CP&L

Carolina Power & Light Company

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United States Nuclear Regulatory Commission
ATTENTION: Document Control Desk
Washington, DC 20555

BRUNSWICK STEAM ELECTRIC PLANT, UNIT NO. 1
DOCKET NO. 50-325/LICENSE NO. DPR-71
RESPONSE TO NRC REQUEST FOR ADDITIONAL INFORMATION
REACTOR RECIRCULATION SYSTEM SAFE END/THERMAL SLEEVE CRACKING

Gentlemen:

On February 8, 1989, technical representatives from Carolina Power & Light Company (CP&L) and the NRC Staff held a telephone conference to discuss the inspection and detection of crack indications in the reactor recirculation system safe ends of Brunswick Steam Electric Plant, Unit 1 (BSEP-1). Subsequently, on February 15, 1989, the NRC Staff provided a request for additional information concerning the recirculation system safe end inspections.

Enclosed are CP&L's responses to the NRC Staff request for additional information. The Company has requested a meeting with the NRC Staff on February 22, 1989 to review the responses provided herein, as well as discuss any additional Staff issues and concerns. Since preparation of this response, the Company has acquired additional data on crack growth rates. Additional analysis using this data is currently being performed and is expected to completed and available for discussion at the February 22, 1989 meeting.

Please refer any questions regarding this submittal to Mr. Stephen D. Floyd at (919) 836-6901.

Yours very truly,

Leonard I. Loflin
Manager
Nuclear Licensing Section

BK/WRM/wrm (\cor\nrc-rai)

Enclosure

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ENCLOSURE 1

RESPONSE TO NRC REQUEST FOR ADDITIONAL INFORMATION
REACTOR RECIRCULATION SYSTEM SAFE END/THERMAL SLEEVE CRACKING

NRC Question 1:

For safe ends A, C, E, and H were the cracks assumed to be a single 360 degree crack? If not provide a description of how Case 2, NUREG-0313, Rev. 2, page 4.3 was satisfied.

Response to Question 1:

The flaws in all safe ends were combined, after growth, in accordance with NUREG-0313, page 4.3, Case 2. This combination resulted in the flaws being treated as a single, 360 degree crack (i.e., Case 3 of NUREG-0313) for purposes of end-of-cycle allowable flaw size determination. The crack growth evaluations, however, were performed using individual flaws where appropriate, and using the flaw proximity rules of ASME Section XI to determine the starting flaw aspect ratio for crack growth analysis.

Crack growth calculations in both the length and depth direction were performed in accordance with NUREG-0313, except for special crack growth rate and residual stress considerations to account for the Inconel 600 material and the thermal sleeve attachment weld configuration, which are particular to this evaluation. These considerations are discussed at length in the responses to Question 4 and Question 8 below.

NRC Question 2:

You stated that 75% of the wall was the acceptable limit for a crack following a crack growth analysis. Please justify this statement since cracks in safe ends A, C, B, and F appear to be Case 3 of NUREG-0313 and, therefore, the values for a long crack per the tables should be utilized.

Response to Question 2:

As noted in the response to Question 1 above, the flaws were considered as single 360 degree cracks for purposes of critical flaw size evaluation. The reason why the allowable flaw size is reported as 75% through wall is that the applied stress ratio for primary stress $(P_m + P_b)/S_m$ is well below the lower cutoff value in the table (0.6). As seen from the response to Question 7 below, the maximum value of this ratio for the safe ends, at the thermal sleeve attachment weld location, is less than 0.25. For purposes of this evaluation, the IWB-3641 tables were extrapolated to lower stress ratios using the source equations, but retaining the 75% upper cutoff. This results in an allowable flaw size of 75% for a 360 degree crack. This approach has been used and accepted in numerous previous IGSCC flaw evaluations on BWRs, and is consistent with NUREG-0313, Section 4.1.

<u>NRC Question 3</u>:

Justify why the methodology of IWB-3640 is appropriate for the analysis in question. Paragraph IWB-3641.2(c) defines the configuration under evaluation in Figure IWB-3641-1 which is a butt weld.

<u>Response to Question 3</u>:

The methodology of ASME Section XI, paragraph IWB-3640 is based on the net section collapse approach described in detail in Reference 1. This methodology is directly applicable to pipes and fittings, such as the subject safe ends at the thermal sleeve attachment weld location. The reference to Figure IWB-3641-1 is only for purposes of defining the interface between base and weld metals when problems of low toughness weld metals may exist. The fact that in this case the observed flaws reside entirely in wrought, Inconel material obviates any concern for low toughness weld metal, and provides even stronger justification for the applicability of the net section collapse approach, than a typical butt weld configuration.

<u>NRC Question 4</u>:

Provide the crack growth rates used in the analysis and the experimental basis for the crack growth rates assumed for the crevice situation that exists for your safe ends.

<u>Response to Question 4</u>:

The crack growth law used for the analysis is the Inconel 182 crack growth law developed for EPRI under Research Project RPT 303-1. A final report on that project has been submitted to EPRI (Reference 2), and the section of that report relevant to this input is included as Attachment 1. Due to the limited amount of data available on Inconel 600 crack growth, the data presented on Figure 1, containing the crack growth law and the supporting data, includes Inconel 182 and 82 weld metal data, as well. The data presented in Figure 1 are the result of General Electric developed data, both laboratory and in-plant (References 3 and 4), and EPRI sponsored data (References 5 through 7), with the investigations performed at Southwest Research Institute and at General Electric. The data are all constant load data and the majority of specimens used in the experimental program were standard fracture mechanics specimens containing a fatigue pre-crack to provide a crevice. The test environments ranged from very high purity water to 1 ppm sulfuric acid providing a water conductivity of 8 μS/cm and a pH of 4.8

(Reference 4). The oxygen level ranged from .2 ppm to 7 ppm oxygen. Table 1 presents a summary of all data including the important loading and environmental variables employed.

