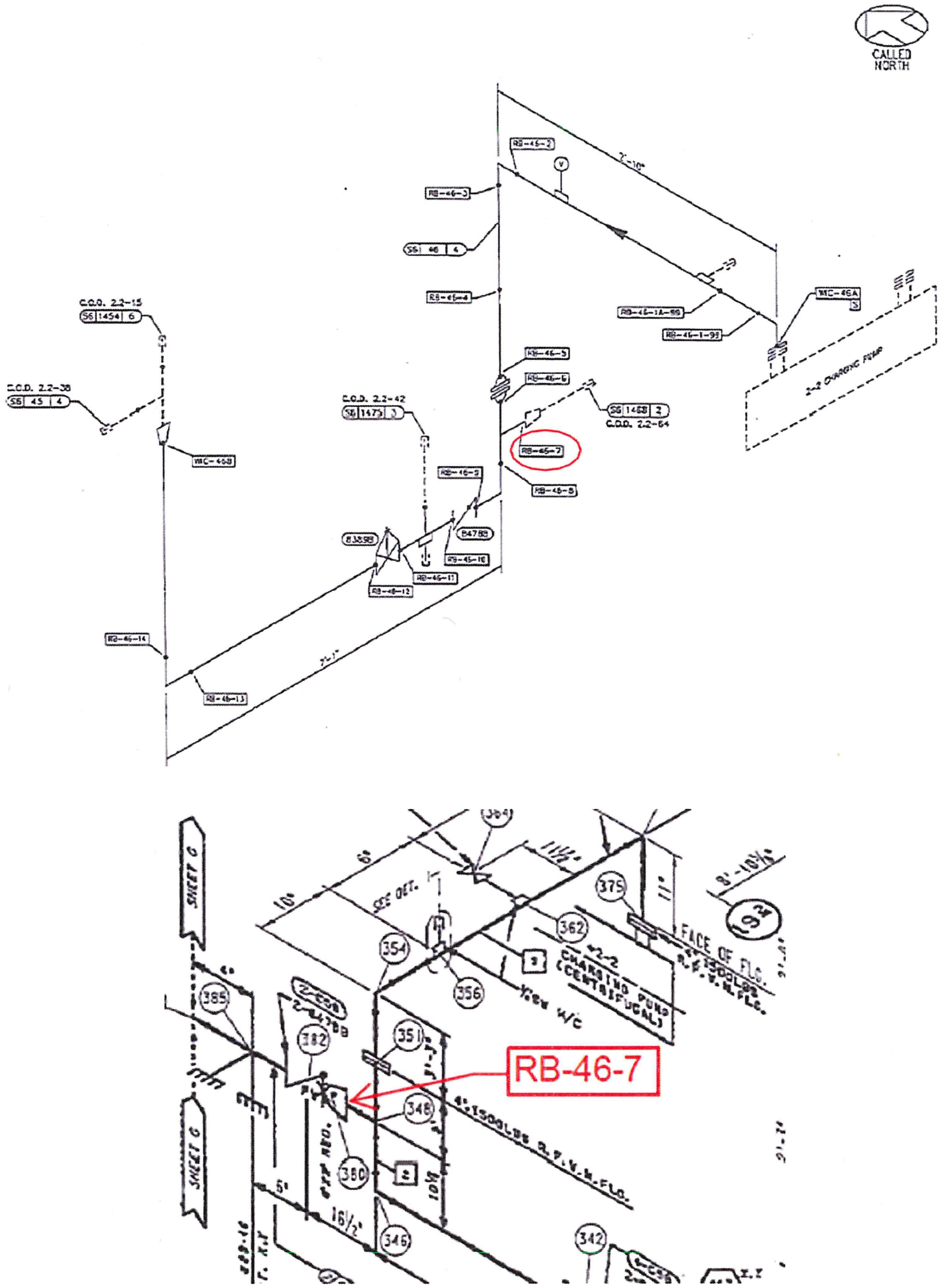



**Figure 2. Isometric Drawing of the Charging Pump 2-2 Line**
Weldment RB-46-7

Note: Location of the flaw is circled in the picture. The node of interest is #348-380. Drawing is from Reference 2.

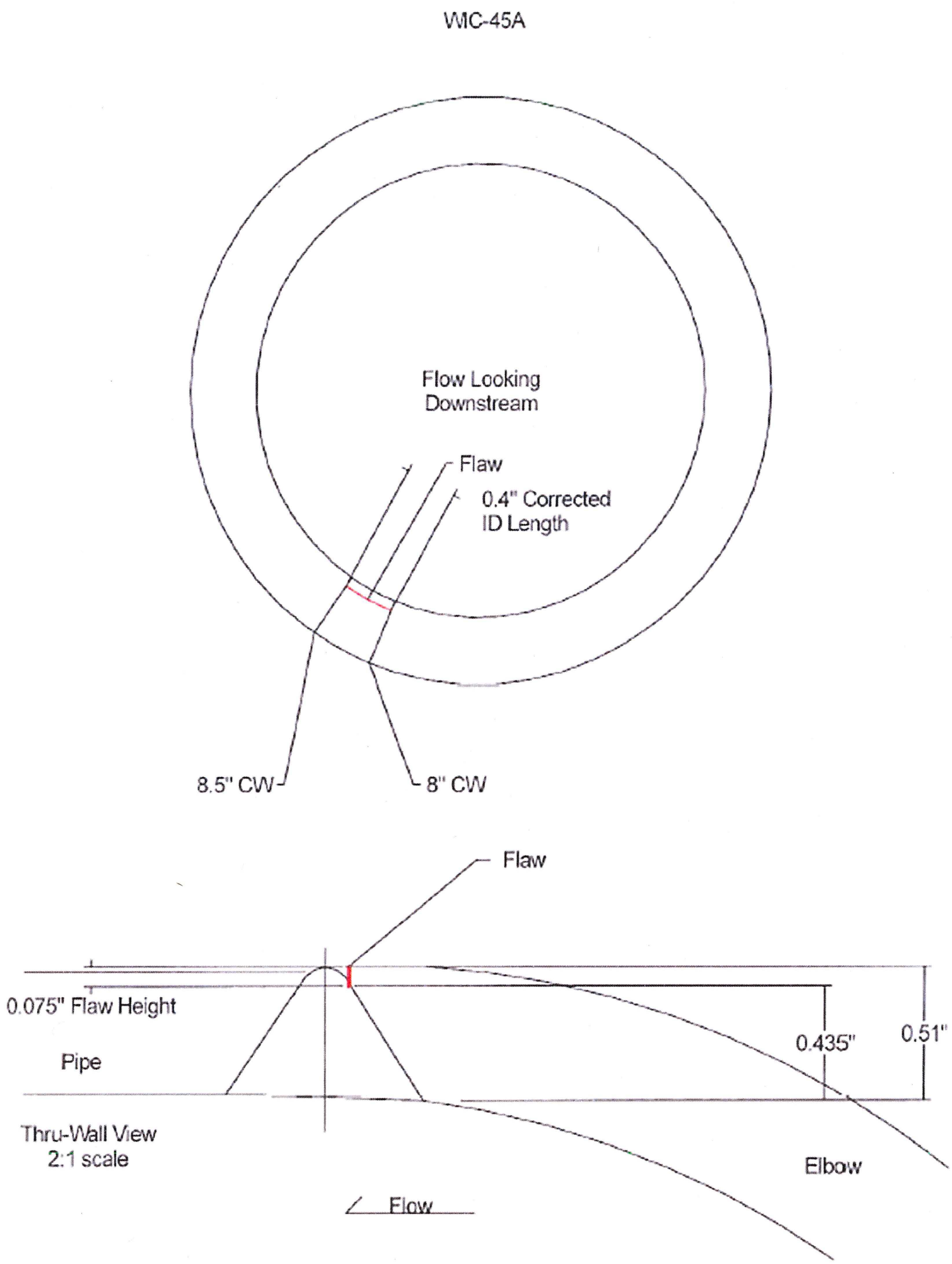
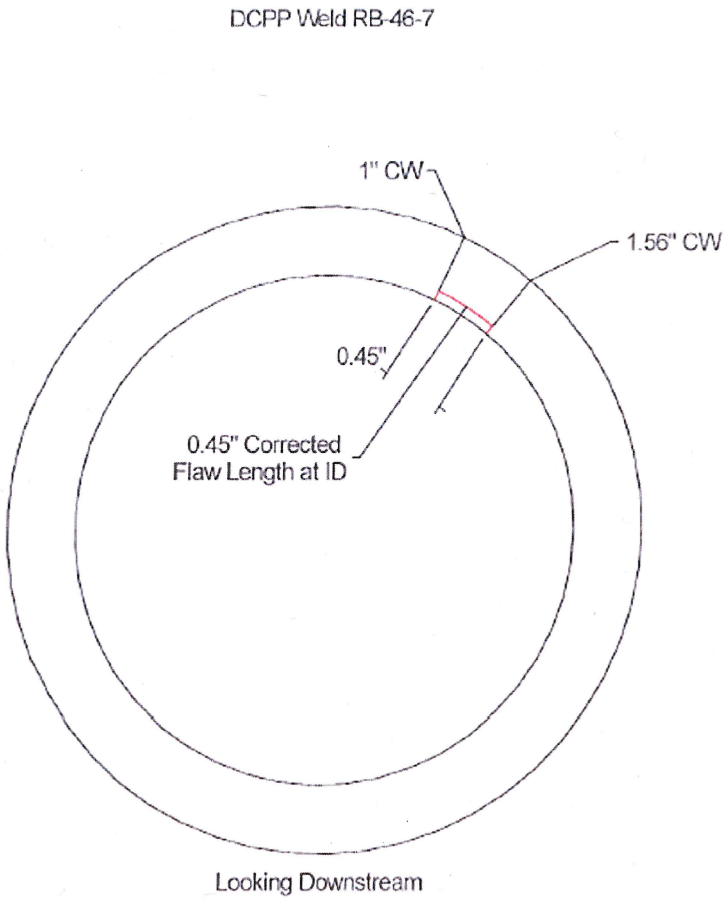



