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MASTER

RESULTS OF FRACTURE MECHANICS TESTS ON PNC SUS 304 PLATE

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CONTENTS

	<u>Page</u>
INTRODUCTION	1
IRRADIATION VEHICLE AND CONDITIONS	3
- Irradiation Vehicle	3
- Thermal Expansion Devices	10
- Dosimeters	12
EXPERIMENTAL PROCEDURES	15
- Material	15
- Tensile Testing	15
- Fatigue-Crack Propagation Testing	21
- Fracture Toughness Testing	28
- Metallographic and Fractographic Examination	37
RESULTS AND DISCUSSIONS	39
- Tensile Tests	39
- Fatigue-Crack Propagation Tests	39
- Fracture Toughness Tests	50
- Microstructure and Fracture Mechanisms	58
SUMMARY AND CONCLUSIONS	65
REFERENCES	67
APPENDIX A - Dosimetry Results and Interpretation	A-1
APPENDIX B - Precracking Schedule	B-1
APPENDIX C - Single-Specimen Unloading-Compliance J_C Testing	C-1
APPENDIX D - Tensile Test Results	D-1
APPENDIX E - Photographs of Irradiated Tensile Specimens	E-1
APPENDIX F - Crack Length Versus Cycles Curves for the Fatigue-Crack Growth Tests	F-1
APPENDIX G - Test Data and Detailed Calculations for the Fatigue-Crack Growth Tests	G-1

CONTENTS (Cont'd)

	<u>Page</u>
APPENDIX H - Load-displacement Records for Fracture Toughness Tests	H-1
APPENDIX I - Photographs of Fracture Surfaces for Irradiated Fracture Toughness Specimens	I-1
APPENDIX J - Calibration Records for the Dual LVDT Extensometer System for Tensile Testing	J-1

FIGURES

<u>Figure</u>		<u>Page</u>
1	Location of Position 2705 in the FFTF	4
2	Reactor Power During Cycle 4	5
3	Schematic of a Typical Canister Arrangement	6
4	Schematic of Canisters Attached to the Stalk and Handling Socket	7
5	Schematic of Fracture Mechanics Assembly (Exterior View)	8
6	Location and Readings of TEDs	11
7	Neutron Energy Spectrum at Core Midplane for a Row 7 Reflector Assembly	14
8	Tensile Specimen, Dimensions in Inches	17
9	Arrangement of Specimens from Plate Supplied by PNC	18
10	Extensometry Fixtures Attached to Tensile Specimen	19
11	Extensometry Fixtures Translate the Specimen Displacement Outside the Furnace where it is Monitored by Two LVDTs	20
12	View of Fatigue-Crack Growth Test Set for Irradiated Specimens	25
13	Photograph of Camera Controls and Video Output for the Closed-Circuit Television System used to Measure Crack Lengths on Irradiated Specimens	26
14	Compact Specimen, Dimensions in Inches	29
15	A Rigid Fixture Translates the Load-Line Displacement Outside the Loading Clevises Where it is Monitored by Two LVDTs	31
16	LVDTs are Centered Along the Specimen Load-Line	32
17	Photograph of Closed-Circuit Television System Output Used for Measuring Average Crack Length and Crack Extension for J-Integral Specimens	34

FIGURES (Cont'd)

<u>Figure</u>		<u>Page</u>
18	Comparison of Postirradiation Yield Strength Levels for PNC SUS 304 Plate with Results Obtained Previously for 304 SS and 304L SS	41
19	Comparison of Postirradiation Ultimate Strength Levels for PNC SUS 304 Plate with Results Obtained Previously for 304 SS and 304L SS	42
20	Comparison of Postirradiation Total Elongation Values from PNC SUS 304 Plate with Results Obtained Previously for 304 SS and 304L SS	43
21	Results for Fatigue-Crack Propagation Tests Conducted on Unirradiated SUS 304 Stainless Steel	45
22	Results for Fatigue-Crack Propagation Tests Conducted on SUS 304 Irradiated to 2.7 dpa	46
23	Results for Fatigue-Crack Propagation Tests Conducted on SUS 301 Irradiated to 5.1 dpa	47
24	The Effect of Irradiation Upon the Fatigue-Crack Propagation Behavior of SUS 304 Stainless Steel	48
25	Comparison of the Results of the Present Study with Those of an Earlier Study	49
26	J _q Curves for Unirradiated and Irradiated SUS 304	53
27	The Three Specimens that Fell Below the 427°C J _q Curve Exhibited Excessive Crack Extension on One Side of the Specimen	54
28	The Three Specimens Tested at 427°C that Fell Above the J _q Curve Displayed Symmetric Stable Tearing Regions	55
29	Specimen Tested at 400°C Exhibited Rather Uniform Crack Extension Regions	56
30	Unetched Metallographic Profiles of Specimen 2753	59
31	Typical Microstructures for Specimen 2753	60

FIGURES (Cont'd)

<u>Figure</u>		<u>Page</u>
32	SEM Fractographs Illustrating Elongated Tear Ridges in (a) Specimen 2752, (b) Specimen 2753	61
33	SEM Fractographs Illustrating Equiaxed Microvoid Coalescence (a) Near the 1/2 T position of Specimen 2753	63
34	Metallographic-Fractographic Interface for Specimen 2752	64

