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St. Lucie Nuclear Power Plant

Unit 2

ATTACHMENT A

FRACTURE MECHANICS EVALUATION OF ST. LUCIE PRESSURIZER INSTRUMENT NOZZLES

Prepared by

B&W NUCLEAR SERVICE COMPANY

For

St. Lucie Nuclear Power Plant
10 Miles South of Ft. Pierce on A1A
Ft. Pierce, Florida 33034

Commercial Service Date:	August 8, 1983
NRC Docket Number:	50-389
Document Number:	32-1235128-01
Revision Number: 0	Date: February 13, 1995

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CALCULATION SUMMARY SHEET (CSS)

DOCUMENT IDENTIFIER 32-1235128-01

TITLE FM Analysis of St Lucie Pressurizer Instrument Nozzle

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PURPOSE AND SUMMARY OF RESULTS:

Purpose

To provide a bounding flaw evaluation for all seven instrument/temperature 1" nozzles in the pressurizer. The evaluation will consider a conservative flaw size and will determine the acceptability of the postulated bounding flaw for the forty year design life of the plant. This flaw evaluation will be performed in accordance with IWB-3612 of Section XI, ASME Boiler and Pressure Vessel Code.

Rev. 1: Purpose of this revision is to issue a "non-proprietary" version of the document.

Summary of Results

The postulated flaw size in the instrument/temperature nozzles of St. Lucie was found to be acceptable for the design life of the plant, per IWB-3612 of the ASME Code Section XI.

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THIS DOCUMENT CONTAINS ASSUMPTIONS THAT MUST BE VERIFIED PRIOR TO USE ON SAFETY-RELATED WORK

YES ( ) NO (X)

RECORD OF REVISIONS

Revision	Description of Revision	Date Released
00	Original Release	12/94
01	Issue of "Non-Proprietary" Version	2/95

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EXECUTIVE SUMMARY

During the 1994 refueling outage external leakage was identified at the pressurizer instrument nozzle "C" of Florida Power & Light Company's St. Lucie Unit 2. Subsequent NDE identified indications on the J-welds for three of four steam space instrument nozzles. Modifications were made and justifications performed to determine the potential for crack growth during plant operation. The evaluation performed at the time was conservatively limited to one fuel cycle.

The purpose of this evaluation was to justify acceptability of indications in the J-weld for all seven 1" (instrument/temperature) nozzles in the pressurizer for 30 future years of plant life. The seven nozzles are located in various regions of the pressurizer and are horizontally and vertically oriented. Four of the instrument nozzles are contained in the pressurizer head steam-space region. The remaining three nozzles are located in the lower region of the pressurizer.

A detailed finite element stress analysis was performed that accounted for all seven nozzle penetration regions. The stress analysis considered and evaluated all significant design transients in the evaluation. The most significant transient produced maximum tensile stresses in the inside of the pressurizer shell at the nozzle penetration region (J-weld location). For the normal and upset condition category, the maximum tensile stress (hoop) was developed when the maximum pressure of 2400 psia is reached during an upset condition transient (abnormal loss of load transient). This transient was conservatively evaluated for 375 cycles to bound all future cycles of plant heatup/cooldown. For the emergency and faulted condition, the loss of secondary pressure transient was evaluated since the significant cooldown during this transient produced maximum tensile stresses at the J-weld location.

The fracture mechanics analysis postulated a conservative flaw size and determined its acceptability for thirty future years of plant life. A fatigue flaw growth analysis was performed for the normal and upset condition loads. Considering all the applicable design transients, the initial postulated flaw size in the instrument/temperature nozzle of the St. Lucie pressurizer was determined to reach an acceptable final flaw size (a_f) at the end of the design life of the plant. The maximum applied stress intensity factor at the final flaw size is 78.0 ksi$\sqrt{in}$. This results in a safety factor greater than the required safety factor of $\sqrt{10}$ (3.16) per IWB-3612(a) of ASME Code Section XI. For the emergency and faulted condition, the maximum applied stress intensity factor at the final flaw size is 76.8 ksi$\sqrt{in}$. The resulting safety factor is greater than the required safety factor of $\sqrt{2}$ (1.414) per IWB-3612(b) of ASME Code Section XI. Therefore, it is concluded that the postulated flaw size in the instrument/temperature nozzle of the St. Lucie pressurizer is acceptable for the design life of the plant (thirty future years) per IWB-3612 of the ASME Code Section XI.