**Figure 3. Indication Sketch WIC-45A**
[Reference 1]



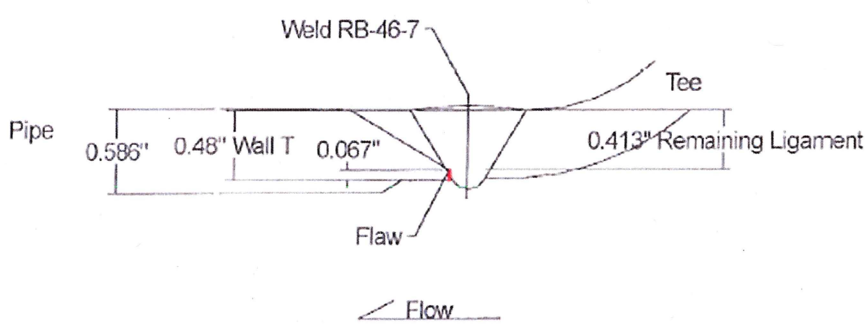




**Figure 4. Indication Sketch RB-46-7**
[Reference 2]

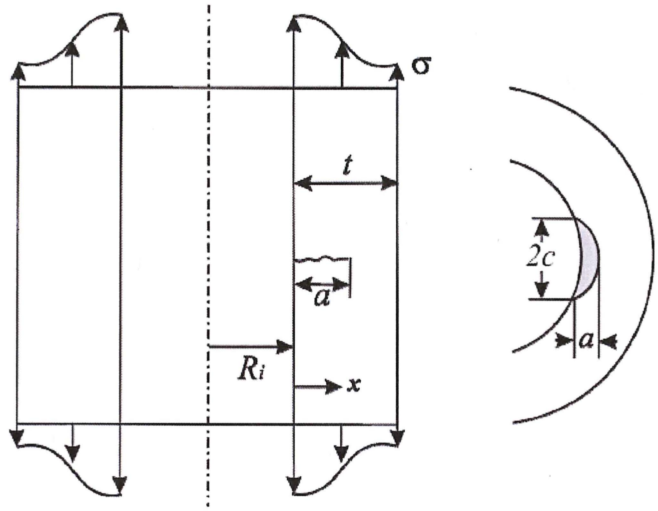
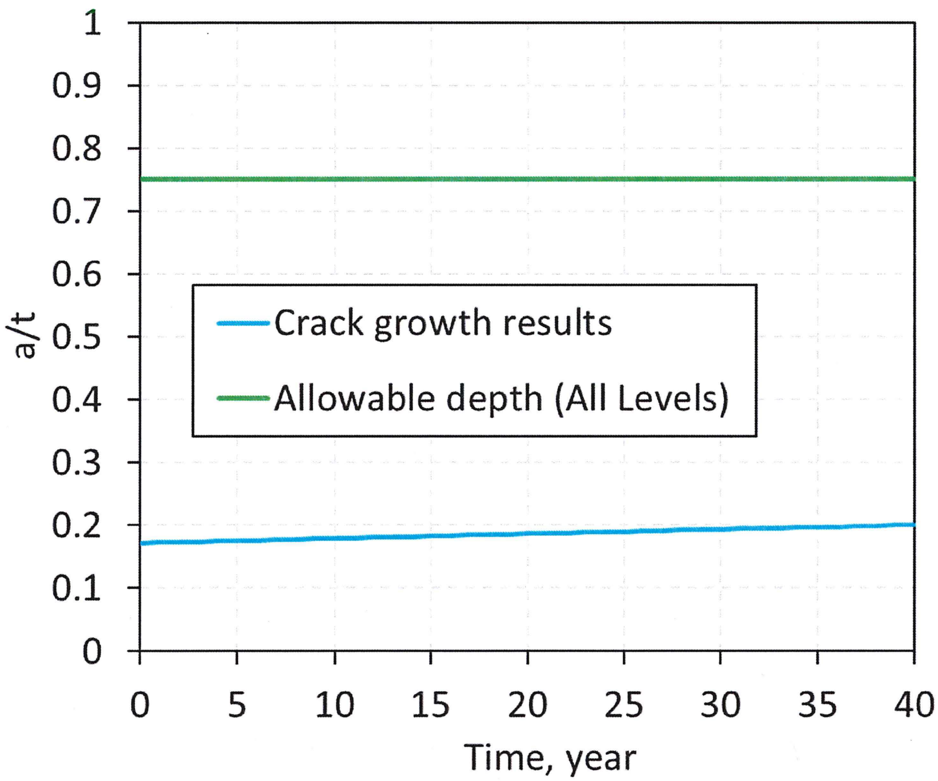



**Figure 5. Semi-Elliptic Flaw on Inside Surface of a Cylinder**

**Figure 6. Flaw Growth and Allowable Flaw Size – Bounding Flaw**



# APPENDIX A

## NDE ISI EXAMINATION DATA

(Selected pages)

DCPP Form 69-22145 (04/25/17)

# U1&2

NDE PDI-UT-3 Attachment 2
Page 1 of 1

## Sizing Examination Data Sheet

Page 6 of 7

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Line | 45-4 | Weld | WIC-45A | Item No. | 32 | Config | Pipe-Elbow | Iso 2.2-38 |
| XDCR Angles | below | XDCR Modes | below | | Scan Gain | var | Weld Crown Width | 0.8 |

| Ind # | Angle Used | dB | OD Tech. | L1 | L2 | Length | Corrected Length | Remaining Ligament | Thru-Wall | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 60 DS | | AATT | 8" | 8.5" | 0.5" | 0.4" | 0.435" | .075 | 2.25 MHz, elbow side |
| 1 | 60 US | | AATT | | | | | 0.450" | .060 | 2.25 MHz, Pipe Side |
| 1 | 60 DS | | AATT | | | | | 0.460" | .05 | 5.0 MHz, elbow side |
| | 60 RL | | AATT | | | | | --- | --- | See Below |
| | ODCR | | Hi > | | | | | --- | --- | See Below |
| | 70 | | AATT | | | | | --- | --- | 2.2 5Mhz, elbow and pipe sides |

Note: Length measurements are determined using the applicable qualified PDI detection procedure and included here for info only.

Comments

60 RL applied to pipe side (through weld), no distinct indications attributable to indication noted.

ODCR elbow side detected an indication at 4+ screen divisions, outside the calibrated depth range. An additional signal is present at ~3 divisions while the transducer is bridging base metal and crown. This signal is attributed to the shear wave component and therefore considered invalid.

70 shear applied to pipe and elbow sides for indication confirmation, length sizing and to confirm the absence of mid-wall relectors. See attached white paper for additional discussion.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Examiner | M. Leger [signature] | Level | III | Examiner | N/A | Level | N/A |
| Review | T. Carraher [signature] L-III | Date | 2-24-18 | ANII | Guadagnoli, C [signature] | Date | 3/6/18 |

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indication data sheet.doc 0224.2223

## WIC-45A Through-wall/Length Sizing Process and Results

- 60° shear wave technique from the elbow side, both 2.25MHz and 5.0MHz were used for the through- wall sizing of record.
  - Both frequencies produced repeatable indications at 0.480" – 0.510" range. In a limited area near the CW end of the flaw, a minimum remaining ligament of 0.435" was detected.
  - The elbow wall thickness is 0.510 in the area, resulting in a flaw through wall dimension of 0.075".
- 70° Shear (detection calibration) was used to determine the length of the indication; length was determined to be 0.5", with an ID corrected length of 0.4".

Supporting results and other information

- 60° shear, 2.2.5 MHz from the far side of the weld (pipe) produced repeatable indications that were typically in the same range as the indications above.
- 60° Dual L-wave from the far side (pipe) did not produce distinctive indications in the area of interest. This is believed to be due to the small through-wall dimension of the flaw and the longer longitudinal search unit wave-length.
  - 60° Dual L-wave from the near side (elbow) was not effective due to lack of contact in the elbow intrados area even though it is a small dual search unit.
- OD Creeper technique produced indications in the area of interest as follows:
  - An indication at approximately 4+ screen divisions, which is well outside the calibrated range of the technique.
  - An indication at approximately 3 screen divisions. This indication is quite large in amplitude, but is obtained with the transducer bridging over a gap between the base material and weld area. This transducer position would place the reflector (detected with the OD creeper) location far outside the area of interest. In addition, the indication has a rapid rise and fall, i.e. short travel, which is characteristic of the shear (unused) component of the search unit rather than the OD creeping wave which is calibrated. For these reasons, the ODCR indications are not considered useful.
- 70° Shear, both 2.25 MHz and 5.0 MHz were applied and produced repeatable indications in the area of interest. Due to the large beam spread from the small diameter search units, repeatable calibration proved difficult in the examination depth. Due to the crisper response of the 60° search units, they provide more accurate measurements at the depth of interest.
  - No deep, (near surface) indications were detected with the 70° search units.
- Phased array 5Mhz shear wave setup produced repeatable indications from the far side (pipe), but cannot be credited for sizing through the weld. Unfortunately, The phased array search unit did not achieve contact on the intrados of the elbow, so no near side data was acquired.