<u>NRC Question 5</u>:

Clarify information on safe end E. Are you showing cracks progressing adjacent to the thermal sleeve attachment weld into the thermal sleeve? If so have you evaluated whether or not failure of the thermal sleeve might be expected and what the consequences of that failure might be?

<u>Response to Question 5</u>:

Some limited crevice attack (cracking) into the thermal sleeve has been evaluated based on the UT inspections. Evaluations performed on the creviced thermal sleeve region in another BWR indicated that given the loading conditions on the thermal sleeve (predominant loads include weld residual stress and reaction loads due to the water flow), the remaining ligament required to maintain the thermal sleeve in place was of the order of one square inch. Since the thermal sleeve is basically a flow channel and does not act as a thermal buffer, the principal function of the thermal sleeve is to direct the recirculation inlet flow through the jet pumps. Any leakage or bypass flow would only reduce the flow through the jet pumps, thereby effectively "derating" the plant. Were the thermal sleeve to completely separate from the safe end, the increased bypass flow would be expected and reduced jet pump flow. This result would lead to a further effective derating of the plant which may result in an orderly shutdown.

<u>NRC Question 6</u>:

Paragraph 5.2.2 of NUREG-0313 addresses uncertainty in flaw sizing. Verify that all examinations were performed with qualified personnel and without the limitations discussed in the NUREG. Further provide your basis of why sizing of the subject flaws is accurate. Include any mock-up or procedure qualification test results that support the current inspection work. Discuss why the shear wave procedure that was supposedly qualified on a mock up for Peach Bottom is now not effective for performing the current examination. If you conclude that the examinations were subject to the limitations described in the NUREG or that qualification of the current inspection method was not sufficient to quantify the uncertainty in flaw sizing, justify why a flaw evaluated with an assumed depth of at least 75% of the wall would not require a standard overlay.

Response to Question 6:

Personnel performing ultrasonic (UT) examinations on austenitic components, or performing evaluation, including flaw sizing had current qualifications in the appropriate area from the EPRI NDE Center. These qualifications can be verified by the EPRI qualification register.

Both circumferential and axial cracks were detected with the examination technique that utilized 31 degree and 45 degree refracted longitudinal (RL) search units from the overlay machined surface and the safe end transition taper. Additionally, a 60 degree RL was applied to the safe ends without an overlay on the adjacent safe end to nozzle weld. The through wall sizing was confirmed by at least two (2) different scanning angles. The through wall sizing was not impaired by the configuration of the safe end . A boat sample was taken from the "D" riser safe end, just above the thermal sleeve attachment weld (wall thickness in this area is 1.125 inches). In the area where the sample was taken, the automated scan data indicated circumferential and axial cracking with a remaining ligament of .560 inches. The depth of the cut was .630 inches leaving the boat sample of .530 inches. Although metallography found no evidence of cracking in the boat sample, the cavity where the sample was taken, leaked water. This supported the sizing accuracy of the automatic scan data.

The UT examination procedure was developed taking guidance from the EPRI report "Improved Ultrasonic Inspection Techniques For Creviced Safe Ends" dated October, 1986. Brunswick Plant procured a like configured Inconel 600 safe end to nozzle mock up in 1986, which is representative of their in-plant nozzle to safe end configuration that included the thermal sleeve attachment weld. Both axial and circumferential 10% through wall EDM notches were placed in the safe end above the attachment weld, which is where the most of the reported cracking was detected. For previous examinations prior to the detection of cracking in the Unit 1 safe ends, the calibrations were established from these notches with 45 degree shear wave as recommended by the EPRI report and supplemented with 60 degree shear wave examinations. The scanning sensitivity was at least five (5) times the response from the calibration notches as opposed to the standard two (2) times for Section XI examinations

As described in the EPRI report, all previous known cases where creviced safe end cracking has been observed, the shear wave examination technique was used. The cracking that was discovered in the Inconel 600 safe ends at Duane Arnold in 1978 was confirmed with 45 degree shear wave. The EPRI report pointed out that the amplitude response from the cracks did increase after those safe ends were removed. This was attributed to a probable stress relaxation which permitted crack opening and better reflectivity. This could explain as to why the Brunswick, Unit 1 cracks could not be seen with the Shear Wave technique. Additionally, the RL exams indicated branching much like a "crazing" effect which could absorb the higher wavelength sound energy from the shear wave, and yield little or no reflectivity.

<u>NRC Question 7</u>:

Provide $P_m + P_b / S_m$ for all the cracked safe ends you desire to operate as is.

<u>Response to Question 7</u>:

Table 2 provides a summary of the primary stress ratios for the ten safe ends at the thermal sleeve attachment weld locations. A complete summary of all applied stresses on the safe ends, including weld overlay shrinkage effects from all overlays applied on the BSEP-1 recirculation system, is included in Attachment 2.

<u>NRC Question 8</u>:

Provide a detailed discussion of how residual stresses from the overlay and thermal sleeve attachment welds were determined and treated analytically. Provide a discussion of the experimental bases to support the analysis.

<u>Response to Question 8</u>:

A thorough residual stress analysis for the BSEP thermal sleeve attachment weld configuration was performed in 1979, in response to concerns raised by the cracking observed in a similar safe end geometry at the Duane Arnold Plant. A report documenting this analysis is included as Attachment 3. This report concluded that the stresses in the BSEP safe ends, although highly tensile at the thermal sleeve attachment weld crevice, attenuate more rapidly than do those in the Duane Arnold design, due to the greater thickness of the safe end at this location. Thus, on the basis of this more rapid attenuation, slower crack growth rates than at Duane Arnold would be expected.