1.0 INTRODUCTION

The purpose of this analysis is to provide a bounding flaw evaluation for all seven instrument/temperature 1" nozzles in the pressurizer. The evaluation will consider a conservative flaw size and will determine the acceptability of the postulated bounding flaw for thirty future years of plant life. This flaw evaluation will be performed in accordance with IWB-3612 of Section XI, ASME Boiler and Pressure Vessel Code.

1.1 Assumptions

a. The flaw type, orientation and a specific flaw size that is considered conservative is postulated in this analysis.

b. { Approach taken for postulation of flaw - BWNT Proprietary }

c. Three hundred and seventy five future cycles of heatup/cooldown are conservatively assumed for the remaining design life of the plant.

d. Eight future cycles of pressure tests at 10% of the operating pressure (2475 psia) are assumed over the next 30 years.

e. A specific upper shelf value for K_{IR} is used for the nozzle penetration region. This toughness value is assumed for the SA 533 Grade B Class 1 base material above a certain temperature range when the material is very ductlie.

2.0 DESIGN INPUTS

a) Geometry of Pressurizer Nozzle Penetrations

The penetration configuration of the pressurizer upper head steam space instrument nozzles (four) with the modified nozzle design is contained in Drawing 2998-19321 of Reference 1. The penetration configuration of the pressurizer bottom head (two) instrument nozzles and side temperature nozzle is contained in Drawing 2998-18709 of Reference 2.

minimum pressurizer head thickness = 3.875 in

minimum pressurizer shell thickness = 4.875 in

b) Design Transients/Number of Cycles

The following information was taken from Reference 3, with the transient specific information from Reference 4 (for the forty year design life of the plant).

i) 500 cycles of normal heatup/cooldown for the design life of the component. The normal operating pressure per Table 5.4-6 of Reference 3 is 2250 psia.

ii) A total of 480 cycles of upset condition transients. The maximum pressure range during upset condition transient is 660 psi and occurs between 2400 psia (abnormal loss of turbine generator load) and 1740 psia (reactor trip transient) with associated temperature difference of 50 °F during loss of load transient (Reference 4).

iii) 200 cycles of leak test at 2250 psia (Reference 4)

iv) The remainder of the normal operating transients i.e. 15,000 cycles of power change cycles from 15% to 100% power, 2,000 cycles of step power changes of 10% of the full load and 1×10^6 cycles of normal variations of 100 psi and temperature differences of less than 20 °F (Reference 4).

v) 5 cycles of emergency condition transient (complete loss of secondary pressure transient), given in Reference 4.

Since the analysis was performed for 30 future years, only 75% of the above number of cycles for a given transient were considered in the evaluation.

c) Materials

The pressurizer head and shell material is made of SA-533 Grade B Class 1 per Reference 1 and Addendum 2 of Reference 4. Per Table 5.2-9 of Reference 5, the RT_{NDT} of the pressurizer shell material is 10 °F.

d) Applicable ASME Section XI Code

Per Reference 6, the applicable ASME Section XI code is 1989 Edition.

