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Fracture Mechanics Evaluation Main Steam Nozzle to Shell Weld N3A

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A FRACTURE MECHANICS EVALUATION ON OBSERVED INDICATION AT N3A STEAM OUTLET NOZZLE TO SHELL WELD AT COOPER NUCLEAR STATION

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Prepared for

Nebraska Public Power District

Prepared by

GE Nuclear Energy

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IMPORTANT NOTICE REGARDING

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1. Purpose/Objective

The manual ultrasonic examination of the category B-D, N3A nozzle to shell weld during Cooper Nuclear Station (CNS) fall 1998 outage (RF18) found a subsurface indication that appears unacceptable when evaluated per the acceptance standards of ASME Section XI, IWB-3512-1 [Reference 1]. The details of the IWB-3500 evaluation are contained in the UT examination report [Reference 2]. The N3A nozzle is one of the four steam outlet nozzles in the reactor pressure vessel. The indication was characterized as a planar indication with a through-wall dimension of 0.88 inch, length of 12.25 inches with a surface separation of 2.56 inches.

The Section XI procedures permit acceptance by analysis (Paragraph IWB-3600) of an indication that is found to be unacceptable per the acceptance standards. This report documents the results of a fracture mechanics evaluation of the observed indication based on the procedures of IWB-3600.

2. Design Inputs

The design inputs and the associated references are indicated in the following:

(1) The indication geometry was obtained from the ultrasonic (UT) inspection report on the N3A steam outlet nozzle prepared by GE [Reference 2].

(2) The reference nil ductility temperature (RT_{NDT}) for the weld, the nozzle forging and the shell course were obtained from References 3 and 4.

(3) The pressure and temperature conditions for various operating conditions were obtained from References 5 and 6.

3. Assumptions

It was assumed that the RT_{NDT} of the weld between the nozzle and the vessel shell is less than 18°F.

4. Units in Equations

English units (lbs, inches, psi, etc.) were used in the equations and the evaluations.

5. Calculation/Analysis Methodology

5.1. Analysis Methodology

The fracture mechanics methods used in the analysis are consistent with the procedures outlined in Section XI of the ASME Code [Reference 1]. The primary stress requirements are based on the Code of Construction of the RPV [Reference 7].

5.2. Operating Conditions Considered

The operating conditions considered were: Hydrotest, Normal (Level A), Upset (Level B), Emergency (Level C), and Faulted (Level D). The thermal cycle drawing for the CNS [Reference 6] does not explicitly identify the operating condition associated with each of the events covered. Therefore, the thermal cycle diagram of a similar but later built BWR plant was used as a guide. The stresses at the location of the indication are primarily from: internal pressure and thermal gradient. The steam outlet nozzle region experiences the pressure and temperature conditions associated with Region A in the thermal cycles drawing.

The internal pressure for the hydrotest condition is 1100 psi [Reference 5] and the thermal gradient during this event is insignificant. For the normal condition, the internal pressure is 1000 psi and the thermal gradient is 100°F, associated with the heatup/cool down event.

During the upset condition, the controlling event is 'Turbine Generator Trip, Feedwater On, Isolation Valves Stay open'. The internal pressure during this event is 1125 psi and the temperature gradient is (565-538) or 27°F.

A thermal transient as shown in Figure 1 was conservatively used for the evaluation of emergency condition. This transient bounds the 'single relief or safety valve blow down' event in the CNS thermal cycle diagram. The internal pressure at the highest thermal stress level was conservatively taken as 400 psi.

Figure 2 shows the bounding thermal transient considered for the faulted condition. The event corresponds to 'pipe rupture and blow down'. The internal pressure at the highest thermal stress level was taken as 22 psi.

5.3. Stress Calculation Due to Internal Pressure

The stress distribution due to internal pressure in the vicinity of the nozzle to shell weld is expected to be complex. Therefore, the stress distribution calculated by Gilman and Rashid [Reference 8] for a three-dimensional analysis of a BWR feedwater nozzle under internal pressure was reviewed. Figure 3 shows the distribution of maximum stress. The stress at the nozzle to weld location appears to vary from 25000 psi at the inside diameter to 12000 psi at the outer surface. The nominal circumferential stress in the vessel modeled in Reference 8 was 17530 psi. The nominal size of the steam outlet nozzle is larger than that of the feedwater nozzle. However, the stress concentration effect introduced by the presence of a nozzle opening in a shell loaded under internal pressure is not a function of opening size. This is evident from the fact that the peak stress to nominal stress ratio for internal pressure loading is the same (equal to 3.1) irrespective of the nozzle opening size. Therefore, for the internal pressure loading, the relationship between the stress distribution at the nozzle to shell weld junction and the nominal stress in the vessel shell is expected to be the same at the steam outlet nozzle as predicted by the three dimensional results shown in Figure 3.