TABLES

<u>Table</u>		<u>Page</u>
1	Location of PNC Specimens within Irradiation Canisters FMA-1B Assembly	9
2	Summary of Dosimetry Results for FMA-1B	13
3	Chemical Composition and Mechanical Properties of PNC Material	16
4	Specimens Employed in the Fatigue-Crack Growth Studies	23
5	Summary of Tensile Properties	40

INTRODUCTION

Austenitic stainless steel alloys are used extensively as structural materials in liquid-metal fast-breeder reactors. Components are typically manufactured and inspected in accordance with codes and procedures which minimize the occurrence of defects that could jeopardize structural integrity.⁽¹⁾ Nevertheless, the significance of crack-like defects (either actual or hypothetical) must often be evaluated to quantify structural integrity margins in support of licensing, safety assessments and inspection requirements. For austenitic stainless steels, these analyses have most often involved considerations of fatigue crack growth.⁽²⁻³⁾ The fracture toughness of these materials is typically so high that final failure from a fatigue crack occurs by extensive plasticity rather than by crack extension.

Permanent structures located inside the reactor vessel can accumulate significant lifetime irradiation exposures which could degrade their fracture resistance. Fracture analyses may need to be considered for such components. Limited fracture toughness data based on elastic-plastic fracture mechanics have been reported for irradiated austenitic stainless steels. Loss, et al.,⁽⁴⁾ showed that irradiation to approximately 10^{20} n/cm² ($E > 1.0$ MeV) resulted in a three-fold degradation in the J-integral initiation toughness for Type 316 base metal and weld. The irradiations, however, were performed in a thermal reactor and tests were conducted at 260 and 277°C. Dufresne, et al.,⁽⁵⁾ studied the effects of fast-neutron irradiation on the J-integral initiation toughness for Types 316L and 304 base metals and welds at 20 and 400°C. Low irradiation exposures of approximately 2 dpa (total fluences from 6 to 8×10^{21} n/cm²) caused essentially no embrittlement of the base metals, but resulted in a dramatic reduction of initiation toughness for welds.

At the DOE/PNC Specialists Meeting on Structural Materials Data held January 25-28, 1982 in Japan, DOE representatives discussed with PNC personnel the concept of conducting irradiations for PNC in FFTF and

performing subsequent fracture mechanics tests. The information from such material tests would provide input for fracture analyses to verify structural integrity of irradiated components.

As a result of further correspondence on this concept, DOE and PNC, in March 1983, agreed on a program to be carried out by Westinghouse Hanford Company (WHC). PNC provided SUS 304 plate to be irradiated in FFTF at about 400°C to a target fluence of $5 \times 10^{21} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$). The actual irradiation included two basically different exposure levels to assure that information would be available for the exposure of interest. After irradiation, tensile properties, fatigue-crack growth rates and J-integral fracture toughness response were determined. These same properties were also measured for the unirradiated material so radiation damage effects could be characterized. This report presents the results of this program.

It is expected that these results would be applicable for detailed fracture analysis of reactor components. Recent advances in elastic-plastic fracture mechanics enable reasonably accurate predictions of failure conditions for flawed stainless steel components. Extensive research has focused on the development of J-integral-based engineering approach for assessing the load carrying capacity of low-strength, high-toughness structural materials. Furthermore, Kanninen, et al.,⁽⁶⁻⁸⁾ have demonstrated that J-integral concepts can accurately predict the fracture response for full-scale cracked structures manufactured from Type 304 stainless steel.

IRRADIATION VEHICLE AND CONDITIONS

Irradiation Vehicle

The PNC specimens were irradiated in four canisters in the FMA-1B (Fracture Mechanics Assembly-1B) irradiation assembly during FFTF Cycle 4. FMA-1B occupied FFTF Position 2705, (see Figure 1), and Cycle 4 ran for 109.5 equivalent full-power days. Figure 2 shows the FFTF ascent to full power, and after January 15, the reactor ran at essentially full power until April 23, 1984.

A typical irradiation canister is shown schematically in Figure 3. The canister can hold three "1T" Compact Type fracture toughness specimens, several tensile specimens, plus the appropriate dosimeters and thermal expansion devices (TEDs). In an alternative configuration, the canister can hold two "1T" fracture toughness and three fatigue-crack propagation specimens of the same "1T" planar dimensions, but only one-quarter as thick. The canisters, themselves, are of sheet metal construction and no welding is required in their assembly.

Sixteen such canisters are then assembled on to a stalk (Figure 4) that is then fitted within a ducted assembly as shown in Figure 5. Sodium coolant enters the assembly at the bottom (left-hand side in Figure 5) and exits at the top. The orifice plates (Figure 5) were set to achieve a nominal sodium flow rate of about 45 liters per minute.

The sixteen canisters are designated "A" through "P", with the upper canister "A" located at the right end of the assembly shown in Figure 4, and the lower canister "P" located at the left end as shown in Figure 4. The PNC specimens were located in canister "J", "K", "N", and "O". Individual specimen locations within each canister are shown in Table 1.