The residual stresses from Attachment 3 have been used in fracture mechanics based crack growth analysis of the observed cracking in the safe ends which will not be weld overlay repaired at the thermal sleeve attachment weld locations (Nozzles A, B, C, E, and H). This analysis, documented in Attachment 4, illustrates that these nozzles are acceptable for continued operation for a period in excess of one fuel cycle of operation, with no credit taken for any residual stress improvement from the nozzle-to safe end weld overlays, which are present on all of these nozzles. The analysis includes worst case applied loadings on the nozzle from Attachment 2, including weld overlay shrinkage effects, and utilized the Inconel crack growth law documented above, in response to Question 4. Some crack growth is predicted, but it does not exceed the ASME Section XI allowable for a 360 degree crack during the 18 month fuel cycle.

It is noteworthy that the above crack growth analysis is considered highly conservative, because significant improvement in the residual stress pattern at the thermal sleeve attachment weld location is expected from the nozzle-to-safe end weld overlays. A residual stress analysis of these overlays has been previously submitted, in Reference 8 (see CP&L letter dated January 27, 1989, serial no. NLS-89-017), and shows that the residual stresses at this location are highly compressive. Use of this residual stress pattern in the crack growth analysis, coupled with other applied loads, would result in no predicted growth of the observed flaws for any crack depth in the safe end. However, the Reference 8 weld overlay analysis did not take into account thermal sleeve attachment weld residual stresses as an initial condition, essentially starting from a stress free condition at this location. The analysis is currently being repeated to include the initial residual stress state, and it is fully expected that it will confirm a substantial improvement in the thermal sleeve attachment weld residual stresses over that presented in Attachment 3. These results will be reported as soon as they are available.

The residual stress analyses of Attachment 3 and Reference 8, as well as the analysis-in-progress discussed above, are based on the "WELDS" methodology developed at Battelle Columbus Laboratories under EPRI sponsorship. A complete description of this methodology, as well as extensive confirmation of it for a number of weld joint configurations, are reported in References 9 through 15.

<u>NRC Question 9</u>:

What criteria were used to determine the end of the crack indications.

<u>Response to Question 9</u>:

The crack length extremities were determined by the points where the indications were no longer discernable from the material noise. There was no length subtraction to account for the beam spread. This would typically oversize the crack length in an area of isolated cracking.

<u>NRC Question 10</u>:

With regard to the JCO for Unit 2, confirm that the calculations referenced by the licensee's contractor have been completed. Provide the calculations, boundary conditions, and sufficient detail on the modeling for the 2 dimensional finite element stress analysis. Describe in detail the computational procedures and bases for determining the stress intensity factors for the various stress components. Does the computational procedure include plastic zone size correction?

Response to Question 10:

The analyses in support of the JCO for Unit 2 have been completed and are currently being independently reviewed and documented. The computational procedures are essentially the same as those described above for the Unit 1 safe ends, except that they use applied loadings which are specific to Unit 2 and consider the worst of the flaw indications observed in Unit 1. The computational procedures do not include plastic zone size correction because the preponderance of applied stresses in crack growth analyses such as this are secondary, or strain controlled, for which application of a plastic zone size correction is considered inappropriate. This is consistent with the standard approach for analyses such as these and with the methodology for stress intensity factor determination recommended in Appendix A of NUREG-0313.

REFERENCES

1. "Evaluation of Flaws in Austenitic Piping," ASME Journal of Pressure Vessel Technology, Vol. 108, August 1986, pp. 352-366.

2. Development of Inconel Weld Overlay Repair for Low Alloy Steel Nozzle-to-Safe End Joint RPT 303-1, final report, June 1988.

3. EPRI/GE Information Exchange.

4. Reactor Primary Coolant System Pipe Rupture Study, U.S. Energy Research & Development Administration Contract AT (04-3)-189, Project Agreement 37.

5. P. L. Andressen, Corrosion '87, Paper #84.

6. EPRI Research Project RP 2006-17, General Electric Contractor, In Progress.

7. EPRI Research Project RP 2293-1, General Electric Contractor, In Progress.

8. Structural Integrity Associates Report SIR-89-003, Rev. 0, "Weld Overlay Repairs of Recirculation Inlet and Core Spray Nozzle-to-Safe End Welds, Brunswick Steam Electric Plant, Unit 1, Volume 1, January 23, 1989.

9. Rybicki, E. F., et. al., "Residual Stresses at Girth-Butt Weld in Pipes and Pressure Vessels," Final Report to U.S. Nuclear Regulatory Commission, Division of Reactor Safety, Research under Contract No. AT (49-24)-0293, NUREG-0276, published November, 1977.

10. Rybicki, E. F., et. al., "Finite Element Model for Residual Stresses and Deflections in Girth Butt Welded Pipes," Journal of Pressure Vessel Technology, Vol. 100, No. 3, August, 1978, pp. 256-262.

11. Rybicki, E. F., et. al., "Residual Stresses Due to Weld Repairs, Cladding and Electron Beam Welds and Effect of Residual Stresses on Fracture Behavior," Final Report to U.S. Nuclear Regulatory Commission, Division of Reactor Safety, Research under Contract No. AT (49-24)-0293, NUREG-0559, published December, 1978.

12. Rybicki, E. F. and Stonesifer, R. B., "Computation of Residual Stresses Due to Multipass Welds in Piping Systems," Journal of Pressure Vessel Technology, Vol. 101, No. 2, May, 1979, pp. 149-154.

13. Rybicki, E. F. and Stonesifer, R. B., "An Analysis Procedure for Predicting Weld Repair Residual Stresses in Thick-Walled Vessels,"

Journal of Pressure Vessel Technology, Vol. 102, No. 3, 1980, pp. 323-331.

14. Brust, F. W. and Stonesifer, R. B., "Effects of Weld Parameters on Residual Stresses in BWR Piping Systems," Final Report to Electric Power Research Institute, NP-1743, Research Project 1174-1, March, 1981.