3.0 GEOMETRY, FLAW SIZE AND ORIENTATION

3.1 Geometry of Bounding Pressurizer Nozzle Penetration

There are a total of seven 1" instrument/temperature nozzles in the pressurizer of St. Lucie Unit 2 as depicted by the drawing of Reference 2. Four of the instrument nozzle are contained in the pressurizer upper head steam space region. These nozzles are horizontally oriented in the lower spherical part of the upper head as illustrated in Figure 1. The remaining three nozzles are located in the lower region of the pressurizer as illustrated in Figure 2. Two of the instrument nozzles (vertically oriented) are located in the lower head of the pressurizer. The seventh nozzle is a 1" temperature nozzle which is located in the lower cylindrical portion of the pressurizer. The cylindrical portion of the pressurizer has a minimum wall thickness of 4.875 inches whereas the minimum wall thickness of the upper and the lower heads is 3.875 inches. The stress analysis of Reference 7 took each of the seven nozzle penetration regions into consideration and constructed a nozzle penetration finite element model to bound all instrument/temperature sensing nozzle locations. For additional details refer to Section 3.3 of Reference 7.

3.2 Flaw Size and Orientation

It is postulated that there exists a specific type flaw (as depicted in Figure 3) with a conservative initial flaw depth. The orientation of this flaw was assumed to be in a x,y plane (see Figure 3). This is the worse case flaw orientation since the maximum stress is primarily due to pressure induced stress as can be seen from the results of the stresses along the flaw plane in Section 6.0 of Reference 7. The analysis will evaluate maximum stress intensity factor and perform fatigue flaw growth analysis.