FTR CORE MAP

FIGURE 1. Location of Position 2705 in the FFTF.

FIGURE 2. Reactor Power During Cycle 4.

"1T" LEVEL PRIOR TO ASSEMBLY

FIGURE 3. Schematic of a Typical Canister Arrangement.

HEDL 7901-007.3

INNER STRUCTURE

FIGURE 4. Schematic of Canisters Attached to the Stalk and Handling Socket.

CONCEPTUAL FRACTURE-MECHANICS SPECIMEN ASSEMBLY TEST

HEDL 7908-140.4

FIGURE 5. Schematic of Fracture Mechanics Assembly (Exterior View).

TABLE 1

LOCATION OF PNC SPECIMENS WITHIN IRRADIATION CANISTERS FMA-1B ASSEMBLY

<u>Canister Number</u>	<u>TED Number</u>	<u>Fatigue Specimens</u>	<u>Toughness Specimens</u>	<u>Tensile Specimens*</u>
J			2740 2741 2742	T919
K	2H-31	2756 2757 2758	2743 2744	T920
N	2H-32		2745 2746 2747	T921
O		2759 2760 2761	2748 2749	T922

*The following tensile specimens (not a part of the PNC work)
were irradiated in Canister J: W3, W4, W7N, W8N, H303, H304.

Thermal Expansion Devices

Thermal expansion devices (TEDs) are sodium-filled capsules that can be used to determine the maximum temperature that a given location of an irradiation subassembly has been subjected to. The TED capsules are filled with sodium and "set" for a given temperature. If that temperature is subsequently exceeded, the capsule undergoes plastic deformation that, thereby, changes its overall density. With proper calibration, TEDs can indicate the maximum temperature achieved to within $\pm 5^{\circ}\text{C}$.

The "set temperature" of the TEDs employed was 359°C , and the nominal sodium temperature at the inlet to the subassembly (lower left-hand corner in Figure 5) is $361^{\circ}\text{C} \pm 1^{\circ}\text{C}$. TEDs were located in four canisters (including the PNC canisters "K" and "N") and the temperatures inferred from these TEDs are shown in Figure 6. The axial temperature distribution along the subassembly shown in Figure 6 is very close to that predicted prior to insertion into the reactor. Sodium enters the inlet to the subassembly at 361°C and exits the specimen irradiation at 452°C , with a smooth axial temperature gradient in between. It will be noted, however, that TED No. 2H-32 indicated a maximum temperature of 469°C . No unusually large masses were located in the vicinity of canister "N", and the temperature of 469°C is considered erroneous in view of the excellent agreement of the other measured temperatures with expected temperatures.* The reason for this TED producing an erroneous measurement is unknown at this time. However, the expected temperature of canister "N" was approximately 382°C , and it is felt that the actual temperature was probably close to that value.

*In addition, a TED located in canister "P" in FMA-1A indicated a maximum temperature of 374°C . FMA-1A was irradiated in FFTF position 2704 (adjacent to position 2705 used in the present study) in Cycle 2. This indication of 374°C for canister "P" gives added assurance that the 469°C indicated for canister "N" is incorrect.

FIGURE 6. Location and Readings of TEDs.

Dosimeters

Dosimeter capsules were included in each of the sixteen canisters in the FMA-1B experiment. The dosimeters were of two types: spectral sets and gradient sets. The spectral sets consist of twelve monitors each which have been selected to respond to differing energy ranges in order that accurate flux spectra and fluence can be determined. The following list indicates the dosimeter material, reaction and type of dosimeter for the spectral sets.

<u>Material</u>	<u>Reaction</u>	<u>Type</u>
Cu	$^{63}\text{Cu} (n, \alpha) ^{60}\text{Co}$	Threshold
Ti	$^{46}\text{Ti} (n, p) ^{46}\text{Sc}$	Threshold
Fe	$^{54}\text{Fe} (n, p) ^{54}\text{Mn}$	Threshold
Ni	$^{58}\text{Ni} (n, p) ^{58}\text{Co}$	Threshold
1% $^{237}\text{NpO}_2$ in MgO	$^{237}\text{Np} (n, f) \text{ F.P.}$	Threshold
Nb	$^{93}\text{Nb} (n, n) ^{93m}\text{Nb}$	Threshold
1% $^{235}\text{UO}_2$ in V	$^{235}\text{U} (n, f)$	Broad Spectrum
1% $^{239}\text{PuO}_2$ in MgO	$^{239}\text{Pu} (n, f)$	Broad Spectrum
0.1% ScO_2 in MgO	$^{45}\text{Sc} (n, \gamma) ^{46}\text{Sc}$	Broad Spectrum
Fe	$^{58}\text{Fe} (n, \gamma) ^{59}\text{Fe}$	Broad Spectrum
0.1% Co in MgO	$^{59}\text{Co} (n, \gamma) ^{60}\text{Co}$	Broad Spectrum
^6LiF	$^6\text{Li} (n, \text{total He})$	Broad Spectrum
NAT B	$^{10}\text{B} (n, \text{total He})$	Broad Spectrum

The gradient sets consist of Fe and Co monitors and are used to correlate between or extrapolate from spectral sets.