15. Rybicki, E. F., et.al., "Computational Residual Stress Analysis for Induction Heating of Welded BWR Pipes," Final Report prepared for the Electric Power Research Institute by the University of Tulsa, EPRI NP-2662-LD, Project T113-6, December, 1982.

TABLE 1

Test Data for Crack Growth of Nickel Based Alloys in Pure Water at 288°C

Material	Heat Treatment	Exposure Time, hours	Initial K, ksi$\sqrt{in}$	Crack Growth mm	Final K, ksi$\sqrt{in}$	Average Growth Rate, in./hr.	Environment	Reference
Alloy 600	FS + LTS	4129	45	4.8	39.5	4.5×10^{-5}	7 ppm O_2, 1 ppm H_2SO_4	2
I-82	FS + LTS	4129	45	4.0	41.2	3.8×10^{-5}	7 ppm O_2, 1 ppm H_2SO_4	2
I-182	FS + LTS	4129	45	2.5	41.9	2.4×10^{-5}	7 ppm O_2, 1 ppm H_2SO_4	2
Alloy 600	As Received(?)	7000	25	-	-	2.5×10^{-6}	200 ppb, O_2 in Reactor	6
Alloy 600	As Received(?)	7000	50	-	-	1×10^{-5}	200 ppb, O_2 in Reactor	6
Alloy 600	LTS	-	33	-	-	7.5×10^{-7}	200 ppb, O_2 0.1 $\mu S/cm$	5
Alloy 600	LTS	-	Cyclic Load 21 - 30	-	-	3×10^{-6}	200 ppb, O_2 0.1 $\mu S/cm$	5
I-182	LTS	-	30	-	-	1.2×10^{-5}	200 ppb, O_2 0.5 $\mu S/cm$	4
Alloy 600	LTS	-	30	-	-	2.4×10^{-5}	200 ppb, O_2 0.3-0.7 $\mu S/cm$	3
Alloy 600	LTS	-	32.4	-	-	9×10^{-6}	200 ppb, O_2 0.1 $\mu S/cm$	7

TABLE 2

Applied Primary Stress Ratio at
Recirculation Inlet Safe End Thermal Sleeve
Attachment Weld Location
BSEP Unit 1