Figure 1: Upper Pressurizer Region

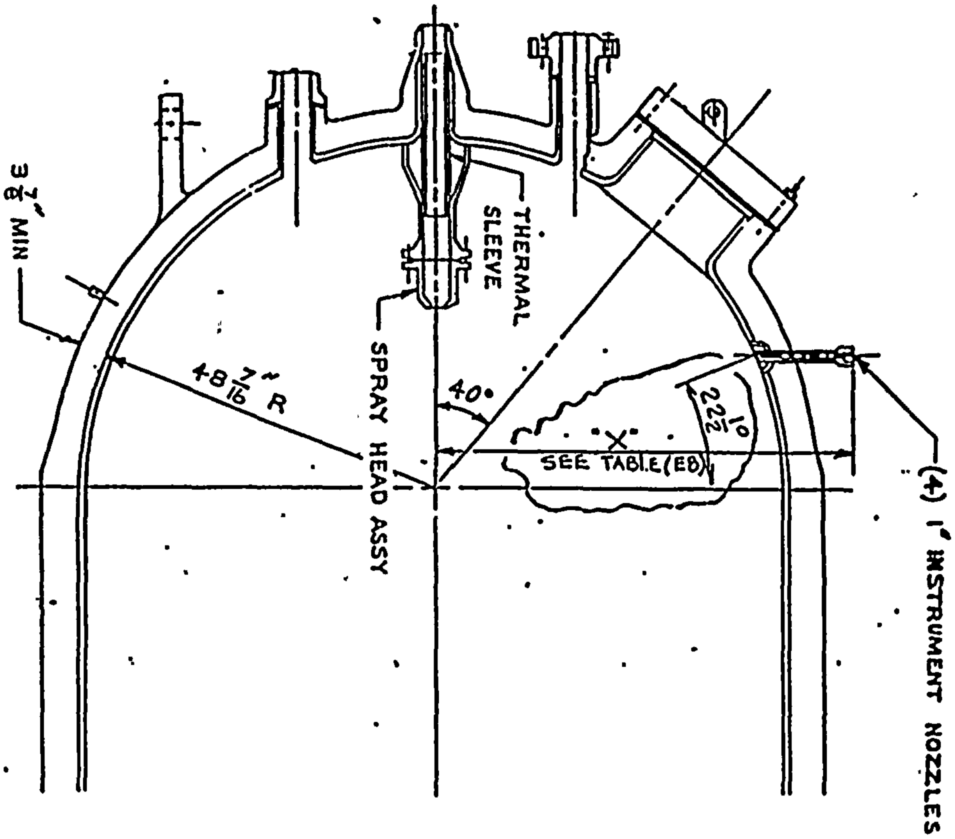

Figure 2: Lower Pressurizer Region

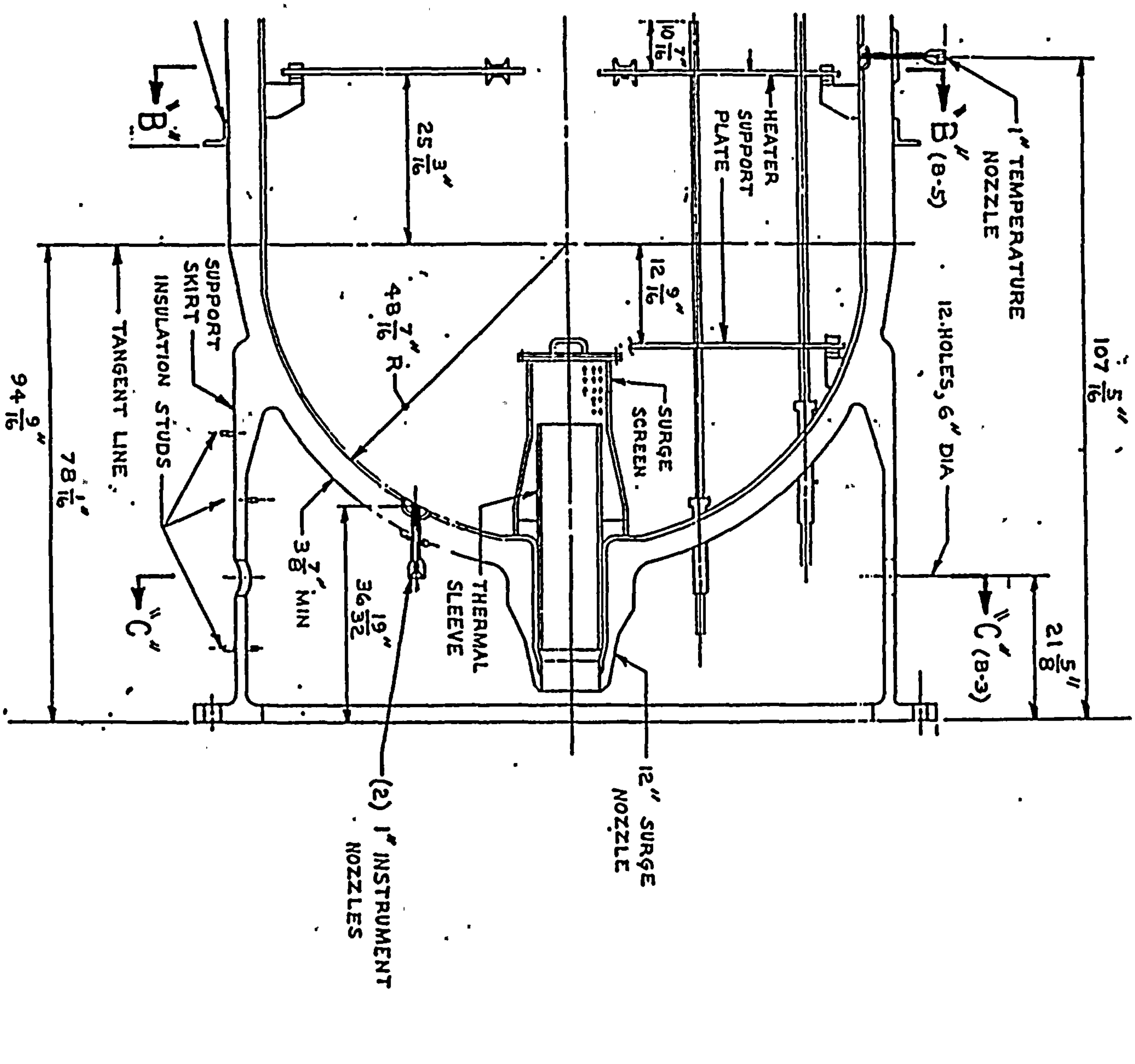

Figure 3: Postulated Flaw

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4.0 MATERIAL TOUGHNESS

The pressurizer shell and head is SA-533, grade B, class 1 per Reference 1 and Addendum 2 of Reference 4. The RT_{NDT} of this material is 10 ^{o}F. According to IWB-3612, the arrest toughness curve, KI_a in Appendix A, Section XI of ASME Boiler & Pressure Vessel Code (Reference 6) was used for this evaluation. Since the RT_{NDT} of the pressurizer is 10 °F, the material is considered to be at the upper shelf region for temperatures above 192 °F. Because the maximum stress is primarily due to pressure, the corresponding temperatures during the transient when the maximum stresses occur in the pressurizer shell/head are above 500 °F. Since the evaluation is based on a flaw in the nozzle penetration region of the base metal with irradiation embrittlement, a specific upper shelf value was used. It is noted that any shift due to irradiation is negligible, i.e. no changes in RT_{NDT} value of the pressurizer with increases in Effective Full Power Years (EFPYs').

5.0 LOADING CONDITIONS/STRESSES

5.1 Normal and Upset Loading Conditions

The stresses due to normal and upset conditions are contained in Section 6.0 of Reference 7. The composite transient evaluated in the analysis consisted of 100 °F/hr heatup, 100 % power steady state condition, a bounding upset condition transient and a 200 °F/hr cooldown rate as described in Section 5.0 of Reference 7. The normal and upset condition transient cases are summarized in Table 1.