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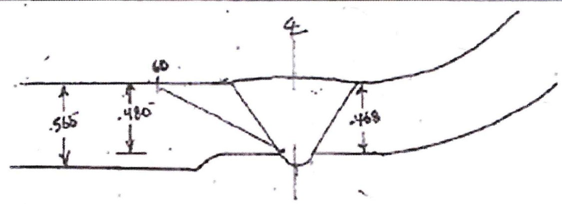
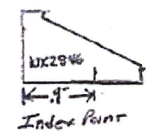
**Indication Data Sheet**

**U1&2** Attachment 3: Page 1 of 1

| Weld No: RB-46-7 | | | | Line: 46 | | | Component Temp: 69°F | | | | | Page 2 of 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ind. No. | Data File Name | Scan Type AX/Circ | Scan Direc. UP/DN CW/CCW | Ind.Start (L1) (check) | Ind.Stop (L2) (check) | Pos. (W) Ref. Point | Pos. (W) Dim. | Sweep or MP | Depth From OD | Pipe Wall Thick | TW Dim. | Technique/Indication Description | Accept/Reject |
| 1 | 28V6F0F9 | AX | US | 1.0" | 1.56" | ¢ .850 | .850 | .825" | .413" | .480" | .067" | PATT 60° Focal Law | Reject |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |

Comments:




| Examiner: David Wilson [signature] | Level: III | Date: 2-24-18 |
|---|---|---|
| Examiner: | Level: | Date: |
| Reviewer: M. Lezer [signature] | Level: III | Date: 2/24/18 |
| ANII: [signature] GUADAGNOLI | | Date: 3/6/18 |

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DCPP Form 69-22145 (04/25/17) **U1&2** NDE PDI-UT-3 Attachment 2
Page 1 of 1
Page 2 of 3

## Sizing Examination Data Sheet

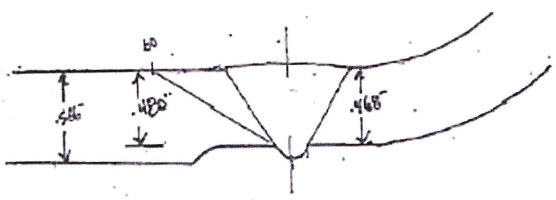
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Line | 46 | Weld | RB-46-7 | Item No. | RB-46-7 | Config | "T" to PIPE | Iso | 2.2.41 |
| XDCR Angles | 60 | XDCR Modes | Shear | Scan Gain | 38dB | Weld Crown Width | .8 | | |

| Ind # | Angle Used | dB | OD Tech. | L1 | L2 | Length | Corrected Length | Remaining Ligament | Thru-Wall | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 60 S | 37 | PATT | 1" | 1.56" | .56" | .45" | .413" | .067" | See Comments |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |

Note: Length measurements are determined using the applicable qualified PDI detection procedure and included here for info only.

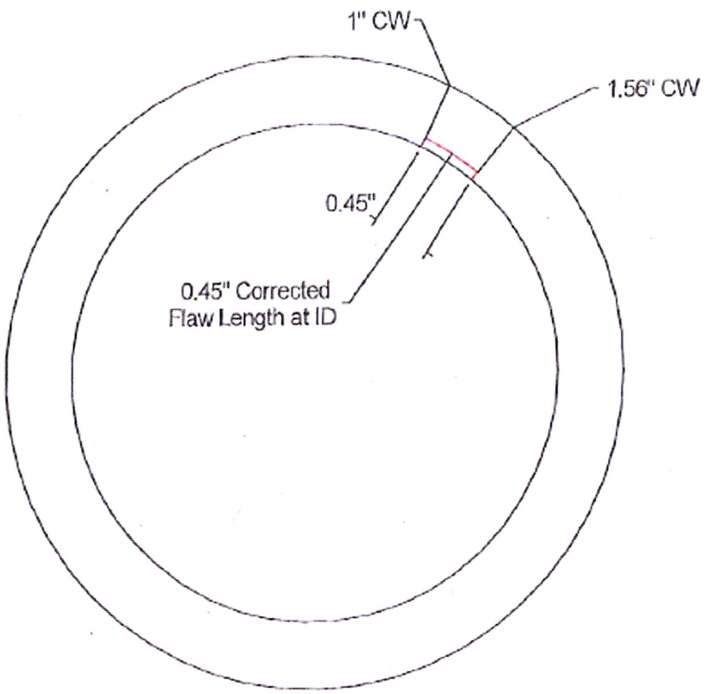
Comments: Indication appears to have good signal to noise over background. No "TIP" signals were observed. Surrounding geometry is clean of signals. Indication and corner trap appear to be one indication – sizing was from the peaked signal with least sound path/depth.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Examiner | David L. Wilson [signature] | Level | III | Examiner | [signature] | Level | |
| Review | M. Hogan [signature] L III | Date | 2/24/18 | ANII | [signature] GUADAGNOLI | Date | 3/6/18 |

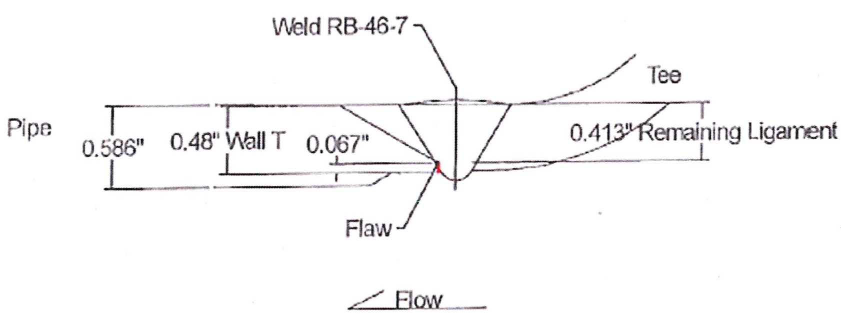


Page 5 of 5

DCPP Weld RB-46-7




Looking Downstream




[signature] 2-24-18

# APPENDIX B

# COMPUTER FILE LISTING

**SI-TIFFANY Files**

| | |
|---|---|
| trans1.dat | **SI-TIFFANY** input file |
| trans1.rpt | **SI-TIFFANY** output file, which echoes the inputs |
| trans1.mnn | **SI-TIFFANY** output file with tabulated $K_{min}$ values |
| trans1.mxn | **SI-TIFFANY** output file with tabulated $K_{max}$ values |

## pc-CRACK Files

| | |
|---|---|
| LevelA.pcf | **pc-CRACK** input file for Service Level A EPFM evaluation |
| LevelB.pcf | **pc-CRACK** input file for Service Level B EPFM evaluation |
| LevelC.pcf | **pc-CRACK** input file for Service Level C EPFM evaluation |
| LevelD.pcf | **pc-CRACK** input file for Service Level D EPFM evaluation |
| LevelA.rpt | **pc-CRACK** output file for Service Level A EPFM evaluation |
| LevelB.rpt | **pc-CRACK** output file for Service Level B EPFM evaluation |
| LevelC.rpt | **pc-CRACK** output file for Service Level C EPFM evaluation |
| LevelD.rpt | **pc-CRACK** output file for Service Level D EPFM evaluation |
| CGVarAC.pcf | **pc-CRACK** input file for fatigue crack growth for variable aspect ratio |
| GrkGrw.rpt | **pc-CRACK** output file for fatigue crack growth for variable aspect ratio |
| CrkGrw.kva | **pc-CRACK** file including K vs A for fatigue crack growth with variable aspect ratio |
| CrkGrw.avn | **pc-CRACK** file including crack depth vs time for fatigue crack growth with variable aspect ratio |

# APPENDIX C

# PC-CRACK OUTPUT FILES

## Service Level A

```
pc-CRACK 4.1 CS

Version Control No. 4.1.0.0

Structural Integrity Associates, Inc.
www.structint.com
pccrack@structint.com

Date: 03/01/2018 14:09

Input Data read from D:\01.Project\11.DCPP\LevelA.pcf

Analysis Title: DCCP Weld WIC-45A

Units Selected: US Customary
      Linear Dimensions - inches
      Stress - ksi
      Load - kips
      Temperature - deg F
      Time - hours
      Jic - in-lbs/in^2


Analysis Type: ASME Section XI IWB-3640 (2004)

Crack Geometry
      Orientation: Circumferential
      Crack Depth =       0.0750
      Crack Length =       0.4500

Pipe Geometry
      Nominal Pipe Size =       4.0000
      Outer Diameter =       4.5000
      Wall Thickness =       0.4370

Service Level: A

The allowable flaw size is determined using Tables

Stresses
      Pm =       7.2380 (safety factor =       2.7000)
      Pb =       0.6000 (safety factor =       2.3000)
      Pe =       1.1960
 K (Residual Stress) =       0.0000

Material: Stainless Steel
      Flux weld
      Flow Stress      =      51.2000

Number of Warnings in Inputs: 0
```

Analysis Results

Failure Mode per Screening Criteria:EPFM (Class 1 screening rules used)

Table C-5310-1 used

```
      Stress Ratio    =       0.2122
      Z factor         =       1.3000
      l/circumference =       0.0318
      allowable a/t    =       0.7500 (Combined Loading)
```

| l/Circumference | Allowable a/t |
|---|---|
| 0.0000 | 0.7500 |
| 0.1000 | 0.7500 |
| 0.2000 | 0.7500 |
| 0.3000 | 0.7500 |
| 0.4000 | 0.7500 |
| 0.5000 | 0.7329 |
| 0.6000 | 0.6829 |
| 0.7500 | 0.6353 |

Table C-5310-5 used

```
      Stress Ratio     =       0.4962
      Z factor         =       1.3000
      l/circumference =       0.0318
      allowable a/t    =       0.7500 (Membrane Loading)
```

| l/Circumference | Allowable a/t |
|---|---|
| 0.0000 | 0.7500 |
| 0.1000 | 0.7500 |
| 0.2000 | 0.7500 |
| 0.3000 | 0.7500 |
| 0.4000 | 0.7115 |
| 0.5000 | 0.6146 |
| 0.6000 | 0.5542 |
| 0.7500 | 0.5038 |

Note: Allowable crack size is calculated based on the failure mode indicated by the screening criteria which is based on the input crack size