Nozzle	$(P_m+P_b)/S_m$
A	0.18
B	0.21
C	0.24
D	0.19
E	0.20
F	0.18
G	0.20
H	0.23

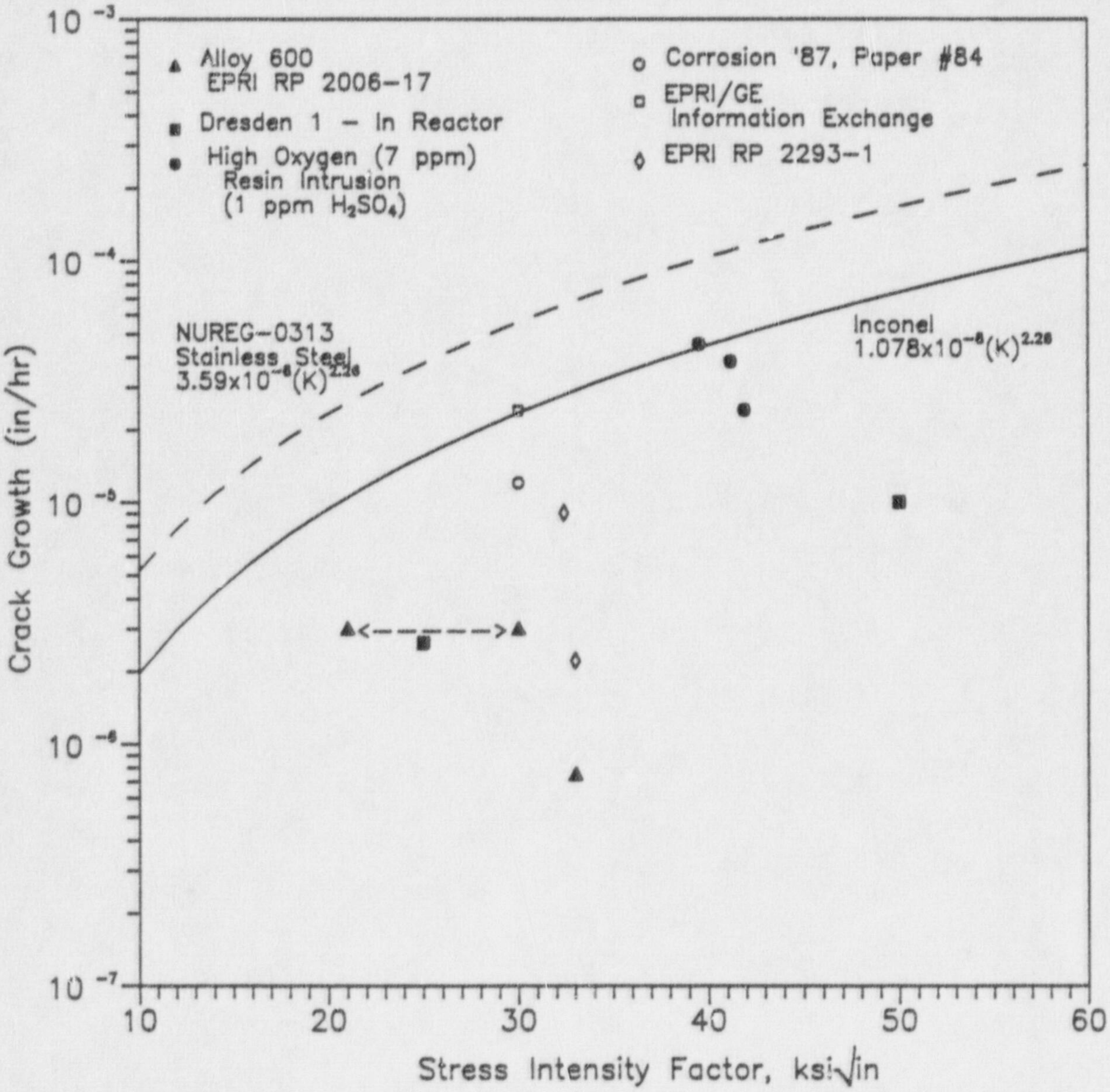

Figure 1. Crack Growth Rate Data for Inconel 600, 82, 182

ATTACHMENT 1

CRACK GROWTH MODELLING FROM
EPRI REPORT

DEVELOPMENT OF INCONEL WELD OVERLAY REPAIR FOR LOW ALLOY STEEL NOZZLE TO SAFE-END JOINT

Research Project No. RPT303-1
Final Report, June, 1988

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model layer), number 3 (2nd model layer), number 6 (3rd model layer), and the cap layer (4th model layer). It is seen from these four figures that the maximum temperature in the original pipe material is 1500°F or more for the first two model layers and is less than 700°F for the last two model layers. This observation verifies the design that requires a heat treatment only after the application of layer 3.

4.4 Inconel 82 Weld Metal Crack Growth Modelling

Weld overlay repairs applied using Type 308L stainless steel weld metal containing controlled carbon and ferrite levels (0.02 wt% carbon maximum and 8FN minimum) exhibit excellent resistance to IGSCC initiation and propagation in the BWR environment [4-9]. As a result, these materials are potentially usable for long time repairs (potentially, remainder of operating life) for IGSCC flaws in stainless steel piping.

In contrast to the IGSCC behavior of metallurgically controlled Type 308L stainless steels, the Inconel family of materials has exhibited some susceptibility to IGSCC, particularly when crevice environments are present. The most commonly used Inconel weld metal, the shielded metal arc material Inconel 182, has been observed to exhibit IGSCC in creviced coupon tests as well as in operating plants, as evidenced by the Inconel 182 cracking at Duane Arnold, in the crevice produced by the thermal sleeve attachment to the recirculation inlet nozzle safe-end and in the Inconel 182 butter in the recirculation inlet and outlet safe-end to nozzle joints at the Pilgrim nuclear power plant. This concern regarding the Inconel 182 weld metal susceptibility to crevice IGSCC prompted the EPRI/Georgia Power study which this report documents.

Because of the crevice cracking behavior of Inconel weld metal in aggressive high temperature water environments, weld overlay repairs constructed using Inconel welding materials can not depend exclusively upon arrest of a growing IGSCC if these repairs are to be effective. Crack growth rates must be bounded taking into account applied and weld (or overlay induced) residual stresses. Additionally, Inconel overlay repairs can be designed for limited operation with sufficient thickness such that design code margins (as described in Section 4-2) are not exceeded during a specific operating interval.

In this section of the report, recent experimental results concerning IGSCC resistance of Inconel weld materials are summarized. A crack growth correlation for use in sizing and evaluating Inconel weld overlay repairs is also developed, based upon the experimental data presented in this section and the applied and residual stresses developed in Section 4.2.

4.4.1 Inconel Weld Metal Experimental Programs

Southwest Research Institute (SwRI) conducted a study of the IGSCC susceptibility of seven different Inconel weld metals [4-10]. Tests were conducted on welds joining Inconel 600 to A508 low alloy steel, a condition similar to but not exactly the condition of our weld overlay repair study. Tests were conducted in an aggressive simulation of the BWR environment at 288°C with water containing 6 ppm dissolved oxygen. Both creviced and uncreviced U-bend specimens were studied. IGSCC susceptibility was examined as a function of chemistry, welding process, heat treatment and crevice condition. This study concluded that alloys Inconel 625, Inconel 182 and Inconel 82 were the most susceptible to IGSCC.

The dominant factor in these tests appears to have been the presence of the weld relative to the A508 material. It was argued that either the presence of a galvanic couple or carbon diffusion at the fusion line can lead to locally high hardness at the fusion line, which in turn produces higher SCC susceptibility. The presence of the A508 shifted the location of the most susceptible location from the weld metal to the fusion line. Another argument which could be advanced was that the fusion line contained a dilution zone alloy not representative of either the weld metal or the low alloy steel.

Nelson and Floreen [4-11] conducted a study of Inconel IGSCC in an accelerated BWR environment. Four different weld chemistries were studied (the nominal equivalents of alloys 600, 690, 625, 671). Welds made with the SMAW and GTAW processes were included. The test environment was water at 316°C, containing 6 ppm O_2, with a pH of 4.6 obtained by addition of sulfuric acid. Tested base metals included Inconel 690 and Inconel 600. Test specimens were subjected to the test environment for a period of 40 weeks.

The results showed that IGSCC susceptibility was a strong function of chromium content. For welds with a chromium content of less than 24%, 31 out of 32 samples failed due to IGSCC. In contrast, for welds with chromium content greater than 24%, only 8 out of 32 specimens failed. Of these, 7 out of 8 occurred in single U-bend SMAW specimens. Only 1 GTAW sample failed. No cracking was observed in either the 690 or 600 base metals, or in the fusion line region. All failures were in the weld metals.

The conclusion presented by the authors of this study is that by using higher chromium weld metals applied with the GTAW process, IGSCC susceptibility can be considerably reduced.