The dosimetry results are summarized in Table 2. Some interpretation was necessary in order to arrive at these results, and the interpretation is detailed in Appendix A. The neutron energy spectrum at the core midplane for a Row 7 reflector assembly is shown in Figure 7.

The uncertainty in total fluence and dpa at the spectral set location is 10% and 14% for fast fluence ($E > 0.1$ MeV). Uncertainty in thermal fluence

TABLE 2
SUMMARY OF DOSIMETRY RESULTS FOR FMA-1B

Canister Number	Fast Fluence (E > 0.1 MeV) n/cm ²	Thermal Fluence (E > 0.414 eV) n/cm ²	Total Fluence n/cm ²	dpa
A	4.15 + 21	6.70 + 17	9.01 + 21	1.32
B	5.92 + 21	7.22 + 17	1.17 + 22	2.06
C	7.55 + 21	1.30 + 18	1.45 + 22	2.75
D	9.25 + 21	1.08 + 18	1.71 + 22	3.46
E	1.06 + 22	8.63 + 17	1.92 + 22	4.05
F	1.18 + 22	8.63 + 17	2.11 + 22	4.52
G	1.27 + 22	9.87 + 17	2.25 + 22	4.95
H	1.33 + 22	1.08 + 18	2.31 + 22	5.16
I	1.36 + 22	1.11 + 18	2.37 + 22	5.29
J*	1.35 + 22	1.11 + 18	2.36 + 22	5.26
K*	1.31 + 22	1.09 + 18	2.30 + 22	5.08
L	1.22 + 22	1.01 + 18	2.16 + 22	4.63
M	1.07 + 22	8.82 + 17	1.97 + 22	3.97
N*	8.99 + 21	9.25 + 17	1.71 + 22	3.25
O*	7.07 + 21	1.15 + 18	1.39 + 22	2.67
P	4.76 + 21	1.23 + 18	1.04 + 22	1.51

*Canisters J, K, N, and O contained the PNC specimens.

is much greater since dosimetry response to thermal neutrons in FFTF is small and available calculations of thermal flux are not of high accuracy. Uncertainties at other locations will be greater, ranging up to 25%. Additional uncertainty must be added due to uncertainty in position of dosimetry and specimens. The adjustments made for dosimetry position are also discussed in Appendix A.

FIGURE 7. Neutron Energy Spectrum at Core Midplane for a Row 7 Reflector Assembly.

EXPERIMENTAL PROCEDURES

Material

The material utilized in this study was the 40-mm thick plate of SUS 304 stainless steel supplied by PNC. The chemical composition and mechanical properties for this material is shown in Table 3. Test specimens were machined by Westinghouse Hanford Company.

Tensile Testing

Miniature buttonhead tensile specimens (Figure 8) with a 2.86-cm gage length and 0.32-cm gage diameter were fabricated with the loading axis normal to the working direction (Figure 9). This orientation is consistent with the loading direction for the fracture mechanics tests. Tensile testing of unirradiated and irradiated specimens was performed on an Instron test machine at 400°C. For strains less than 2%, the nominal strain rate was 0.44%/min, and for strains greater than 2%, the strain rate was increased to 4.4%/min (strain rates were computed by dividing the crosshead rates [0.005 and 0.05 in./min] by the original reduced section length [1.125 in.]). Two unirradiated specimens were also tested at 427°C at a strain rate of 0.16%/min.

Conventional strain-gage load cells were used to determine load. Specimen extension was monitored by a dual LVDT extensometer* mounted on the specimen gage length (Figures 10 and 11) and by relative crosshead displacement. During the initial portion of the test (strains $\leq 2\%$), the applied load was plotted on an X-Y recorder as a function of the LVDT deflection. This plot was used to determine the yield strength level. At higher strains, the load and relative crosshead displacement were recorded on a strip chart. Ultimate strength was computed from the maximum load read from the strip

*Calibration records for the dual LVDT extensometer system are given in Appendix J.

TABLE 3

CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF PNC MATERIAL

Chemical Composition (%)														
C	Si	Mn	P	S	Ni	Cr	Cu	V	Co	Nb + Ta	B	Al	N	O
0.05	0.60	0.87	0.026	0.002	8.94	18.59	0.09	0.05	0.12	0.001	0.0005	0.015	0.0220	0.0048

Tensile Properties					
Temperature (°C)	0.2% Y.S. (kgf/mm ²)	V.T.S (kgf/mm ²)	El. (%)	Hardness HB	G.S. Number
RT	23	64	63	135	4.5
550	12	39	40		

Solution Heat Treatment: 1100°C x 48 min, W.Q.

GENERAL NOTES :

(UNLESS OTHERWISE SPECIFIED)

- 1 TOLERANCE DECIMAL ± 0.005
- 2 PARTS TO SHOW GOOD WORKMANSHIP, FREE FROM BURRS, UNMARRED AND CLEAN.
- 3 MACHINED SURFACES 63√ IN ACCORDANCE WITH ANSI B46.1 (LATEST REV)
- 4 ALL DIAMETERS CONCENTRIC WITHIN .002 TIR.
- 5 TAPERED GAGE SECTION BLEND DIAMETERS FROM RADIUS THROUGH CENTER TO RADIUS.