Number of Runtime Warnings: 0

*** End of pc-CRACK output ***

## Service Level B

```
pc-CRACK 4.1 CS

Version Control No. 4.1.0.0

Structural Integrity Associates, Inc.
www.structint.com
pccrack@structint.com

Date: 02/27/2018 14:33

Input Data read from D:\DCPP 1800289\Weld WIC-45A\LevelB.pcf

Analysis Title: DCCP Weld WIC-45A

Units Selected: US Customary
      Linear Dimensions - inches
      Stress - ksi
      Load - kips
      Temperature - deg F
      Time - hours
      Jic - in-lbs/in^2


Analysis Type: ASME Section XI IWB-3640 (2004)

Crack Geometry
      Orientation: Circumferential
      Crack Depth =       0.0750
      Crack Length =       0.4500

Pipe Geometry
      Nominal Pipe Size =       4.0000
      Outer Diameter =       4.5000
      Wall Thickness =       0.4370

Service Level: B

The allowable flaw size is determined using Tables

Stresses
      Pm =       7.2600 (safety factor =       2.4000)
      Pb =       1.1916 (safety factor =       2.0000)
      Pe =       1.1950
 K (Residual Stress) =       0.0000

Material: Stainless Steel
      Flux weld
      Flow Stress       =       51.2000

Number of Warnings in Inputs: 0
```

```
Analysis Results

Failure Mode per Screening Criteria:EPFM (Class 1 screening rules used)

Table C-5310-2 used
      Stress Ratio    =       0.2298
      Z factor         =       1.3000
      l/circumference =       0.0318
      allowable a/t   =       0.7500 (Combined Loading)

 l/Circumference  Allowable a/t

      0.0000         0.7500
      0.1000         0.7500
      0.2000         0.7500
      0.3000         0.7500
      0.4000         0.7500
      0.5000         0.7381
      0.6000         0.6983
      0.7500         0.6502

Table C-5310-5 used
      Stress Ratio    =       0.4424
      Z factor         =       1.3000
      l/circumference =       0.0318
      allowable a/t   =       0.7500 (Membrane Loading)

 l/Circumference  Allowable a/t

      0.0000         0.7500
      0.1000         0.7500
      0.2000         0.7500
      0.3000         0.7500
      0.4000         0.7330
      0.5000         0.6791
      0.6000         0.6134
      0.7500         0.5576

Note: Allowable crack size is calculated based on the failure mode indicated
      by the screening criteria which is based on the input crack size


Number of Runtime Warnings: 0


      *** End of pc-CRACK output ***
```

# Service Level C

```
pc-CRACK 4.1 CS

Version Control No. 4.1.0.0

Structural Integrity Associates, Inc.
www.structint.com
pccrack@structint.com

Date: 02/27/2018 14:33

Input Data read from D:\DCPP 1800289\Weld WIC-45A\LevelC.pcf

Analysis Title: DCCP Weld WIC-45A

Units Selected: US Customary
      Linear Dimensions - inches
      Stress - ksi
      Load - kips
      Temperature - deg F
      Time - hours
      Jic - in-lbs/in^2


Analysis Type: ASME Section XI IWB-3640 (2004)

Crack Geometry
      Orientation: Circumferential
      Crack Depth =       0.0750
      Crack Length =       0.4500

Pipe Geometry
      Nominal Pipe Size =      4.0000
      Outer Diameter =      4.5000
      Wall Thickness =      0.4370

Service Level: C

The allowable flaw size is determined using Tables

Stresses
      Pm =      7.2850 (safety factor =      1.8000)
      Pb =      1.7930 (safety factor =      1.6000)
      Pe =      4.0050
 K (Residual Stress) =      0.0000

Material: Stainless Steel
      Flux weld
      Flow Stress      =      51.2000

Number of Warnings in Inputs: 0
```

```
Analysis Results

Failure Mode per Screening Criteria:EPFM (Class 1 screening rules used)

Table C-5310-3 used
      Stress Ratio    =       0.2941
      Z factor          =       1.3000
      l/circumference =       0.0318
      allowable a/t   =       0.7500 (Combined Loading)

 l/Circumference  Allowable a/t

      0.0000        0.7500
      0.1000        0.7500
      0.2000        0.7500
      0.3000        0.7500
      0.4000        0.7500
      0.5000        0.7030
      0.6000        0.6465
      0.7500        0.5983

Table C-5310-5 used
      Stress Ratio      =       0.3329
      Z factor          =       1.3000
      l/circumference =       0.0318
      allowable a/t   =       0.7500 (Membrane Loading)

 l/Circumference  Allowable a/t

      0.0000        0.7500
      0.1000        0.7500
      0.2000        0.7500
      0.3000        0.7500
      0.4000        0.7500
      0.5000        0.7434
      0.6000        0.7203
      0.7500        0.6671

Note: Allowable crack size is calculated based on the failure mode indicated
      by the screening criteria which is based on the input crack size


Number of Runtime Warnings: 0


      *** End of pc-CRACK output ***
```

## Service Level D

```
pc-CRACK 4.1 CS

Version Control No. 4.1.0.0

Structural Integrity Associates, Inc.
www.structint.com
pccrack@structint.com

Date: 02/27/2018 14:34

Input Data read from D:\DCPP 1800289\Weld WIC-45A\LevelD.pcf

Analysis Title: DCCP Weld WIC-45A

Units Selected: US Customary
      Linear Dimensions - inches
      Stress - ksi
      Load - kips
      Temperature - deg F
      Time - hours
      Jic - in-lbs/in^2


Analysis Type: ASME Section XI IWB-3640 (2004)

Crack Geometry
      Orientation: Circumferential
      Crack Depth =        0.0750
      Crack Length =        0.4500

Pipe Geometry
      Nominal Pipe Size =        4.0000
      Outer Diameter =       4.5000
      Wall Thickness =       0.4370

Service Level: D

The allowable flaw size is determined using Tables

Stresses
      Pm =       7.3020 (safety factor =       1.3000)
      Pb =       2.2700 (safety factor =       1.4000)
      Pe =       4.0050
 K (Residual Stress) =       0.0000

Material: Stainless Steel
      Flux weld
      Flow Stress      =      51.2000

Number of Warnings in Inputs: 0
```

```
Analysis Results

Failure Mode per Screening Criteria:EPFM (Class 1 screening rules used)

Table C-5310-4 used
      Stress Ratio    =       0.3157
      Z factor         =       1.3000
      l/circumference =       0.0318
      allowable a/t   =       0.7500 (Combined Loading)

 l/Circumference  Allowable a/t

      0.0000        0.7500
      0.1000        0.7500
      0.2000        0.7500
      0.3000        0.7500
      0.4000        0.7500
      0.5000        0.7328
      0.6000        0.6912
      0.7500        0.6328

Table C-5310-5 used
      Stress Ratio     =       0.2410
      Z factor         =       1.3000
      l/circumference =       0.0318
      allowable a/t   =       0.7500 (Membrane Loading)

 l/Circumference  Allowable a/t

      0.0000        0.7500
      0.1000        0.7500
      0.2000        0.7500
      0.3000        0.7500
      0.4000        0.7500
      0.5000        0.7500
      0.6000        0.7500
      0.7500        0.7295

Note: Allowable crack size is calculated based on the failure mode indicated
      by the screening criteria which is based on the input crack size


Number of Runtime Warnings: 0


      *** End of pc-CRACK output ***
```

# Fatigue Crack Growth – Variable Aspect Ratio

```
pc-CRACK 4.1 CS

Version Control No. 4.1.0.0

Structural Integrity Associates, Inc.
www.structint.com
pccrack@structint.com

Date: 03/01/2018 06:18

Input Data read from D:\DCPP 1800289\Weld WIC-45A\CGVarAC.pcf

Analysis Title: DCCP Weld WIC-45A

Units Selected: US Customary
        Linear Dimensions - inches
        Stress - ksi
        Load - kips
        Temperature - deg F
        Time - hours

Analysis Type: Crack Growth (LEFM)

Crack Growth Calculation Method - Cycle/Time Stepping
Maxinum Number of Load Blocks = 40
Block Print Interval = 1

Crack Model: 309-Semi-Elliptical Circumferential Crack in Cylinder on the Inside Surface (Chapuliot)
Crack Depth, a =       0.0750
Half Crack Length, c =       0.2250
Wall Thickness, t =       0.4370
Inside Radius, Ri =       1.8130
Aspect ratio allowed to vary
Maximum a/t = 0.7
Crack Depth Print Increment for SIF Tabulation = 0.1
Maximum Aspect Ratio (c/a) for SIF Tabulation = 5
Aspect Ratio Increment for SIF Tabulation = 0.2


Total Load Cases: 6

Load Case 1:DW
Type: Stress Coefficients Input by User

 Coefficient C0 =       0.6290
 Coefficient C1 =       0.0000
 Coefficient C2 =       0.0000
 Coefficient C3 =       0.0000

Load Case 2:OBE
Type: Stress Coefficients Input by User

 Coefficient C0 =       0.6130
 Coefficient C1 =       0.0000
 Coefficient C2 =       0.0000
 Coefficient C3 =       0.0000

Load Case 3:Residual
Type: Stress Coefficients Input by User

 Coefficient C0 =      27.4000
 Coefficient C1 =       0.0000
 Coefficient C2 =       0.0000
 Coefficient C3 =       0.0000

Load Case 4:Trans Max
```

2-d SIF Input by User

The SIF originally read from D:\DCPP 1800289\Weld WIC-45A\trans1.mxn

No. of aspect ratios (a/c) in the tables = 6

a/c = 0.1250

| Crack Depth | Kdeepest | Ksurface |
|---|---|---|
| 4.370E-03 | 2.4027 | 0.8950 |
| 0.0437 | 6.2314 | 2.7154 |
| 0.0874 | 7.1142 | 3.6305 |
| 0.1311 | 7.4768 | 4.3819 |
| 0.1748 | 7.3526 | 4.9733 |
| 0.2185 | 7.0997 | 5.5248 |
| 0.2622 | 8.3834 | 5.9997 |
| 0.3059 | 10.2240 | 6.6660 |
| 0.3452 | 11.9800 | 7.2282 |
| 0.3496 | 12.1800 | 7.2886 |

a/c = 0.1500

| Crack Depth | Kdeepest | Ksurface |
|---|---|---|
| 4.370E-03 | 2.3769 | 0.9790 |
| 0.0437 | 6.1473 | 2.9656 |
| 0.0874 | 6.9980 | 3.9621 |
| 0.1311 | 7.2875 | 4.7948 |
| 0.1748 | 7.0807 | 5.4596 |
| 0.2185 | 6.9092 | 6.0647 |
| 0.2622 | 8.1272 | 6.5791 |
| 0.3059 | 9.8355 | 7.2603 |
| 0.3452 | 11.4590 | 7.8222 |
| 0.3496 | 11.6450 | 7.8816 |