The results of the analysis in Reference 7 showed that the maximum stresses occur during an upset condition when the pressure. The next largest stress state occurs during steady state conditions when the pressure is 2250 psia. These maximum stress states are primarily due to pressure induced hoop stress and occurs at temperatures well above 500 °F when the material is at upper-shelf. Transient case 2a was conservatively evaluated for 375 cycles, in Section 6.1, to bound the 360 cycles associated with all the upset condition transients as well as the 375 cycles of plant startup and shutdown and 150 cycles of leak tests. In addition, 8 cycles of pressure tests were evaluated.

During normal cooldown the maximum stress occurs at 560 °F when the material is at upper-shelf. To ensure that the fracture toughness margin (factor of safety of $\sqrt{10}$ per IWB-3612) is maintained, throughout the entire cooldown transient, the time at the end of 200 °F/hr cooldown is also evaluated. At this time, the bulk fluid temperature is at 70 °F and maximum thermal stresses are developed in the pressurizer shell/head. Adequate fracture toughness margin during the entire heatup/cooldown was demonstrated in Section 6.1.

Table 1: Normal and Upset Condition Transient Cases

Transient Category, Case	Description of Transient Time	Pressure (psia)	Temperature (°F)	Number of Cycles[1]
Normal, 1a	End of 100 °F/hr heatup (max. stress during heatup)	2250	653	375
Normal, 1b	100 % power steady state	2250	653	"
Normal, 1c	Cooldown at 560 °F (max. stress during cooldown)	1133	560	"
Normal, 1d	Cooldown at 70 °F (max. thermal stress during cooldown)	0	70	"
Normal, 1e	Pressure and temperature fluctuations during operation	$\Delta P \leq 100$ [2]	$\Delta T \leq 20$ [2]	765,000 [3]
Upset, 2a	At max. pressure (loss of turbine generator load)	2400	653	360 [4]
Upset, 2b	53 °F step up	2400	600 - 653	"
Upset, 2c	53 °F step down	1740	653 - 600	"
Test, 3	110% of operating pressure	2475	653	8

1 Associated with 30 future years of plant life. Based on considering 75% of the design cycles given in References 3 and 4.

2 This case is not specifically evaluated in Reference 7. Conservatively assumed to be one-half the stresses due to the transient cases 2b and 2c.