FIGURE 8. Tensile Specimen, Dimensions in Inches.

FIGURE 9. Arrangement of Specimens from Plate Supplied by PNC.

FIGURE 10. Extensometry Fixtures Attached to Tensile Specimen.

FIGURE 11- EXTENSOMETRY FIXTURES TRANSLATE THE SPECIMEN DISPLACEMENT OUTSIDE THE FURNACE WHERE IT IS MONITORED BY TWO LVDTs

chart. Uniform and total (chart) elongation values were obtained by combining the two load-displacement records at a common point and determining the plastic strain at maximum load and at fracture. Total (measured) elongation and reduction in area values were obtained from pre- and post-test specimen measurements. Specifically, the specimen halves were held together and the total length and minimum diameter were measured after each test. The pre- and post-test total length measurements (L_i and L_f , respectively) were used to compute total elongation:

$$\% \text{ total elongation} = \frac{L_f - L_i}{L_o} \times 100$$

where:

L_o = The length of the reduced section
(approximately 28.58 mm or 1.125 in.)

The pre- and post-test diameter measurements (d_i and d_f , respectively) were used to determine reduction of area:

$$\% \text{ reduction of area} = \frac{\frac{\pi d_i^2}{4} - \frac{\pi d_f^2}{4}}{\frac{\pi d_i^2}{4}} \times 100$$

A travelling microscope with an accuracy of 0.0025 mm (0.0001 in.) was used to determine all pre-test measurements and post-test measurements for unirradiated specimens. Post-test measurements for irradiated specimens were based on photographs (see Appendix E).

Fatigue-Crack Propagation Testing

The fatigue-crack propagation (FCP) specimens were machined from one of the 40 mm thick plates of SUS 304 supplied by PNC. The FCP specimens were

arranged as shown in Figure 9, and were taken from approximately the quarter-thickness plane. The FCP and fracture toughness specimens were oriented such that the specimens match and plane of crack extension is parallel to the working direction: i.e., a T-L orientation.* The FCP specimens were of the Compact Type (CT) design⁽¹⁰⁾ and nominal thickness ("B") and width ("W") dimensions of 6.28 mm and 50.8 mm, respectively. Actual specimen dimensions and test parameters are shown in Table 4. The specimens were pre-cracked following irradiation. The pre-cracking load was equal to the test load as given in Table 4.

All FCP tests were conducted using feedback-controlled electro-hydraulic testing machines (MTS Systems Corporation). The testing machines were operated in the load-controlled mode at a cyclic frequency of 1 Hz using a triangular loading waveform. The cyclic stress ratio ($R = K_{\min}/K_{\max}$) was 0.05 for all tests. Two FCP specimens were tested at each irradiation level, with a third specimen held in reserve in case it was needed. At each irradiation level, a different value of maximum load was employed for each of the two specimens tested (see Table 4). This allowed a wider range of ΔK to be characterized at each irradiation level.

All FCP specimens were tested in an air-circulating furnace at 400°C. Temperatures were controlled to within about $\pm 1^\circ\text{C}$. Tests on irradiated specimens were conducted within a hot cell. Crack lengths were optically determined periodically throughout each test. The furnace doors were opened for each crack length measurement. It is estimated that the specimens cooled about 60°C during each measurement. Measurements were made at the mean load. A travelling microscope was employed for the unirradiated specimens, while a high-resolution closed-circuit television system was employed

*In the ASTM system of designating crack orientations (see Reference 9) the first letter designates the direction of applied load and the second letter designates the direction of crack extension. T = transverse direction, L = longitudinal or working direction, and S = short transverse or thickness direction.

TABLE 4
SPECIMENS EMPLOYED IN THE FATIGUE-CRACK GROWTH STUDIES

Spec No.	Irradiation Level (dpa)	Thickness "B"		Width "W"		Maximum Cyclic Load	
		(mm)	(in.)	(mm)	(in.)	(N)	(lb)
2756*	5.08	6.284	0.2474	50.78	1.9991	--	--
2757	5.08	6.289	0.2476	50.76	1.9986	3336	750
2758	5.08	6.294	0.2478	50.78	1.9991	4448	1000
2759	2.67	6.281	0.2473	50.79	1.9995	4448	1000
2760	2.67	6.307	0.2483	50.79	1.9996	3336	750
2761*	2.67	6.289	0.2476	50.78	1.9992	--	--
2762	0	6.317	0.2487	50.75	1.9982	3336	750
2763	0	6.322	0.2489	50.78	1.9992	4448	1000
2764*	0	6.317	0.2487	50.69	1.9957	--	--

*Note: These specimens were not tested and were held in reserve to be used only if difficulties arose in the testing of the other specimens.

for the irradiated specimens.* The overall test set-up is pictured in Figure 12, and the camera controls and video output of the closed-circuit television system is shown in Figure 13. Crack lengths were measured using the "Video Micrometer" as shown in Figure 13. The video micrometer was calibrated prior to each reading by use of a steel scale which was clamped to the face of each specimen. Care was taken to ensure that the face of the scale and the face of the specimen were parallel to one another, and this was verified by noting that when the camera (in a fixed position) was focused on the scale the entire scale was in focus, and when it was focused on the specimens, the entire specimen was in focus. Two different testing machines were used: one for unirradiated specimens, and another for irradiated specimens. No difference is expected between results from the two machines because each is calibrated once each year by personnel from the MTS factory using U.S. National Bureau of Standards calibration load cells, and both load cells were well within the specified limits of $\pm 0.1\%$ load accuracy.