a/c = 0.2000

| Crack Depth | Kdeepest | Ksurface |
|---|---|---|
| 4.370E-03 | 2.3209 | 1.1403 |
| 0.0437 | 5.9688 | 3.4465 |
| 0.0874 | 6.7550 | 4.5989 |
| 0.1311 | 6.9014 | 5.5885 |
| 0.1748 | 6.5354 | 6.3947 |
| 0.2185 | 6.5216 | 7.1039 |
| 0.2622 | 7.6085 | 7.6951 |
| 0.3059 | 9.0542 | 8.4044 |
| 0.3452 | 10.4180 | 8.9640 |
| 0.3496 | 10.5730 | 9.0217 |

a/c = 0.2500

| Crack Depth | Kdeepest | Ksurface |
|---|---|---|
| 4.370E-03 | 2.2607 | 1.2925 |
| 0.0437 | 5.7809 | 3.9001 |
| 0.0874 | 6.5028 | 5.2000 |
| 0.1311 | 6.5119 | 6.3373 |
| 0.1748 | 5.9939 | 7.2778 |
| 0.2185 | 6.1308 | 8.0857 |
| 0.2622 | 7.0887 | 8.7491 |
| 0.3059 | 8.2777 | 9.4841 |
| 0.3452 | 9.3875 | 10.0400 |
| 0.3496 | 9.5131 | 10.0960 |

a/c = 0.5000

| Crack Depth | Kdeepest | Ksurface |
|---|---|---|
| 4.370E-03 | 1.9620 | 1.6314 |
| 0.0437 | 4.9421 | 4.9206 |
| 0.0874 | 5.4405 | 6.5758 |
| 0.1311 | 5.2241 | 7.8334 |
| 0.1748 | 4.5586 | 8.7938 |

| | | |
|---|---|---|
| 0.2185 | 4.9422 | 9.7181 |
| 0.2622 | 5.5776 | 10.4790 |
| 0.3059 | 6.2845 | 10.9070 |
| 0.3452 | 6.9250 | 11.1770 |
| 0.3496 | 6.9965 | 11.2010 |

a/c = 1.0000

| Crack Depth | Kdeepest | Ksurface |
|---|---|---|
| 4.370E-03 | 1.4605 | 1.7158 |
| 0.0437 | 3.5619 | 5.1232 |
| 0.0874 | 3.7551 | 6.7634 |
| 0.1311 | 3.5226 | 7.9784 |
| 0.1748 | 3.1763 | 8.8914 |
| 0.2185 | 3.6039 | 9.6159 |
| 0.2622 | 4.0057 | 10.1960 |
| 0.3059 | 4.4364 | 10.7160 |
| 0.3452 | 5.2345 | 11.1020 |
| 0.3496 | 5.3757 | 11.1400 |

Load Case 5:Trans Min
2-d SIF Input by User

The SIF originally read from D:\DCPP 1800289\Weld WIC-45A\trans1.mnn

No. of aspect ratios (a/c) in the tables = 6

a/c = 0.1250

| Crack Depth | Kdeepest | Ksurface |
|---|---|---|
| 4.370E-03 | -1.7725 | -0.6664 |
| 0.0437 | -4.1372 | -1.9929 |
| 0.0874 | -4.0350 | -2.6082 |
| 0.1311 | -3.3699 | -3.0849 |
| 0.1748 | -2.2281 | -3.4235 |
| 0.2185 | -0.8004 | -3.7180 |
| 0.2622 | -0.6973 | -3.9398 |
| 0.3059 | -0.8545 | -4.2621 |
| 0.3452 | -1.0047 | -4.5028 |
| 0.3496 | -1.0219 | -4.5266 |

a/c = 0.1500

| Crack Depth | Kdeepest | Ksurface |
|---|---|---|
| 4.370E-03 | -1.7533 | -0.7288 |
| 0.0437 | -4.0792 | -2.1730 |
| 0.0874 | -3.9631 | -2.8373 |
| 0.1311 | -3.2558 | -3.3610 |
| 0.1748 | -2.0673 | -3.7384 |
| 0.2185 | -0.6151 | -4.0448 |
| 0.2622 | -0.6751 | -4.2618 |
| 0.3059 | -0.8215 | -4.5486 |
| 0.3452 | -0.9611 | -4.7405 |
| 0.3496 | -0.9770 | -4.7581 |

a/c = 0.2000

| Crack Depth | Kdeepest | Ksurface |
|---|---|---|
| 4.370E-03 | -1.7118 | -0.8486 |
| 0.0437 | -3.9563 | -2.5189 |
| 0.0874 | -3.8135 | -3.2781 |
| 0.1311 | -3.0260 | -3.8911 |
| 0.1748 | -1.7508 | -4.3442 |
| 0.2185 | -0.5357 | -4.6734 |
| 0.2622 | -0.6301 | -4.8805 |
| 0.3059 | -0.7553 | -5.0979 |
| 0.3452 | -0.8737 | -5.1951 |
| 0.3496 | -0.8872 | -5.2005 |

a/c = 0.2500

| Crack Depth | Kdeepest | Ksurface |
|---|---|---|
| 4.370E-03 | -1.6673 | -0.9617 |
| 0.0437 | -3.8275 | -2.8449 |
| 0.0874 | -3.6593 | -3.6935 |
| 0.1311 | -2.7974 | -4.3913 |
| 0.1748 | -1.4425 | -4.9162 |
| 0.2185 | -0.5017 | -5.2661 |
| 0.2622 | -0.5852 | -5.4649 |
| 0.3059 | -0.6894 | -5.6155 |
| 0.3452 | -0.7872 | -5.6221 |
| 0.3496 | -0.7983 | -5.6156 |

a/c = 0.5000

| Crack Depth | Kdeepest | Ksurface |
|---|---|---|
| 4.370E-03 | -1.4464 | -1.2131 |
| 0.0437 | -3.2524 | -3.5708 |
| 0.0874 | -2.9947 | -4.6264 |
| 0.1311 | -2.0874 | -5.3399 |
| 0.1748 | -0.7805 | -5.7952 |
| 0.2185 | -0.4066 | -6.1415 |
| 0.2622 | -0.4645 | -6.3160 |
| 0.3059 | -0.5289 | -6.2050 |
| 0.3452 | -0.5880 | -5.9858 |
| 0.3496 | -0.5946 | -5.9552 |

a/c = 1.0000

| Crack Depth | Kdeepest | Ksurface |
|---|---|---|
| 4.370E-03 | -1.0755 | -1.2756 |
| 0.0437 | -2.3088 | -3.7096 |
| 0.0874 | -1.9570 | -4.7323 |
| 0.1311 | -1.2031 | -5.4016 |
| 0.1748 | -0.2593 | -5.8146 |
| 0.2185 | -0.2980 | -6.0523 |
| 0.2622 | -0.3353 | -6.1579 |
| 0.3059 | -0.3774 | -6.1768 |
| 0.3452 | -0.7821 | -6.1110 |
| 0.3496 | -0.8822 | -6.0992 |

Load Case 6:Crack Face Pres
Type: Stress Coefficients Input by User

Coefficient C0 = 2.8000
Coefficient C1 = 0.0000
Coefficient C2 = 0.0000
Coefficient C3 = 0.0000

Total Load Sub-Blocks: 1

Load Sub-Block # 1

Load Sub-block Name: Charging Line Transient

Maximum

| Load Case Multiplier | Load Case ID |
|---|---|
| 1.0000 | Trans Max |
| 1.0000 | DW |
| 1.0000 | OBE |
| 1.0000 | Residual |
| 1.0000 | Crack Face Pres |

Minimum

| Load Case Multiplier | Load Case ID |
|---|---|
| 1.0000 | Trans Min |
| 1.0000 | DW |
| -1.0000 | OBE |
| 1.0000 | Residual |

```
Growth Law: Paris
Cycles/Time: 14
Calc. Interval: 1
Print Interval: 14


Material: 3
Stainless Steel: Type 316

Paris Fatigue Crack Growth Equation
 C =    1.260E-07
 n =       2.2500
 Delta K Threshold =       0.0000
*****************************************************************

Paris Crack Growth Law

The Fatigue Crack Growth Rate in/cycle (or m/cycle) is given by:

  da/dN = C * (Delta K)^n

 where
   Delta K = Kmax - Kmin
   C,n = empirical constants

 da/dN = 0 for Delta K < Delta K Threshold

*****************************************************************


No. of Data in the KIC Table = 2

    Crack Depth       KIC
      0.0000        200.0000
     10.0000        200.0000

messages/Warnings:
Solution for Ri/t of 0.2 and 0.5 will be used

Number of Warnings in Inputs: 0


 - - - - - - - - - - ANALYSIS RESULTS - - - - - - - - -


   STRESS INTENSITY FACTORS


    Load Case # 1: DW
      ------------ Crack Dimensions ------------          K at tips
         a            c           a/t          c/a          a            c
   c/a =        3.0000

      0.0750       0.2250       0.1716       3.0000       0.2995       0.1915
      0.1750       0.5250       0.4005       3.0000       0.4949       0.3171
      0.2750       0.8250       0.6293       3.0000       0.6982       0.4530

   c/a =        3.2000

      0.0750       0.2400       0.1716       3.2000       0.3032       0.1884
      0.1750       0.5600       0.4005       3.2000       0.5028       0.3127
      0.2750       0.8800       0.6293       3.2000       0.7127       0.4474

   c/a =        3.4000

      0.0750       0.2550       0.1716       3.4000       0.3065       0.1856
      0.1750       0.5950       0.4005       3.4000       0.5098       0.3088
      0.2750       0.9350       0.6293       3.4000       0.7254       0.4425
```

c/a = 3.6000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2700 | 0.1716 | 3.6000 | 0.3094 | 0.1832 |
| 0.1750 | 0.6300 | 0.4005 | 3.6000 | 0.5159 | 0.3053 |
| 0.2750 | 0.9900 | 0.6293 | 3.6000 | 0.7367 | 0.4381 |

c/a = 3.8000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2850 | 0.1716 | 3.8000 | 0.3120 | 0.1810 |
| 0.1750 | 0.6650 | 0.4005 | 3.8000 | 0.5215 | 0.3022 |
| 0.2750 | 1.0450 | 0.6293 | 3.8000 | 0.7468 | 0.4341 |

c/a = 4.0000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3000 | 0.1716 | 4.0000 | 0.3143 | 0.1791 |
| 0.1750 | 0.7000 | 0.4005 | 4.0000 | 0.5264 | 0.2994 |
| 0.2750 | 1.1000 | 0.6293 | 4.0000 | 0.7560 | 0.4306 |

c/a = 4.2000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3150 | 0.1716 | 4.2000 | 0.3166 | 0.1750 |
| 0.1750 | 0.7350 | 0.4005 | 4.2000 | 0.5329 | 0.2924 |
| 0.2750 | 1.1550 | 0.6293 | 4.2000 | 0.7709 | 0.4198 |

c/a = 4.4000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3300 | 0.1716 | 4.4000 | 0.3187 | 0.1714 |
| 0.1750 | 0.7700 | 0.4005 | 4.4000 | 0.5388 | 0.2860 |
| 0.2750 | 1.2100 | 0.6293 | 4.4000 | 0.7844 | 0.4101 |

c/a = 4.6000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3450 | 0.1716 | 4.6000 | 0.3206 | 0.1680 |
| 0.1750 | 0.8050 | 0.4005 | 4.6000 | 0.5441 | 0.2802 |
| 0.2750 | 1.2650 | 0.6293 | 4.6000 | 0.7968 | 0.4011 |

c/a = 4.8000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3600 | 0.1716 | 4.8000 | 0.3223 | 0.1650 |
| 0.1750 | 0.8400 | 0.4005 | 4.8000 | 0.5490 | 0.2748 |
| 0.2750 | 1.3200 | 0.6293 | 4.8000 | 0.8081 | 0.3929 |