In a study performed at SwRI, [4-12], tests were conducted on Inconel 600 and Inconel 690 base metals and on Inconel 82 and 182 weld metals in oxygenated high purity water. The testing included creviced and uncreviced slow strain rate tests (SSR), constant load tests, and fracture mechanics tests. The slow strain rate tests revealed that in the uncreviced conditions none of the Inconel alloys were observed to be susceptible to IGSCC initiation. However, in the creviced condition, SSR specimens of Inconel 600 and 182 exhibited susceptibility to IGSCC initiation. Inconel 82 demonstrated only a slight susceptibility to initiation while Inconel 690 was immune. In the constant load tests, both Inconel 600 and Inconel 182 exhibited IGSCC at loads of 1.25 of the 288°C yield strength whereas no IGSCC was observed in Inconel 690 even at stresses of 1.5 of 288°C yield strength. Inconel 82 was not included in this part of the study. Finally, fracture mechanics specimens revealed a K_{ISCC} threshold of below 31 MPa x $m^{1.2}$ for Inconel 600 and Inconel 182 with crack propagation rates of 5 x 10^{-7} mm/sec to 5 x 10^{-6} mm/sec in these alloys. No IGSCC propagation was observed at K levels greater than 49 MPa x $m^{1/2}$ or Inconel 690.

Additional slow strain rate, constant load and fracture mechanics testing was performed on this class of materials at SwRI and reported recently in the literature [4-13]. These tests included a combination of creviced and uncreviced slow strain rate specimens. These tests were run in a simulated resin intrusion environment of 1 ppm H_2SO4 in oxygenated, high temperature water and compared to the high purity oxygenated results in the study [4-12]. The important feature of these tests was that in the resin intrusion fracture mechanics tests, Inconel 600, Inconel 82, Inconel 182 and Inconel 690 were all susceptible to IGSCC. As presented in Table 4-2, the crack growth rates for Inconel 600, Inconel 82 and Inconel 182 varied from 1.7×10^{-7} to 3.2×10^{-7} mm/sec at an average stress intensity of approximately 45 MPa x $m^{1/2}$. This modest difference in crack growth rates among these alloys is believed to be within the experimental error in assessing crack initiation times and therefore crack growth rates. In contrast to these results, only the Inconel 690 specimen loaded to a stress intensity of approximately 65 MPa x $m^{1/2}$ exhibited any crack growth and that rate was approximately one order to magnitude lower than the crack growth rates for the Inconel 600, Inconel 82 and Inconel 182 specimens. It is noteworthy that in both the resin intrusion environments and in the pure water environment, the alloys exhibiting the highest resistance in IGSCC contained chromium levels of at least 28%. The more susceptible alloys contained chromium levels of from 15 to 20 wt%. In addition, those alloys containing lower carbon content appeared to be more resistant.

4.4.2 Development of Inconel Crack Growth Correlation

In order to evaluate the effectiveness of the Inconel weld overlay repair to provide the ASME Code designed structural margin to stress corrosion cracking failure, it is necessary to examine the growth of an IGSCC flaw in the weld metal. Using the data of Table 4-1, converted to English units, and the Paris crack growth law [4-14] of the form

$$da/dt = CK^n$$

the data were plotted on Figure 4-14, and compared to the crack growth rates observed in austenitic stainless steel in the BWR environment. As crack growth rate data at only one stress intensity level was available for the Inconel alloys, it was assumed that the crack growth correlation would parallel the best estimate crack growth rate stainless steel curve and be displaced according to the data at the single data point. Thus, a crack growth law given as

$$da/dt = 1.078 \times 10^{-8} K^{2.26} \text{ in/hr}$$

was developed as bounding the available data for this class of material.

These results are believed to be conservative since the data presented in Figure 4 present results of crack growth tests in a very aggressive simulated resin intrusion environment where the oxygen level and ionic impurity levels are artificially high. The limited listing in the high purity water environment on the Inconel 82 indicated only slight susceptibility to surface cracking in the very severe slow strain rate tests. These crack growth rate data provide the basis from which a structural weld overlay can be designed. The design of the overlay however, is also dependent upon applied and residual stress and the operating lifetime desired since some crack growth is predicted using this model. However, the Inconel 82 overlay can be designed such that the applied and residual stresses combine to produce a negative stress intensity thereby eliminating IGSCC growth of an initiated crack. Under such circumstances, the overlay may potentially be used indefinitely.

4.5 References

4-1 General Electric Report, "Results of Seismic Evaluations of As-Built Recirculation Piping Including Replacement Action for F031 Discharge Valve", Design Memo 170-113, September 26, 1984.

4-2 Rybicki, E. F., et al., "Residual Stresses at Girth-Butt Welds in Pipes and Pressure Vessels," Final Report to U.S. Nuclear Regulatory Commission, Division of Reactor Safety, Research under Contract No. AT 949-24)-0293, NUREG-0376, published November, 1977.