3 11,250 cycles of plant loading/unloading, 1,500 cycles of 10% step load increase/decrease and 750,000 cycles of normal pressure variation are conservatively grouped by this transient case.

4 There are only 30 cycles of loss of turbine generator load, however, 300 cycles of reactor trip transient and 30 cycles of loss of primary flow transient are conservatively grouped by this transient case.

In addition to the 375 cycles of plant startup/shutdown and 8 cycles of pressure tests there are 11,250 cycles of plant loading/unloading, 1,500 cycles of 10% step load increase/decrease and 750,000 cycles of normal pressure variation (+/- 100 psi, +/- 7 °F) as given in References 3 and 4. Review of these transients show that these transients can be grouped as a single transient with 765,000 associated cycles of maximum pressure variation of 100 psi and temperature variation of less than 20 °F. The associated stress range due to this transient should be less than one-half the stress range for the upset condition step change transient given in Reference 7. The step change condition transient considered pressure variation of 660 psi and temperature variation of 53 °F. Therefore, it is conservative to use one half the stress range of the step change upset condition transient.

5.2 Emergency and Faulted Loading Conditions

The only emergency and faulted condition design transient (pressurizer pressure and temperature versus time) provided in References 3 and 4 is the loss of secondary pressure transient (an emergency condition transient). The faulted condition transients described in References 3 and 4 are; i) those due to safe shutdown earthquake with normal operation at full power and with and without pipe rupture condition and ii) those due to LOCA. However, per Table 3.9-3B of Reference 3, there are no associated cycles for the faulted condition transients. Therefore, the only transient evaluated (in Reference 7) for this loading condition is the loss of secondary pressure transient. During this transient the pressurizer experiences a significant cooldown rate. As a result of this cooldown rate, high tensile stresses at the inside surface of the nozzle penetration region can be produced. This is reflected in the stress results given in Section 6.0 of Reference 7 which produced the maximum hoop surface stress amongst all the transients analyzed. However, the stresses (hoop) along the flaw plane at the postulated flaw size and beyond are in fact lower than those during steady state condition at 2250 psia. Also, the material remains at upper shelf since the minimum transient temperature reached during this transient is 348 °F. This transient case will nonetheless be evaluated in Section 6.2. There are 4 cycles associated with this transient case.

6.0 FLAW EVALUATION

A specific flaw type is assumed for this analysis. The stress intensity factor, K_I, for this flaw geometry is given in Reference 8. The flaw solution given in this reference is utilized to evaluate the postulated flaw in the one inch pressurizer instrument/temperature nozzles of St. Lucie unit 2. The solution given above is applicable for the flaw plane illustrated in Figure 3. Hence, the stresses are obtained along this flaw plane as illustrated in Figure 6.2 of Reference 7. To address the stress intensity factors along the entire crack front, the information contained in Reference 9 is utilized. Reference 9 has evaluated the stress intensity factors due to pressure induced hoop stresses in a nozzle corner with a quarter circular crack geometry. Three flaw sizes with flaw size to thickness ratios of 0.15, 0.26 and 0.34 were investigated in this study. This study provided the non-dimensional stress intensity factors as a function of the crack front angle, θ for each of the three flaw sizes as illustrated in Figure 11 of Reference 9. From this figure it is clear that the stress intensity factor near the surfaces of both the vessel and the nozzle bore side is slightly greater than the stress intensity factor along the flaw plane considered in this analysis. For the two larger flaw sizes (flaw size to thickness ratio comparable to this evaluation), the stress intensity factor near the surfaces is about 5 to 10 percent higher than along the postulated flaw plane. Therefore, to determine maximum flaw growth with consideration of all crack front angles, the stress intensity factors obtained using the above equations will be increased by 10 percent. This is a conservative practice.

The postulated flaw in the instrument nozzle is evaluated for normal/upset condition and emergency/faulted condition as given below.