Load Case # 2: OBE

| ------------ Crack Dimensions | ------------ | | | K at tips | |
|---|---|---|---|---|---|
| a | c | a/t | c/a | a | c |

c/a = 3.0000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2250 | 0.1716 | 3.0000 | 0.2919 | 0.1866 |
| 0.1750 | 0.5250 | 0.4005 | 3.0000 | 0.4823 | 0.3091 |
| 0.2750 | 0.8250 | 0.6293 | 3.0000 | 0.6805 | 0.4415 |

c/a = 3.2000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2400 | 0.1716 | 3.2000 | 0.2955 | 0.1836 |
| 0.1750 | 0.5600 | 0.4005 | 3.2000 | 0.4900 | 0.3048 |
| 0.2750 | 0.8800 | 0.6293 | 3.2000 | 0.6945 | 0.4360 |

c/a = 3.4000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2550 | 0.1716 | 3.4000 | 0.2987 | 0.1809 |
| 0.1750 | 0.5950 | 0.4005 | 3.4000 | 0.4968 | 0.3010 |
| 0.2750 | 0.9350 | 0.6293 | 3.4000 | 0.7069 | 0.4312 |

c/a = 3.6000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2700 | 0.1716 | 3.6000 | 0.3015 | 0.1786 |
| 0.1750 | 0.6300 | 0.4005 | 3.6000 | 0.5028 | 0.2976 |
| 0.2750 | 0.9900 | 0.6293 | 3.6000 | 0.7180 | 0.4269 |

c/a = 3.8000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2850 | 0.1716 | 3.8000 | 0.3040 | 0.1764 |
| 0.1750 | 0.6650 | 0.4005 | 3.8000 | 0.5082 | 0.2945 |
| 0.2750 | 1.0450 | 0.6293 | 3.8000 | 0.7279 | 0.4231 |

c/a = 4.0000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3000 | 0.1716 | 4.0000 | 0.3063 | 0.1745 |
| 0.1750 | 0.7000 | 0.4005 | 4.0000 | 0.5131 | 0.2918 |
| 0.2750 | 1.1000 | 0.6293 | 4.0000 | 0.7367 | 0.4196 |

c/a = 4.2000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3150 | 0.1716 | 4.2000 | 0.3086 | 0.1706 |
| 0.1750 | 0.7350 | 0.4005 | 4.2000 | 0.5193 | 0.2850 |
| 0.2750 | 1.1550 | 0.6293 | 4.2000 | 0.7513 | 0.4092 |

c/a = 4.4000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3300 | 0.1716 | 4.4000 | 0.3106 | 0.1670 |
| 0.1750 | 0.7700 | 0.4005 | 4.4000 | 0.5251 | 0.2787 |
| 0.2750 | 1.2100 | 0.6293 | 4.4000 | 0.7645 | 0.3996 |

c/a = 4.6000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3450 | 0.1716 | 4.6000 | 0.3124 | 0.1638 |
| 0.1750 | 0.8050 | 0.4005 | 4.6000 | 0.5303 | 0.2730 |
| 0.2750 | 1.2650 | 0.6293 | 4.6000 | 0.7765 | 0.3909 |

c/a = 4.8000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3600 | 0.1716 | 4.8000 | 0.3141 | 0.1608 |
| 0.1750 | 0.8400 | 0.4005 | 4.8000 | 0.5351 | 0.2678 |
| 0.2750 | 1.3200 | 0.6293 | 4.8000 | 0.7876 | 0.3829 |

Load Case # 3: Residual

| ------------ Crack Dimensions ------------ | | | | K at tips | |
|---|---|---|---|---|---|
| a | c | a/t | c/a | a | c |

c/a = 3.0000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2250 | 0.1716 | 3.0000 | 13.0476 | 8.3401 |
| 0.1750 | 0.5250 | 0.4005 | 3.0000 | 21.5594 | 13.8153 |
| 0.2750 | 0.8250 | 0.6293 | 3.0000 | 30.4158 | 19.7331 |

c/a = 3.2000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2400 | 0.1716 | 3.2000 | 13.2087 | 8.2054 |
| 0.1750 | 0.5600 | 0.4005 | 3.2000 | 21.9027 | 13.6224 |
| 0.2750 | 0.8800 | 0.6293 | 3.2000 | 31.0445 | 19.4891 |

c/a = 3.4000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2550 | 0.1716 | 3.4000 | 13.3509 | 8.0865 |
| 0.1750 | 0.5950 | 0.4005 | 3.4000 | 22.2056 | 13.4521 |
| 0.2750 | 0.9350 | 0.6293 | 3.4000 | 31.5993 | 19.2739 |

c/a = 3.6000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2700 | 0.1716 | 3.6000 | 13.4772 | 7.9809 |
| 0.1750 | 0.6300 | 0.4005 | 3.6000 | 22.4748 | 13.3008 |
| 0.2750 | 0.9900 | 0.6293 | 3.6000 | 32.0924 | 19.0825 |

c/a = 3.8000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2850 | 0.1716 | 3.8000 | 13.5902 | 7.8864 |
| 0.1750 | 0.6650 | 0.4005 | 3.8000 | 22.7156 | 13.1654 |

| | | | | | |
|---|---|---|---|---|---|
| 0.2750 | 1.0450 | 0.6293 | 3.8000 | 32.5336 | 18.9113 |

c/a = 4.0000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3000 | 0.1716 | 4.0000 | 13.6920 | 7.8013 |
| 0.1750 | 0.7000 | 0.4005 | 4.0000 | 22.9324 | 13.0435 |
| 0.2750 | 1.1000 | 0.6293 | 4.0000 | 32.9307 | 18.7572 |

c/a = 4.2000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3150 | 0.1716 | 4.2000 | 13.7918 | 7.6254 |
| 0.1750 | 0.7350 | 0.4005 | 4.2000 | 23.2134 | 12.7370 |
| 0.2750 | 1.1550 | 0.6293 | 4.2000 | 33.5799 | 18.2886 |

c/a = 4.4000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3300 | 0.1716 | 4.4000 | 13.8825 | 7.4654 |
| 0.1750 | 0.7700 | 0.4005 | 4.4000 | 23.4689 | 12.4583 |
| 0.2750 | 1.2100 | 0.6293 | 4.4000 | 34.1701 | 17.8626 |

c/a = 4.6000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3450 | 0.1716 | 4.6000 | 13.9654 | 7.3193 |
| 0.1750 | 0.8050 | 0.4005 | 4.6000 | 23.7022 | 12.2039 |
| 0.2750 | 1.2650 | 0.6293 | 4.6000 | 34.7090 | 17.4736 |

c/a = 4.8000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3600 | 0.1716 | 4.8000 | 14.0413 | 7.1855 |
| 0.1750 | 0.8400 | 0.4005 | 4.8000 | 23.9160 | 11.9706 |
| 0.2750 | 1.3200 | 0.6293 | 4.8000 | 35.2030 | 17.1171 |

Load Case # 4: Trans Max

| ------------ Crack Dimensions ------------ | | | | K at tips | |
|---|---|---|---|---|---|
| a | c | a/t | c/a | a | c |

c/a = 3.0000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2250 | 0.1716 | 3.0000 | 5.9650 | 5.2561 |
| 0.1750 | 0.5250 | 0.4005 | 3.0000 | 5.5165 | 7.7870 |
| 0.2750 | 0.8250 | 0.6293 | 3.0000 | 6.8862 | 9.5110 |

c/a = 3.2000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2400 | 0.1716 | 3.2000 | 6.0482 | 5.1499 |
| 0.1750 | 0.5600 | 0.4005 | 3.2000 | 5.6360 | 7.6606 |
| 0.2750 | 0.8800 | 0.6293 | 3.2000 | 7.0239 | 9.3744 |

c/a = 3.4000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2550 | 0.1716 | 3.4000 | 6.1217 | 5.0561 |
| 0.1750 | 0.5950 | 0.4005 | 3.4000 | 5.7414 | 7.5491 |
| 0.2750 | 0.9350 | 0.6293 | 3.4000 | 7.1454 | 9.2538 |

c/a = 3.6000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2700 | 0.1716 | 3.6000 | 6.1870 | 4.9728 |
| 0.1750 | 0.6300 | 0.4005 | 3.6000 | 5.8352 | 7.4500 |
| 0.2750 | 0.9900 | 0.6293 | 3.6000 | 7.2534 | 9.1466 |

c/a = 3.8000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2850 | 0.1716 | 3.8000 | 6.2454 | 4.8983 |
| 0.1750 | 0.6650 | 0.4005 | 3.8000 | 5.9190 | 7.3613 |
| 0.2750 | 1.0450 | 0.6293 | 3.8000 | 7.3500 | 9.0507 |