Thus, the stresses at the nozzle to shell weld section due to internal pressure loading (i.e., membrane and bending stress magnitudes) were obtained by scaling up or down the Figure 3 stress magnitudes by the nominal pressure stress in the shell.

5.4. Stress Distribution Due to Thermal Gradient

The bounding fluid temperature change rate during heat-up/cool down is 100°F/hr. The linear temperature gradient through the vessel wall was calculated using the following equation, based on one dimensional heat conduction equation:

$$\Delta T = GC^2/2\beta \qquad (1)$$

where, G = Heat-up/cool down rate (°F/hr)
C = Vessel thickness including clad (ft)

β = Thermal diffusivity at 550°F (ft²/hr)

With a heat-up/cool down rate of 100°F/hr, vessel thickness of 0.526 ft. (6.31 inches) including clad, and β = 0.354 ft²/hr, the ΔT value was calculated as 39.0°F. The bending stress due to this temperature gradient was calculated using the following equation:

$$\sigma_{th,b} = [E\alpha\Delta T/\{2(1-\nu)\}] \quad (2)$$

where, E = Youngs modulus
α = coefficient of thermal expansion
ν = Poisson's ratio = 0.3

During the bounding upset condition event, "turbine generator trip feedwater on, isolation valves stay open", the temperature change is (565-538) or 27°F. The ΔT value was also conservatively assumed to be the same.

For the emergency and faulted conditions, calculated finite element stress distributions from previous analyses [Reference 9] of the bounding transients were reviewed and characterized in terms of membrane and bending components, as required by ASME Section XI, Appendix A procedures for the evaluation of subsurface indications (see Figure 4). The values calculated are the following:

<u>Emergency Condition</u>

σ_m = -3.0 ksi
σ_b = 11.0 ksi
Pressure = 400 psi
Temp. = 259°F

<u>Faulted Condition</u>

σ_m = -8.0 ksi
σ_b = 26.0 ksi
Pressure = 22 psi
Temp. = 259°F

5.5. Fracture Toughness

The highest RT_{NDT} of the steam outlet nozzle forgings was 18°F. The highest RT_{NDT} of the upper shell plate was 14°F. The RT_{NDT} of the nozzle to shell weld itself could not be located. However, the other welds for which information is available have RT_{NDT} values of -50°F. Based on the previous data on file with GE on the measured RT_{NDT} values of various RPV welds, it is reasonable to assume that the weld RT_{NDT} will be less than 10°F. Therefore, the limiting RT_{NDT} was determined to be 18°F based on the nozzle forging material. This value was used in calculating the reference fracture toughness or K_{IR} value for each of the operating conditions.

5.6. Fatigue Crack Growth Evaluation

The fatigue crack growth was calculated using the following crack growth rate relationship for subsurface flaws given in Reference 1 (Figure A-4300-1):

$$da/dN = 2.67 \times 10^{-11} (\Delta K)^{3.726} \qquad (3)$$

where, da/dN = Crack growth rate in in./cycle
ΔK = Stress intensity factor range in ksi√in.

The major contributors to fatigue crack growth are the start-up/shut down cycles. The number of such cycles specified for the design life are 120. Therefore this value was conservatively used in updating the through-wall depth of the subject indication.

5.7. Fracture Mechanics Evaluation Results

The applied stress magnitudes described in the preceding Subsections were used to calculate the applied stress intensity factor value at the subject indication for various operating conditions. The K_I values were calculated using the following equation from Reference 1:

$$K_I = \sigma_m M_m \sqrt{\pi}\sqrt{(a/Q)} + \sigma_b M_b \sqrt{\pi}\sqrt{(a/Q)}$$

where, σ_m, σ_b = membrane and bending stresses, psi.
a = minor half-diameter, in., of subsurface flaw

Q = flaw shape parameter
M_m = correction factor for membrane stress
M_b = correction factor for bending stress

Table 1 shows the calculated values of the applied K_I values for various operating conditions. The last column shows the allowable K_I values which were obtained by dividing the K_{IR} value by the safety factor. A safety factor of $\sqrt{10}$ was used for hydrotest, normal and upset conditions and a safety factor of $\sqrt{2}$ was used for emergency and faulted conditions.