Absolute accuracy of optical crack length measurements is difficult to assess because all such measurements involve a certain degree of subjectivity- in other words, the operator must make a subjective decision as to the location of the crack tip. The resolutions of the optical microscope used on the unirradiated specimens, and the video micrometer used on the irradiated specimens were 0.00254 mm (0.0001 in.) and 0.0254 mm (0.001 in.), respectively. Taking into account the resolution of the systems, the subjectivity of such measurements, and the better lighting conditions available for unirradiated specimens, it is estimated that the accuracy of crack length measurements for the optical microscope and video micrometer systems is 0.0254 to 0.0508 mm (0.001 to 0.002 in.) and 0.0508 to 0.0762 mm (0.002 to 0.003 in.),

*The television system was not operating properly as testing was commencing on the last irradiated FCP specimen to be tested (Specimen 2757). Therefore, a travelling telemicroscope was employed through a leaded glass window to measure the crack lengths on Specimen 2757. The telemicroscope method has been used successfully on previous crack growth studies at Westinghouse Hanford Company (e.g., see Reference 21).

FIGURE 12- VIEW OF FATIGUE-CRACK GROWTH TEST SET FOR IRRADIATED SPECIMENS.

FIGURE 13 - PHOTOGRAPH OF CAMERA CONTROLS AND VIDEO OUTPUT FOR THE CLOSED-CIRCUIT TELEVISION SYSTEM USED TO MEASURE CRACK LENGTHS ON IRRADIATED SPECIMENS.

respectively. Previous tests using both measurement systems on the same specimen have shown that the resulting regression equations are the same within 5 to 6% over the range of values of ΔK tested.

The tests were conducted, and the resulting data was analyzed, in accordance with the provisions of ASTM Test Method E647-83.⁽¹⁰⁾ Fatigue-crack growth rates (da/dN) were calculated using the "secant method", one of two methods that is allowed by E647-83. The standard formula given in ASTM E647-83 was used to calculate the stress intensity factor (K). In a few cases, data was taken prior to the attainment of the minimum acceptable pre-crack length: 2.38 mm for the specimens employed. In these cases, such data was not included in formulating the crack growth equations. Data taken after a certain level of plasticity occurred in the remaining uncracked specimen ligament was also not included in formulating the crack growth equations. The point at which excessive plasticity developed in the remaining ligament on irradiated specimens was found using the relationship of ASTM E647-83⁽¹⁰⁾:

$$(W-a) \geq \frac{4}{\pi} \left(\frac{K_{\max}}{\sigma_y} \right)^2 \quad \text{Eq. [1]}$$

where σ_y is the 0.2% offset yield strength. Because cyclic work-hardening can significantly reduce crack-tip plasticity in annealed unirradiated austenitic stainless steels, a modification^(10,11) of Equation [1] is normally employed for such materials:

$$(W-a) \geq \frac{4}{\pi} \left(\frac{K_{\max}}{\sigma_f} \right)^2 \quad \text{Eq. [2]}$$

where the "flow stress" is defined by

$$\sigma_f = 0.5 (\sigma_y + \sigma_u) \quad \text{Eq. [3]}$$

and σ_u is the ultimate tensile strength. Therefore, Equation [1] was used for the irradiated specimens, and Equation [2] was employed for the unirradiated specimens.

The results were displayed as logarithmic plots of da/dN as a function of ΔK . Linear least-squares regression analyses were then conducted to produce crack growth equations of the form first proposed by Paris and Erdogan:⁽¹²⁾

$$\frac{da}{dN} = C(\Delta K)^n \quad \text{Eq. [4]}$$

where "C" and "n" are functions of the material and test conditions (e.g., temperature, cyclic frequency, stress ratio, etc.).

Fracture Toughness Testing

Fracture toughness specimens were machined from the 40-mm thick plates of SUS 304 supplied by PNC.* Specimen orientation is shown in Figure 9. The fracture specimens were of the CT design⁽¹³⁾ with a nominal thickness of 25.4 mm and width of 50.8 mm (Figure 14). Specimens were precracked to an $a/W \geq 0.6$ at a maximum stress intensity factor of approximately $22 \text{ MPa} \sqrt{\text{m}}$ (the precracking scheme for each specimen is given in Appendix B). Precracking was performed after the specimens were irradiated.