c/a = 4.0000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3000 | 0.1716 | 4.0000 | 6.2980 | 4.8311 |

| | | | | | |
|---|---|---|---|---|---|
| 0.1750 | 0.7000 | 0.4005 | 4.0000 | 5.9945 | 7.2815 |
| 0.2750 | 1.1000 | 0.6293 | 4.0000 | 7.4370 | 8.9644 |

c/a = 4.2000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3150 | 0.1716 | 4.2000 | 6.3537 | 4.6980 |
| 0.1750 | 0.7350 | 0.4005 | 4.2000 | 6.1233 | 7.0711 |
| 0.2750 | 1.1550 | 0.6293 | 4.2000 | 7.5786 | 8.7116 |

c/a = 4.4000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3300 | 0.1716 | 4.4000 | 6.4043 | 4.5769 |
| 0.1750 | 0.7700 | 0.4005 | 4.4000 | 6.2403 | 6.8799 |
| 0.2750 | 1.2100 | 0.6293 | 4.4000 | 7.7074 | 8.4819 |

c/a = 4.6000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3450 | 0.1716 | 4.6000 | 6.4505 | 4.4664 |
| 0.1750 | 0.8050 | 0.4005 | 4.6000 | 6.3472 | 6.7053 |
| 0.2750 | 1.2650 | 0.6293 | 4.6000 | 7.8250 | 8.2721 |

c/a = 4.8000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3600 | 0.1716 | 4.8000 | 6.4929 | 4.3651 |
| 0.1750 | 0.8400 | 0.4005 | 4.8000 | 6.4452 | 6.5452 |
| 0.2750 | 1.3200 | 0.6293 | 4.8000 | 7.9328 | 8.0798 |

Load Case # 5: Trans Min

| ------------ Crack Dimensions ------------ | | | | K at tips | |
|---|---|---|---|---|---|
| a | c | a/t | c/a | a | c |

c/a = 3.0000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2250 | 0.1716 | 3.0000 | -3.4940 | -3.7441 |
| 0.1750 | 0.5250 | 0.4005 | 3.0000 | -1.2184 | -5.2108 |
| 0.2750 | 0.8250 | 0.6293 | 3.0000 | -0.5716 | -5.7672 |

c/a = 3.2000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2400 | 0.1716 | 3.2000 | -3.5472 | -3.6712 |
| 0.1750 | 0.5600 | 0.4005 | 3.2000 | -1.2733 | -5.1375 |
| 0.2750 | 0.8800 | 0.6293 | 3.2000 | -0.5826 | -5.7026 |

c/a = 3.4000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2550 | 0.1716 | 3.4000 | -3.5942 | -3.6070 |
| 0.1750 | 0.5950 | 0.4005 | 3.4000 | -1.3218 | -5.0729 |
| 0.2750 | 0.9350 | 0.6293 | 3.4000 | -0.5924 | -5.6457 |

c/a = 3.6000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2700 | 0.1716 | 3.6000 | -3.6360 | -3.5498 |
| 0.1750 | 0.6300 | 0.4005 | 3.6000 | -1.3649 | -5.0155 |
| 0.2750 | 0.9900 | 0.6293 | 3.6000 | -0.6010 | -5.5951 |

c/a = 3.8000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2850 | 0.1716 | 3.8000 | -3.6734 | -3.4987 |
| 0.1750 | 0.6650 | 0.4005 | 3.8000 | -1.4035 | -4.9641 |
| 0.2750 | 1.0450 | 0.6293 | 3.8000 | -0.6088 | -5.5498 |

c/a = 4.0000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3000 | 0.1716 | 4.0000 | -3.7070 | -3.4527 |
| 0.1750 | 0.7000 | 0.4005 | 4.0000 | -1.4382 | -4.9178 |
| 0.2750 | 1.1000 | 0.6293 | 4.0000 | -0.6157 | -5.5090 |

c/a = 4.2000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3150 | 0.1716 | 4.2000 | -3.7420 | -3.3598 |
| 0.1750 | 0.7350 | 0.4005 | 4.2000 | -1.5113 | -4.7816 |
| 0.2750 | 1.1550 | 0.6293 | 4.2000 | -0.6279 | -5.3745 |

c/a = 4.4000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3300 | 0.1716 | 4.4000 | -3.7738 | -3.2754 |
| 0.1750 | 0.7700 | 0.4005 | 4.4000 | -1.5778 | -4.6578 |
| 0.2750 | 1.2100 | 0.6293 | 4.4000 | -0.6389 | -5.2523 |

c/a = 4.6000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3450 | 0.1716 | 4.6000 | -3.8029 | -3.1983 |
| 0.1750 | 0.8050 | 0.4005 | 4.6000 | -1.6384 | -4.5447 |
| 0.2750 | 1.2650 | 0.6293 | 4.6000 | -0.6490 | -5.1406 |

c/a = 4.8000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3600 | 0.1716 | 4.8000 | -3.8295 | -3.1277 |
| 0.1750 | 0.8400 | 0.4005 | 4.8000 | -1.6941 | -4.4411 |
| 0.2750 | 1.3200 | 0.6293 | 4.8000 | -0.6583 | -5.0383 |

Load Case # 6: Crack Face Pres

| ------------ Crack Dimensions ------------ | | | | K at tips | |
|---|---|---|---|---|---|
| a | c | a/t | c/a | a | c |

c/a = 3.0000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2250 | 0.1716 | 3.0000 | 1.3333 | 0.8523 |
| 0.1750 | 0.5250 | 0.4005 | 3.0000 | 2.2032 | 1.4118 |
| 0.2750 | 0.8250 | 0.6293 | 3.0000 | 3.1082 | 2.0165 |

c/a = 3.2000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2400 | 0.1716 | 3.2000 | 1.3498 | 0.8385 |
| 0.1750 | 0.5600 | 0.4005 | 3.2000 | 2.2382 | 1.3921 |
| 0.2750 | 0.8800 | 0.6293 | 3.2000 | 3.1724 | 1.9916 |

c/a = 3.4000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2550 | 0.1716 | 3.4000 | 1.3643 | 0.8264 |
| 0.1750 | 0.5950 | 0.4005 | 3.4000 | 2.2692 | 1.3747 |
| 0.2750 | 0.9350 | 0.6293 | 3.4000 | 3.2291 | 1.9696 |

c/a = 3.6000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2700 | 0.1716 | 3.6000 | 1.3772 | 0.8156 |
| 0.1750 | 0.6300 | 0.4005 | 3.6000 | 2.2967 | 1.3592 |
| 0.2750 | 0.9900 | 0.6293 | 3.6000 | 3.2795 | 1.9500 |

c/a = 3.8000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.2850 | 0.1716 | 3.8000 | 1.3888 | 0.8059 |
| 0.1750 | 0.6650 | 0.4005 | 3.8000 | 2.3213 | 1.3454 |
| 0.2750 | 1.0450 | 0.6293 | 3.8000 | 3.3246 | 1.9325 |

c/a = 4.0000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3000 | 0.1716 | 4.0000 | 1.3992 | 0.7972 |
| 0.1750 | 0.7000 | 0.4005 | 4.0000 | 2.3435 | 1.3329 |
| 0.2750 | 1.1000 | 0.6293 | 4.0000 | 3.3652 | 1.9168 |

c/a = 4.2000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3150 | 0.1716 | 4.2000 | 1.4094 | 0.7792 |
| 0.1750 | 0.7350 | 0.4005 | 4.2000 | 2.3722 | 1.3016 |
| 0.2750 | 1.1550 | 0.6293 | 4.2000 | 3.4315 | 1.8689 |

c/a = 4.4000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3300 | 0.1716 | 4.4000 | 1.4187 | 0.7629 |
| 0.1750 | 0.7700 | 0.4005 | 4.4000 | 2.3983 | 1.2731 |
| 0.2750 | 1.2100 | 0.6293 | 4.4000 | 3.4918 | 1.8254 |

c/a = 4.6000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3450 | 0.1716 | 4.6000 | 1.4271 | 0.7480 |
| 0.1750 | 0.8050 | 0.4005 | 4.6000 | 2.4221 | 1.2471 |
| 0.2750 | 1.2650 | 0.6293 | 4.6000 | 3.5469 | 1.7856 |

c/a = 4.8000

| | | | | | |
|---|---|---|---|---|---|
| 0.0750 | 0.3600 | 0.1716 | 4.8000 | 1.4349 | 0.7343 |
| 0.1750 | 0.8400 | 0.4005 | 4.8000 | 2.4440 | 1.2233 |
| 0.2750 | 1.3200 | 0.6293 | 4.8000 | 3.5974 | 1.7492 |