6.1 Flaw Evaluation for Normal and Upset Loading Condition Loads

As discussed in Section 5.1, the following bounding transient case was analyzed for the normal and upset condition loading. Transient case 2a was evaluated for 375 cycles. The maximum tensile stress state along the flaw plane occurs during this condition when the pressurizer is assumed to cycle from an initial stress-free state to a maximum pressure of 2400 psi at 653 °F. This stress state will be conservatively assumed to occur for all 375 cycles of normal heatup/cooldown. This is not an overly conservative assumption considering the fact that the hoop stresses are largely pressure induced and the upset pressure is only slightly greater than the steady state pressure.

As a first step, a third order polynomial equation to the stresses from the finite element analysis results was made. The resulting stresses using the polynomial equation agree very well with the finite element model (FEM) stresses as illustrated in Figure 4. The numerical values for these stresses are also given in Table 2. The FEM stresses are for the maximum upset condition pressure stress at 2400 psia as given in Table 6.4 of Reference 7.

The stress intensity factor, K_I, for the initial flaw size is determined first. Next a fatigue flaw growth analysis was performed for 375 cycles using the above maximum upset condition stresses as given in Table 3a. The fatigue crack growth rate is:

$$da/dN = C_o(\Delta K_I)^n$$

where da/dN is the crack growth rate in micro-inch per cycle, ΔK_I is the maximum K_I minus minimum K_I (in this case the minimum K_I is zero), C_o and n are material constants and are obtained from the fatigue crack growth rate curve which is given in Figure A-4300-1 of Reference 6. From this figure, it can be seen that for a surface flaw (water reactor environment) with an R ratio ≤ 0.25 and $\Delta K_I \geq 19$ ksi$\sqrt{\text{in}}$, the applicable material constants are $C_o = 1.01 \times 10^{-7}$in/cycle and n = 1.95. The flaw size at the end of 375 cycles, was determined and the maximum applied K_I was calculated to be 75.30 ksi$\sqrt{\text{in}}$. Also, 8 cycles of pressure tests at 2475 psig were considered in the analysis.

Figure 4: FEM throughwall stresses versus polynomial fit stresses

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Table 2: Spreadsheet for third order polynomial equation and comparison to FEM stresses

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Table 2 (cont'd)

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At the end of 8 cycles of pressure tests, the maximum applied $K_I = 77.75$ ksi$\sqrt{in}$. In addition, there are 765,000 cycles of pressure and temperature variations. The R ratio (K_{Imin}/K_{Imax}) for this case is 0.95 and since ΔK_I is less than 3.3 ksi$\sqrt{in}$, the applicable material constants are $C_o = 1.2 \times 10^{-11}$ in/cycle and n = 5.95. The fatigue flaw growth due to 765,000 cycles of the above transient is computed using the flaw size after 375 cycles of heatup/cooldown and 8 cycles of pressure tests as the initial flaw size. The results given in Table 3b also shows the consideration of 765,000 cycles discussed above.

The maximum applied stress intensity factor at the final flaw size is:

$$K_I(a_f) = 78.0 \text{ ksi}\sqrt{in}.$$

This results in a safety factor greater than the required safety factor of $\sqrt{10}$ (3.16) per IWB-3612(a) of Reference 6. Also, as discussed in Section 5.1, to ensure that the fracture toughness margin is maintained, through the entire cooldown transient, the time at the end of the 200 °F/hr cooldown is evaluated. The maximum applied K_I at the end of cooldown was determined to be 9.0 ksi$\sqrt{in}$. The associated fracture toughness, K_{IR}, was obtained from the equation given on Page C-18 of Reference 8. Using this equation, the fracture toughness at 60°F is 56.5 ksi$\sqrt{in}$. Therefore, there is a safety factor of 6.28 for this condition which is significantly greater than the required safety factor of $\sqrt{10}$ per IWB-3612(a) of Reference 6.