A comparison of the applied and allowable K_I values shows that the applied K_I values are less than the allowable K_I values for all operating conditions. Based on this, it is concluded that the subject indication meets the criteria of IWB-3612 of Reference 1 and on this basis continued operation is acceptable.

5.8. Local Membrane Stress Evaluation

The procedures in IWB-3610 require a primary stress evaluation in addition to the fracture mechanics requirements of IWB-3612. The maximum primary membrane stress cannot exceed 1.5 S_m. Assuming that the clad does not bear any part of the load, the maximum through-wall flaw depth must therefore be limited to 1/3 the low alloy steel (LAS) wall thickness. For the UT reported LAS wall thickness of 6 inches, the maximum allowable through-wall dimension for a subsurface flaw is 2.0 inches. Since the subject indication dimension of 0.883 inch, including projected fatigue crack growth, is less than this value, the primary membrane stress requirements are satisfied.

6. Conclusions

The manual ultrasonic examination of the category B-D, N3A nozzle to shell weld during CNS fall 1998 outage (RF18) found a subsurface indication that appears unacceptable when evaluated per the acceptance standards of ASME Section XI, IWB-3512-1. Fracture mechanics and primary stress evaluations per the requirements of IWB-3610 were conducted the results of which are documented in this report. The evaluation results show that subject indication meets criteria of IWB-3612, Section XI, and the primary stress requirements of Section III of the ASME Code. Therefore, continued operation "as is" is acceptable.

7. References

[1] ASME Boiler & Pressure Vessel Code, Section XI, 1989 Edition, No Addenda.

[2] GE Nuclear Energy UT Examination Report No. R-196 for Cooper Nuclear Station RE18 (October 1998).

[3] GE Design Record File No. B13-01389, "RPV Surveillance Test".

[4] "Cooper Nuclear Station Vessel Surveillance Materials Testing and Fracture Toughness Analysis," GE Report No. GE-NE-523-159-1292, February 1993.

[5] (a) Cooper Nuclear Station USAR Volume II, Section IV-2.6.1, "Design Loadings".
(b) Paragraph IWB-5000 of Reference 1.

[6] GE Drawing No. 729E762, "Reactor Thermal Cycles".

[7] "Analytical Report for Consumers Reactor Vessel Cooper Station," Combustion Engineering Report No. CENC 1150, April 1971.

[8] J.D. Gilman and Y.R. Rashid, "Three-Dimensional Analysis of Reactor Pressure Vessel Nozzles," Transactions of the 1st International Conference for Structural Mechanics in reactor Technology (SMiRT), Vol. 4, Part G, September 1971.

[9] GE Design Record File No. A00-05611,"Equivalent Margin Analysis".

Table 1 Comparison of Allowable and Applied K values

Operating Condition	K, Applied (Ksi√in.)	K, Allowable (Ksi√in.)
Hydro Test	32.9	59.7
Normal Operation (Level A)	29.5	63.2
Upset Condition (Level B)	34.0	63.2
Emergency Condition (Level C)	12.3	141.4
Faulted Condition (Level D)	3.7	141.4