Fracture tests were performed on an electro-hydraulic closed loop machine in stroke control (stroke rate for irradiated specimens was 0.51 mm/min and for unirradiated specimens it was 1.3 mm/min. The two stroke rates were chosen so that the time to reach maximum load was approximately the same for both unirradiated and irradiated specimens. The 2.5-fold

*Irradiated specimens and unirradiated specimens tested at 427°C were taken from one plate, and the unirradiated specimens tested at 400°C were taken from the second plate.

GENERAL NOTES (UNLESS OTHERWISE SPECIFIED)

1. DIMENSIONING AND TOLERANCING PER ANSI Y14.5
TOLERANCES .XX $\pm$.01; .XXX $\pm$.005 ANGULAR $\pm$ 0°30'
2. ALL MACHINED SURFACES $\sqrt{2}$ IN ACCORDANCE
WITH ANSI B46.1 (LATEST REVISION)

FIGURE 14. Compact Specimen, Dimensions in Inches.

difference in stroke rate had no effect on fracture toughness results). Displacements were measured along the load line by a high-temperature LVDT displacement monitoring technique.⁽¹⁴⁾ This method utilized a rigid fixture attached to the specimen directly over the loading pin holes (i.e., fastened to two threaded holes machined along the specimen axis). This fixture translates the load-line displacement outside the loading clevises (Figure 15). The displacement is then monitored by two linear variable differential transformers (LVDT's) attached to the outer portion of the rigid fixture and centered on the load pin holes (Figure 16). The output from each LVDT is summed in series to eliminate any misalignment phenomena. During each test, the load-line displacement was recorded continuously on an X-Y recorder as a function of load.

The postirradiation J_{IC} fracture toughness was determined by the multiple-specimen J_R -curve technique, in accordance with ASTM Specification E813-81.⁽¹⁵⁾ Compact specimens were loaded to various displacements producing different amounts of crack extension, Δa , and then unloaded. After unloading, each specimen was heat tinted at 538°C to discolor the crack growth region and subsequently broken open so that the amount of crack extension could be measured. The value of J for each specimen was determined from the load versus load-line displacement curve by the following equation:⁽¹⁵⁾

$$J = \frac{2A}{Bb} \frac{(1 + \alpha)}{(1 + \alpha^2)} \quad \text{Eq. [5]}$$

where:

A = Area under load versus load-line displacement curve

b = Unbroken ligament size

$\alpha = [(2a/b)^2 + 2(2a/b) + 2]^{1/2} - (2a/b + 1)$

a = Crack length

B = Specimen thickness

FIGURE 15 - A RIGID FIXTURE TRANSLATES THE LOAD-LINE DISPLACEMENT OUTSIDE THE LOADING CLEVISES WHERE IT IS MONITORED BY TWO LVDTs

FIGURE 16 - LVDTs ARE CENTERED ALONG THE SPECIMEN LOAD-LINE.

The initial fatigue crack size and the final crack extension were measured at 17 evenly spaced locations* from one side to the other. The two surface measurements were averaged and this value was used with the remaining 15 measured values to determine the average initial crack size, a_0 , and amount of stable crack growth, Δa . A travelling microscope was used to measure crack lengths for the unirradiated specimens, and a high-resolution closed-circuit television system with a digital video micrometer was used for irradiated specimens. The video output for a broken specimen half is shown in Figure 17.

The J_R curves were constructed by plotting values of J as a function of Δa . The initiation J_C value was then taken to be that value where a least-squares regression line through the crack extension data points:

$$J = J_0 + \frac{dJ_R}{da} (\Delta a) \quad \text{Eq. [6]}$$

where J_0 and dJ_R/da are regression constants, intersected the stretch zone line:⁽¹⁵⁾

$$J = 2\sigma_f (\Delta a) \quad \text{Eq. [7]}$$

and σ_f is given by Equation [3].

The ASTM specimen size criteria for valid J_{IC} determination:⁽¹⁵⁾

$$B, b \geq 15 \frac{J}{\sigma_f} \quad \text{Eq. [8]}$$

*ASTM Specification E813 requires that the crack length parameters (a_p and Δa_p) be measured at nine or more evenly spaced locations. Seventeen locations were selected in this study to enable an accurate measure of Δa_p , particularly for specimens that exhibited uneven crack extension.

FIGURE 17. Photograph of Closed-Circuit Television System Output Used for Measuring Average Crack Length and Crack Extension for J-Integral Specimens.

and

$$B, b \geq 25 \frac{J_{IC}}{\sigma_f} \quad \text{Eq. [9]}$$

were met for all irradiated specimens.

The fracture toughness response for the unirradiated material was determined at 400° and 427°C by the multiple-specimen J_R -curve technique, but the analysis methods differed slightly from those given in ASTM Specification E813-81. The ASTM procedures were established based on fracture toughness results for intermediate and high strength steel and titanium alloys with very limited strain-hardening capacities. Consequently, these testing and analysis procedures are not strictly applicable to high-ductility, high-toughness alloys, such as austenitic stainless steels. Test methods for the unirradiated material were based on other studies performed at WHC for similar solid-solution Fe-Ni-Cr alloys. The J_R curve was obtained by fitting a linear regression line through crack extension data points falling between the 0.25- and 2.0-mm exclusion lines (as defined by two lines parallel to the stretch zone line, but offset 0.25 and 2.0 mm). Data points falling outside these exclusion limits are denoted by a vertical slash. The minimum limit is designed to exclude from the regression analysis the non-linear behavior that occurs at the onset of crack extension, which is consistent with the ASTM approach. The 0.25-mm limit is slightly larger than the ASTM recommended limit of 0.15 mm because stainless steel alloys tend to exhibit slightly more initial rounding of the J_R curve, relative to the higher strength alloys used to establish the ASTM procedure.