6.2 Flaw Evaluation for Emergency and Faulted Condition Loads

As discussed in Section 5.2, the only emergency and faulted condition transient requiring evaluation is the loss of secondary pressure transient which has 4 cycles associated with it. The results of the analysis are provided in Table 5. Since this transient occurs following a steady state condition, ΔK_I associated with this transient is only 5.68 ksi$\sqrt{in}$. Also, the flaw growth associated with this transient is insignificant . The maximum applied stress intensity factor at the final flaw size (a_f) for the emergency and faulted condition is:

$$K_I(a_f) = 76.79 \text{ ksi}\sqrt{in}.$$

As previously noted in Section 5.2, the material remains at upper shelf during this transient Therefore, this results in a safety factor for the emergency and faulted condition which is significantly greater than the required safety factor of $\sqrt{2}$ per IWB-3612 (b) of Reference 6.

Table 3a: Fatigue Flaw Growth Analysis for 375 cycles of normal heatup/cooldown

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Table 3b: Fatigue Flaw Growth Analysis (cont'd) for remaining normal operating transients

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Table 4: Summary of flaw sizes an check with acceptance criteria for normal and upset condition

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Table 5: Summary of flaw growth analysis and check with acceptance criteria for emergency and faulted condition

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7.0 CONCLUSIONS

Considering all the applicable design transients, the initial postulated flaw size of 0.875 inches in the instrument/temperature nozzle of the St. Lucie pressurizer was determined to reach a final flaw size (a_f) of 1.055 inches after 30 future years plant life. For the normal and upset condition the maximum applied stress intensity factor at the final flaw size is 78.00 ksi$\sqrt{in}$. The resulting safety factor is greater than the required safety factor of $\sqrt{10}$ (3.16) per IWB-3612(a) of Reference 6. The analysis considered all crack front angles to determine the maximum applied stress intesity factor and ensure bounding fatigue flaw growth. For the emergency and faulted condition, the maximum applied stress intensity factor at the final flaw size is 76.79 ksi$\sqrt{in}$. The resulting safety factor is greater than the required safety factor of $\sqrt{2}$ per IWB-3612(b) of Reference 6. Therefore, it is concluded that the postulated flaw size in the instrument/temperature nozzle of the St. Lucie pressurizer is acceptable for the thirty future yearss of plant life per IWB-3612 of the ASME Code Section XI.

8.0 REFERENCES

1.* Florida Power & Light Drawing No. 2998-19321, Rev. 0, "Top Head Instrument Nozzles Repair".

2.* Florida Power & Light Drawing No. 2998-18709, Rev. 1, "Pressurizer General Arrangement".

3. BWNT Document 38-1210589-00, "Pressurizer Instrument Nozzles, FM Design Input," for St. Lucie Unit 2, dated 11/11/94 (FP&L Number JPN-PSLP-94-603, File: PSL-100-14).

4. BWNT Document 38-1210588-00, "Pressurizer Instrument Nozzles, FM Design Input," for St. Lucie Unit 2, dated 11/11/94 (FP&L Number JPN-PSLP-94-631, File: PSL-100-14).

5.* St. Lucie Unit 2 Updated Final Safety Analysis Report, through Amendment No. 9, dated October 1994.

6. ASME Boiler and Pressure Vessel Code, Section XI, 1989 Edition.

7. BWNT Document 32-1235127-00, "Stresses for St. Lucie Unit 2, Pressurizer LEFM," by A.M. Miller, dated November 1994 (BWNT PROPRIETARY DOCUMENT).

8. Source Reference for FM analysis approach used in analysis. FM analysis approach considered "BWNT-PROPRIETARY".

9. Source Reference for FM analysis approach used in analysis. FM analysis approach considered "BWNT-PROPRIETARY".

* References marked with an "asterisk" are retrievable from the Utilities Record System.

K.E. Moore for W.L. Redd

Authorized Project Manager's Signature