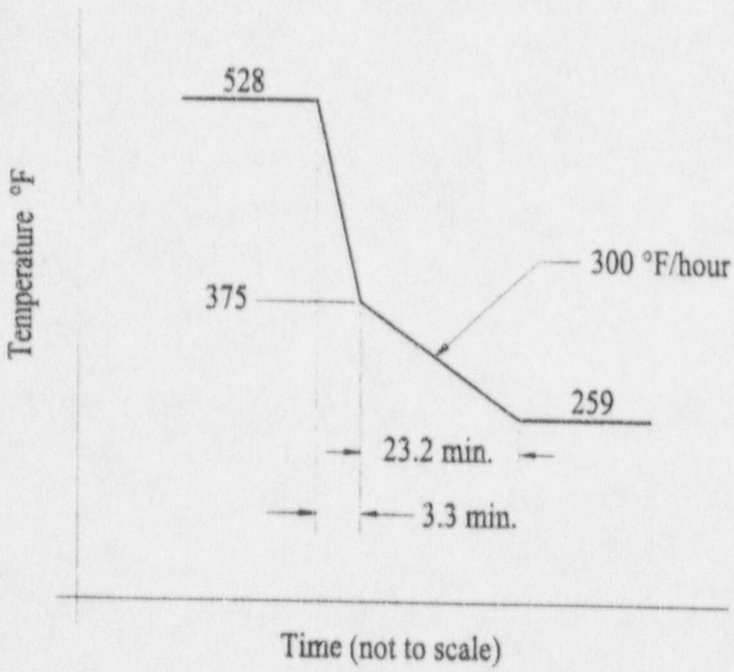

Figure 1 Assumed Emergency Condition Transient

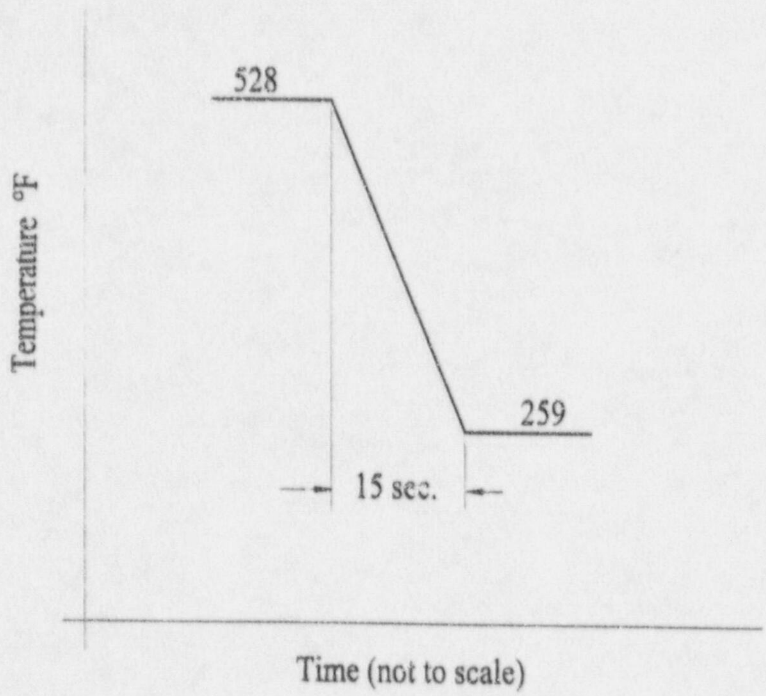

Figure 2 Assumed Faulted Condition Transient

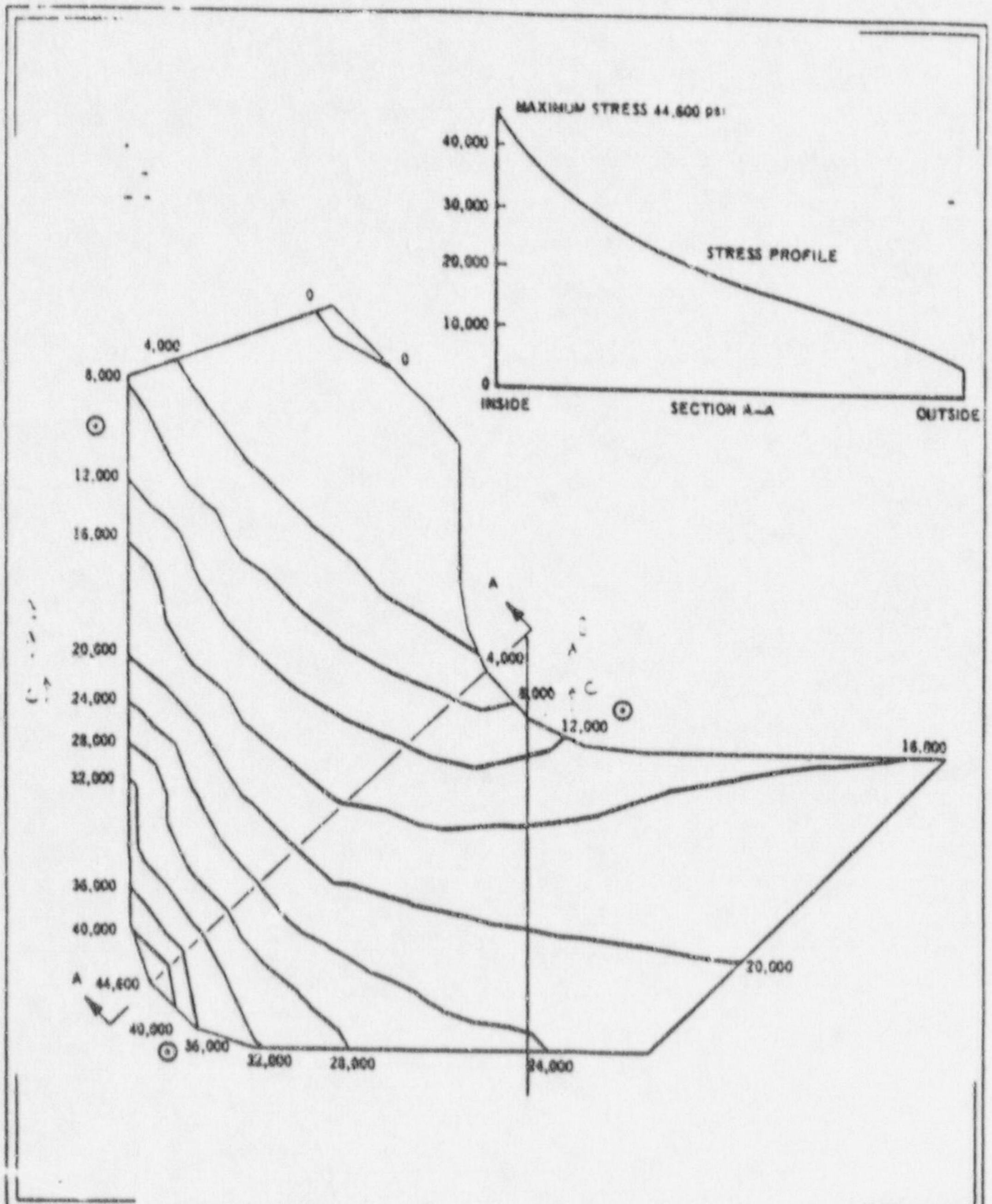