CRACK GROWTH ANALYSIS RESULTS

| Total Cycles /Time | Subblock Cycles /Time | Kmax | Kmin | DeltaK | DaDn /DaDt | Crack Dimensions a / c | a/t / c/a |
|---|---|---|---|---|---|---|---|
| Blocks: | 1 | | | | | | |
| 14.0000 | 14.0000 | 20.9676 | 9.5920 | 11.3755 | 2.994E-05 | 0.0754 | 0.1726 |
| | | 14.8815 | 4.6194 | 10.2620 | 2.375E-05 | 0.2253 | 2.9877 |
| Blocks: | 2 | | | | | | |
| 28.0000 | 14.0000 | 20.9999 | 9.6250 | 11.3749 | 2.994E-05 | 0.0758 | 0.1735 |
| | | 14.9406 | 4.6394 | 10.3012 | 2.395E-05 | 0.2257 | 2.9756 |
| Blocks: | 3 | | | | | | |
| 42.0000 | 14.0000 | 21.0322 | 9.6579 | 11.3743 | 2.994E-05 | 0.0763 | 0.1745 |
| | | 14.9996 | 4.6593 | 10.3403 | 2.416E-05 | 0.2260 | 2.9637 |
| Blocks: | 4 | | | | | | |
| 56.0000 | 14.0000 | `21.0643 | 9.6906 | 11.3737 | 2.993E-05 | 0.0767 | 0.1755 |
| | | 15.0585 | 4.6791 | 10.3794 | 2.436E-05 | 0.2263 | 2.9519 |
| Blocks: | 5 | | | | | | |
| 70.0000 | 14.0000 | 21.0964 | 9.7233 | 11.3731 | 2.993E-05 | 0.0771 | 0.1764 |
| | | 15.1173 | 4.6989 | 10.4184 | 2.457E-05 | 0.2267 | 2.9403 |
| Blocks: | 6 | | | | | | |
| 84.0000 | 14.0000 | 21.1284 | 9.7558 | 11.3725 | 2.993E-05 | 0.0775 | 0.1774 |
| | | 15.1760 | 4.7186 | 10.4574 | 2.478E-05 | 0.2270 | 2.9289 |
| Blocks: | 7 | | | | | | |
| 98.0000 | 14.0000 | 21.1602 | 9.7882 | 11.3720 | 2.992E-05 | 0.0779 | 0.1783 |
| | | 15.2346 | 4.7382 | 10.4964 | 2.499E-05 | 0.2274 | 2.9176 |
| Blocks: | 8 | | | | | | |
| 112.0000 | 14.0000 | 21.1920 | 9.8206 | 11.3714 | 2.992E-05 | 0.0784 | 0.1793 |
| | | 15.2932 | 4.7578 | 10.5354 | 2.520E-05 | 0.2277 | 2.9065 |
| Blocks: | 9 | | | | | | |
| 126.0000 | 14.0000 | 21.2236 | 9.8528 | 11.3709 | 2.992E-05 | 0.0788 | 0.1803 |
| | | 15.3516 | 4.7773 | 10.5743 | 2.541E-05 | 0.2281 | 2.8955 |
| Blocks: | 10 | | | | | | |
| 140.0000 | 14.0000 | 21.2552 | 9.8849 | 11.3703 | 2.991E-05 | 0.0792 | 0.1812 |
| | | 15.4099 | 4.7968 | 10.6132 | 2.562E-05 | 0.2284 | 2.8847 |
| Blocks: | 11 | | | | | | |
| 154.0000 | 14.0000 | 21.2867 | 9.9169 | 11.3698 | 2.991E-05 | 0.0796 | 0.1822 |
| | | 15.4682 | 4.8162 | 10.6520 | 2.583E-05 | 0.2288 | 2.8741 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Blocks: | 12 | | | | | | |
| 168.0000 | 14.0000 | 21.3181 | 9.9488 | 11.3693 | 2.991E-05 | 0.0800 | 0.1831 |
| | | 15.5263 | 4.8355 | 10.6908 | 2.604E-05 | 0.2292 | 2.8636 |
| Blocks: | 13 | | | | | | |
| 182.0000 | 14.0000 | 21.3494 | 9.9806 | 11.3688 | 2.990E-05 | 0.0804 | 0.1841 |
| | | 15.5843 | 4.8547 | 10.7296 | 2.625E-05 | 0.2295 | 2.8532 |
| Blocks: | 14 | | | | | | |
| 196.0000 | 14.0000 | 21.3807 | 10.0123 | 11.3684 | 2.990E-05 | 0.0809 | 0.1850 |
| | | 15.6423 | 4.8739 | 10.7683 | 2.647E-05 | 0.2299 | 2.8430 |
| Blocks: | 15 | | | | | | |
| 210.0000 | 14.0000 | 21.4118 | 10.0439 | 11.3679 | 2.990E-05 | 0.0813 | 0.1860 |
| | | 15.7001 | 4.8931 | 10.8070 | 2.668E-05 | 0.2303 | 2.8330 |
| Blocks: | 16 | | | | | | |
| 224.0000 | 14.0000 | 21.4429 | 10.0754 | 11.3675 | 2.990E-05 | 0.0817 | 0.1870 |
| | | 15.7579 | 4.9122 | 10.8457 | 2.690E-05 | 0.2306 | 2.8230 |
| Blocks: | 17 | | | | | | |
| 238.0000 | 14.0000 | 21.4739 | 10.1069 | 11.3671 | 2.989E-05 | 0.0821 | 0.1879 |
| | | 15.8155 | 4.9312 | 10.8843 | 2.711E-05 | 0.2310 | 2.8132 |
| Blocks: | 18 | | | | | | |
| 252.0000 | 14.0000 | 21.5049 | 10.1382 | 11.3667 | 2.989E-05 | 0.0825 | 0.1889 |
| | | 15.8730 | 4.9501 | 10.9229 | 2.733E-05 | 0.2314 | 2.8036 |
| Blocks: | 19 | | | | | | |
| 266.0000 | 14.0000 | 21.5357 | 10.1695 | 11.3663 | 2.989E-05 | 0.0830 | 0.1898 |
| | | 15.9305 | 4.9690 | 10.9615 | 2.755E-05 | 0.2318 | 2.7941 |
| Blocks: | 20 | | | | | | |
| 280.0000 | 14.0000 | 21.5665 | 10.2006 | 11.3659 | 2.989E-05 | 0.0834 | 0.1908 |
| | | 15.9878 | 4.9878 | 11.0000 | 2.777E-05 | 0.2322 | 2.7847 |
| Blocks: | 21 | | | | | | |
| 294.0000 | 14.0000 | 21.5973 | 10.2317 | 11.3656 | 2.988E-05 | 0.0838 | 0.1917 |
| | | 16.0450 | 5.0066 | 11.0385 | 2.798E-05 | 0.2326 | 2.7755 |
| Blocks: | 22 | | | | | | |
| 308.0000 | 14.0000 | 21.6279 | 10.2627 | 11.3653 | 2.988E-05 | 0.0842 | 0.1927 |
| | | 16.1022 | 5.0253 | 11.0769 | 2.820E-05 | 0.2330 | 2.7664 |
| Blocks: | 23 | | | | | | |
| 322.0000 | 14.0000 | 21.6586 | 10.2936 | 11.3650 | 2.988E-05 | 0.0846 | 0.1937 |
| | | 16.1592 | 5.0439 | 11.1153 | 2.842E-05 | 0.2334 | 2.7574 |
| Blocks: | 24 | | | | | | |
| 336.0000 | 14.0000 | 21.6891 | 10.3244 | 11.3647 | 2.988E-05 | 0.0850 | 0.1946 |
| | | 16.2161 | 5.0625 | 11.1536 | 2.865E-05 | 0.2338 | 2.7485 |
| Blocks: | 25 | | | | | | |
| 350.0000 | 14.0000 | 21.7196 | 10.3552 | 11.3644 | 2.988E-05 | 0.0855 | 0.1956 |
| | | 16.2729 | 5.0810 | 11.1919 | 2.887E-05 | 0.2342 | 2.7398 |
| Blocks: | 26 | | | | | | |
| 364.0000 | 14.0000 | 21.7501 | 10.3858 | 11.3642 | 2.988E-05 | 0.0859 | 0.1965 |
| | | 16.3296 | 5.0994 | 11.2302 | 2.909E-05 | 0.2346 | 2.7311 |
| Blocks: | 27 | | | | | | |
| 378.0000 | 14.0000 | 21.7805 | 10.4164 | 11.3640 | 2.988E-05 | 0.0863 | 0.1975 |
| | | 16.3862 | 5.1178 | 11.2684 | 2.931E-05 | 0.2350 | 2.7226 |
| Blocks: | 28 | | | | | | |
| 392.0000 | 14.0000 | 21.8108 | 10.4469 | 11.3638 | 2.987E-05 | 0.0867 | 0.1984 |
| | | 16.4427 | 5.1362 | 11.3065 | 2.954E-05 | 0.2354 | 2.7143 |

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Blocks:             29
    406.0000        14.0000     21.8411     10.4774     11.3637   2.987E-05     0.0871     0.1994
                                16.4991      5.1544     11.3446   2.976E-05     0.2358     2.7060

Blocks:             30
    420.0000        14.0000     21.8702     10.5106     11.3596   2.985E-05     0.0876     0.2004
                                16.5552      5.1739     11.3813   2.998E-05     0.2362     2.6979

Blocks:             31
    434.0000        14.0000     21.8969     10.5502     11.3467   2.977E-05     0.0880     0.2013
                                16.6107      5.1962     11.4145   3.018E-05     0.2366     2.6898

Blocks:             32
    448.0000        14.0000     21.9234     10.5895     11.3339   2.970E-05     0.0884     0.2023
                                16.6660      5.2185     11.4476   3.037E-05     0.2371     2.6820

Blocks:             33
    462.0000        14.0000     21.9498     10.6287     11.3211   2.962E-05     0.0888     0.2032
                                16.7211      5.2406     11.4804   3.057E-05     0.2375     2.6742

Blocks:             34
    476.0000        14.0000     21.9762     10.6677     11.3084   2.955E-05     0.0892     0.2042
                                16.7758      5.2627     11.5132   3.077E-05     0.2379     2.6666

Blocks:             35
    490.0000        14.0000     22.0024     10.7066     11.2958   2.947E-05     0.0896     0.2051
                                16.8303      5.2846     11.5457   3.096E-05     0.2384     2.6592

Blocks:             36
    504.0000        14.0000     22.0285     10.7453     11.2833   2.940E-05     0.0900     0.2061
                                16.8845      5.3065     11.5781   3.116E-05     0.2388     2.6518

Blocks:             37
    518.0000        14.0000     22.0546     10.7838     11.2708   2.933E-05     0.0905     0.2070
                                16.9385      5.3283     11.6103   3.135E-05     0.2392     2.6446

Blocks:             38
    532.0000        14.0000     22.0806     10.8222     11.2584   2.925E-05     0.0909     0.2079
                                16.9922      5.3499     11.6423   3.155E-05     0.2397     2.6375

Blocks:             39
    546.0000        14.0000     22.1065     10.8605     11.2461   2.918E-05     0.0913     0.2089
                                17.0456      5.3715     11.6741   3.174E-05     0.2401     2.6306

Blocks:             40
    560.0000        14.0000     22.1324     10.8985     11.2338   2.911E-05     0.0917     0.2098
                                17.0988      5.3930     11.7058   3.194E-05     0.2406     2.6237

Maximum number of blocks reached. The analysis terminated.

Number of Runtime Warnings: 0


      *** End of pc-CRACK output ***
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