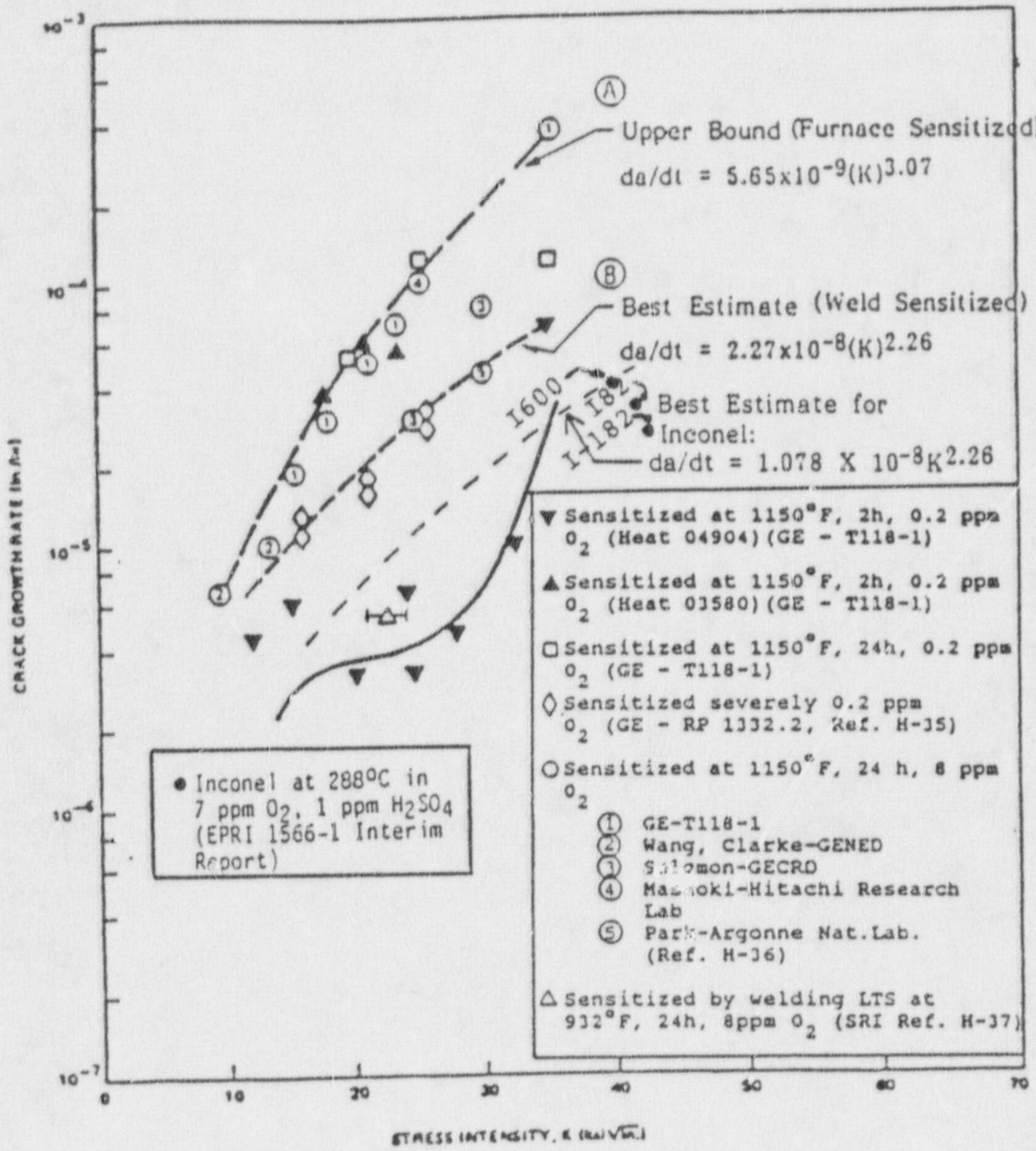

Figure 4-14. Crack Growth Rate Curves Used in Analysis and Supporting Data (from EPRI NP-2472 and EPRI-1566-2, Interim Report)

ATTACHMENT 2

SAFE END APPLIED LOADING SUMMARY
AT THERMAL SLEEVE ATTACHMENT WELD LOCATION

BSEP UNITS 1 - APPLIED STRESS SUMMARY
WELD # A - Th.Sl.Attach.

PIPE OD (in)	15.00
PIPE THICK. (in)	1.125
PIPE ID (in)	12.75
PRESSURE (psi)	1325.00
X-SECT AREA (in^2)	49.04
SECT.MOD (in^3)	171.22

STRESS TYPE	Fx (kip)	My (in-kip)	Mz (in-kip)	TOT.MOM. (in-kip)	SIG-AX (ksi)
PRES					3.45
DW	0.11	-14.60	4.70	15.34	0.09
OBE1,x	1.20	66.40	64.80		
OBE2,y	0.20	8.60	12.90		
OBE3,z	1.10	59.80	53.30		
COMB.OBE	1.40	75.00	77.70	107.99	0.66
THERMAL	0.72	83.40	97.00	127.92	0.76
SHRK.	2.40	98.80	42.50	107.55	0.68
Pm					3.45
Pb					0.75
Pb-sust					1.53
(Pm+Pb)/Sm					0.18

BSEP UNITS 1 - APPLIED STRESS SUMMARY
WELD #   B - Th.Sl.Attach.

PIPE OD (in)	15.00
PIPE THICK. (in)	1.125
PIPE ID (in)	12.75
PRESSURE (psi)	1325.00
X-SECT AREA (in^2)	49.04
SECT.MOD (in^3)	171.22

STRESS TYPE	Fx (kip)	My (in-kip)	Mz (in-kip)	TOT.MOM. (in-kip)	SIG-AX (ksi)
PRES					3.45
DW	0.29	11.10	40.40	41.90	0.25
OBE1,x	0.75	46.80	148.10		
OBE2,y	0.10	5.20	30.60		
OBE3,z	0.83	41.90	102.60		
COMB.OBE	0.93	52.00	178.70	186.11	1.11
THERMAL	0.43	84.00	88.20	121.80	0.72
SHRK.	3.80	24.70	89.20	92.56	0.62
Pm					3.45
Pb					1.36
Pb-sust					1.59
(Pm+Pb)/Sm					0.21

BSEP UNITS 1 & 2 - APPLIED STRESS SUMMARY
WELD # C(U1) - Th.Sl.Attach.

PIPE OD (in)	15.00
PIPE THICK. (in)	1.125
PIPE ID (in)	12.75
PRESSURE (psi)	1325.00
X-SECT AREA (in^2)	49.04
SECT.MOD (in^3)	171.22

STRESS TYPE	Fx (kip)	My (in-kip)	Mz (in-kip)	TOT.MOM. (in-kip)	SIG-AX (ksi)
PRES					3.45
DW	1.10	-10.80	-102.30	102.87	0.62
OBE1,x	1.50	39.50	196.30		
OBE2,y	0.20	4.40	44.10		
OBE3,z	1.30	31.20	164.50		
COMB.OBE	1.70	43.90	240.40	244.38	1.46
THERMAL	0.50	103.70	139.00	173.42	1.02
SHRK.	0.40	21.90	287.60	288.43	1.69
Pm					3.45
Pb					2.09
Pb-sust					3.34

$$\frac{P_m + P_b}{S_m} = \frac{5.54}{23.3} = .24$$

BSEP UNITS 1 - APPLIED STRESS SUMMARY
WELD # D - Th.Sl.Attach.