Figure 3 **Distribution of Maximum stress at a Nozzle Penetration**

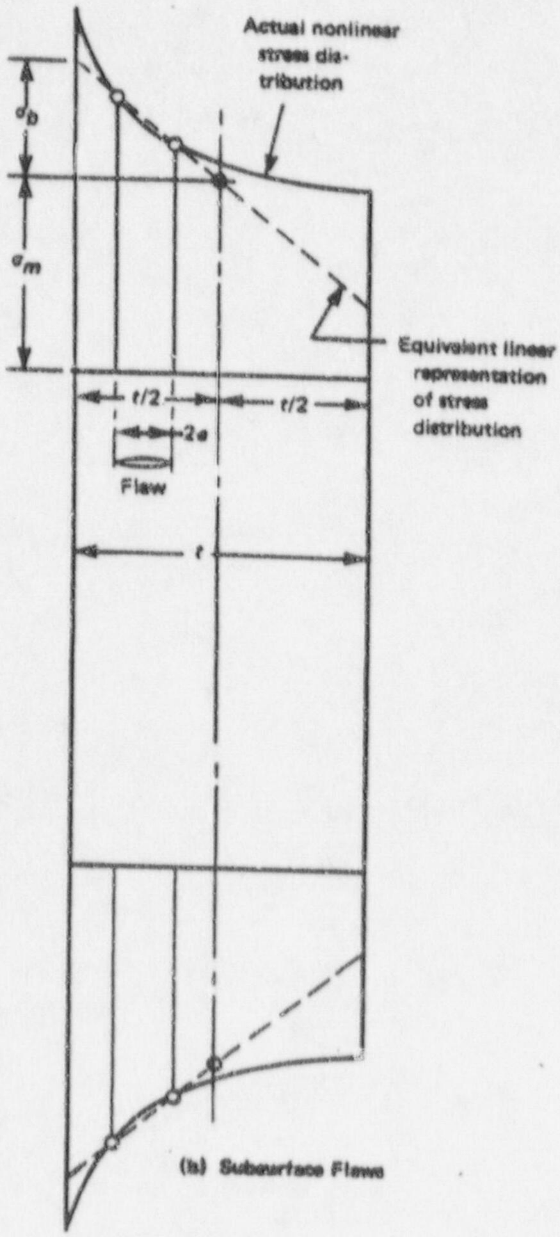

Figure 4 ASME Section XI Procedure for evaluating Subsurface Flaws

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COMMITMENT	COMMITTED DATE OR OUTAGE
None	N/A