PIPE OD (in)	15.00
PIPE THICK. (in)	1.125
PIPE ID (in)	12.75
PRESSURE (psi)	1325.00
X-SECT AREA (in^2)	49.04
SECT.MOD (in^3)	171.22

STRESS TYPE	Fx (kip)	My (in-kip)	Mz (in-kip)	TOT.MOM. (in-kip)	SIG-AX (ksi)
PRES					3.45
DW	0.20	-10.00	-30.80	32.38	0.19
OBE1,x	0.60	20.20	106.90		
OBE2,y	0.10	3.10	24.20		
OBE3,z	0.50	18.60	109.90		
COMB.OBE	0.70	23.30	134.10	136.11	0.81
THERMAL	0.40	40.70	141.40	147.14	0.87
SHRK.	5.70	20.90	386.00	386.57	2.37
Pm					3.45
Pb					1.00
Pb-sust					3.43
(Pm+Pb)/Sm					0.19

BSEP UNITS 1 - APPLIED STRESS SUMMARY
WELD # E - Th.Sl.Attach.

PIPE OD (in)	15.00
PIPE THICK. (in)	1.125
PIPE ID (in)	12.75
PRESSURE (psi)	1325.00
X-SECT AREA (in^2)	49.04
SECT.MOD (in^3)	171.22

STRESS TYPE	Fx (kip)	My (in-kip)	Mz (in-kip)	TOT.MOM. (in-kip)	SIG-AX (ksi)
PRES					3.45
DW	0.50	7.60	130.30	130.52	0.77
OBE1,x	0.30	17.50	48.40		
OBE2,y	0.10	3.20	27.00		
OBE3,z	0.40	20.20	41.50		
COMB.OBE	0.50	23.40	75.40	78.95	0.47
THERMAL	1.20	9.30	128.10	128.44	0.77
SHRK.	4.40	30.30	67.30	73.81	0.52
Pm					3.45
Pb					1.24
Pb-sust					2.07
(Pm+Pb)/Sm					0.20

BSEP UNITS 1 & 2 - APPLIED STRESS SUMMARY
WELD # F - Th.Sl.Attach.

PIPE OD (in)	15.00
PIPE THICK. (in)	1.125
PIPE ID (in)	12.75
PRESSURE (psi)	1325.00
X-SECT AREA (in^2)	49.04
SECT.MOD (in^3)	171.22

STRESS TYPE	Fx (kip)	My (in-kip)	Mz (in-kip)	TOT.MOM. (in-kip)	SIG-AX (ksi)
PRES					3.45
DW	0.20	-13.90	-32.60	35.44	0.21
OBE1,x	0.40	18.50	54.30		
OBE2,y	0.10	3.40	27.00		
OBE3,z	0.40	20.40	48.40		
COMB.OBE	0.50	23.80	81.30	84.71	0.50
THERMAL	1.10	-40.40	143.60	149.17	0.89
SHRK.	0.60	16.80	596.00	596.24	3.49
Pm					3.45
Pb-prim					0.72
Pb-sust					4.60

$$\frac{P_m + P_b}{S_m} = \frac{4.17}{23.3} = .18$$

ALLOW a/t (360° CRACK) = 75%

BSEP UNITS 1 & 2 - APPLIED STRESS SUMMARY
WELD #   G(U1) - Th.Sl.Attach.

PIPE OD (in)	15.00
PIPE THICK. (in)	1.125
PIPE ID (in)	12.75
PRESSURE (psi)	1325.00
X-SECT AREA (in^2)	49.04
SECT.MOD (in^3)	171.22

STRESS TYPE	Fx (kip)	My (in-kip)	Mz (in-kip)	TOT.MOM. (in-kip)	SIG-AX (ksi)
PRES					3.45
DW	0.11	11.58	70.56	71.50	0.42
OBE1.x	0.45	18.45	106.90		
OBE2.y	0.09	3.48	22.92		
OBE3.z	0.50	19.89	110.10		
COMB.OBE	0.59	23.37	133.02	135.06	0.80
THERMAL	0.26	-58.67	135.08	147.27	0.87
SHRK.	5.90	11.40	616.00	616.11	3.72
Pm					3.45
Pb					1.22
Pb-sust					5.00

$$\frac{P_m + P_b}{S_m} = \frac{4.67}{23.3} = 0.20$$

BSEP UNITS 1 & 2 - APPLIED STRESS SUMMARY
WELD #   H(U1) - Th.Sl.Attach.

PIPE OD (in)	15.00
PIPE THICK. (in)	1.125
PIPE ID (in)	12.75
PRESSURE (psi)	1325.00
X-SECT AREA (in^2)	49.04
SECT.MOD (in^3)	171.22

STRESS TYPE	Fx (kip)	My (in-kip)	Mz (in-kip)	TOT.MOM. (in-kip)	SIG-AX (ksi)
PRES					3.45
DW	1.30	18.80	106.80	108.44	0.66
OBE1.x	1.60	27.12	162.50		
OBE2.y	0.24	4.09	40.60		
OBE3.z	1.70	33.22	173.20		
COMB.OBE	1.94	37.31	213.80	217.03	1.31
THERMAL	0.86	-108.00	52.30	120.00	0.72
SHRK.	3.50	8.13	491.00	491.07	2.94
Pm					3.45
Pb					1.97
Pb-sust					4.32

$$\frac{P_m + P_b}{S_m} = \frac{5.42}{23.3} = .23$$

ATTACHMENT 3

BSEP THERMAL SLEEVE ATTACHMENT
WELD RESIDUAL STRESS ANALYSIS