To minimize potential nonlinear behavior at high crack extension values, the ASTM procedure excludes data beyond 1.5 mm from the blunting line. However, a previous study⁽¹⁶⁾ demonstrated that J_R curves for stainless steel alloys remain linear well beyond the ASTM limit. Hence, a 2.0-mm exclusion limit was employed because it provided a linear J_R curve.

The initiation J_c fracture toughness for the unirradiated material was taken to be the value of J at the intersection of the least squares regression line through the crack extension data points Equation [6] and the stretch zone line for low-strength, high strain-hardening materials:⁽¹⁷⁾

$$J = 4 \sigma_f (\Delta a) \quad \text{Eq. [10]}$$

The initiation toughness values are termed J_c rather than J_{IC} , because they are not in complete accordance with ASTM test procedures.

The variances of J_c and dJ_R/da (S_1^2 and S_2^2 , respectively) were determined from statistical analysis of the J_R -curve data using the following equations:

$$S_1^2 = S^2 \left\{ \frac{1}{n} + \frac{[J_c/(2m\sigma_f) - \bar{a}]^2}{\sum_{i=1}^n (\Delta a_i - \bar{a})^2} \right\} \quad \text{Eq. [11]}$$

and

$$S_2^2 = \frac{S^2}{\sum_{i=1}^n (\Delta a_i - \bar{a})^2} \quad \text{Eq. [12]}$$

where:

n = Number of data pairs being analyzed

$\bar{a}$ = Mean value of Δa

S^2 = Sample estimate of the variance of J , given by

$$S^2 = \frac{\sum_{i=1}^n \left[J_i - J_0 - \frac{dJ_R}{da} (\Delta a_i) \right]^2}{n - 2}$$

m = Constraint factor: m = 1 for irradiated material and m = 2 for unirradiated material (17)

Values of $J_C \pm S_1$ and $dJ_R/da \pm S_2$ are reported for each J_R curve.

Values of the tearing modulus, T, were determined using the following equation: (18)

$$T = \frac{dJ_R}{da} \frac{E}{\sigma_f^2} \quad \text{Eq. [13]}$$

where

E = Elastic modulus (E = 168,000 MPa or 24,400 ksi at 400°C;
E = 166,000 MPa or 24,100 ksi at 427°C)

An attempt was made to use the single-specimen unloading-compliance method to determine J_C for the irradiated material. However, the extensive rotation and high ductility exhibited by the irradiated specimens precluded meaningful single-specimen J_C determination. Large specimen rotation caused an over-estimation of crack extension at low J values which resulted in overly pessimistic J_C values. Therefore, the standard multiple-specimen J_R -curve method was selected for characterizing the postirradiation fracture toughness because it provided more accurate results. The unloading-compliance procedures and a compilation of the test results are detailed in Appendix C.

Metallographic and Fractographic Examination

Metallographic specimens were prepared for optical microscopic examination using standard metallographic procedures. To reveal the general microstructure, specimens were electrolytically etched in a 10% oxalic acid solution.

Fracture surface morphologies were characterized by direct fractographic examination on an SEM operated at an accelerating potential of 25 kV. To relate fracture surface appearance to key microstructural features, selected areas of fracture surfaces were electropolished so that the fracture surface and underlying microstructure could be studied simultaneously. This technique, originally developed by Chesnutt and Spurling,⁽¹⁹⁾ utilized a protective lacquer applied to portions of the fracture surface that were to remain intact during the electropolishing process. The exposed surface was then electropolished in the following electrolyte: 25 gr CrO_3 , 7 ml water, and 130 ml acetic acid. When electropolishing was completed, specimens were cleaned ultrasonically in acetone to remove the protective lacquer from the unexposed fracture surface. Examination of the interfacial region between the original fracture surface and the electropolished region revealed both the fracture surface topography and the underlying microstructural features.

RESULTS AND DISCUSSION

Tensile Tests

Tensile properties for the SUS 304 plate are summarized in Table 5. Specimen dimensions and test data are tabulated in Appendix D. Photographs of the test specimens and fracture surfaces for the irradiated material are given in Appendix E.

Neutron irradiation is seen to cause considerable strengthening. Figures 18 to 20 reveal that postirradiation tensile properties for the PNC material were consistent with previously obtained strength values for irradiated 304 SS.⁽²⁰⁾

Fatigue-Crack Propagation Tests

Fatigue-crack propagation (FCP) tests were conducted as detailed in the previous section on Experimental Procedures. As previously described, crack lengths were periodically determined throughout each test as a function of the number of cycles. These data are plotted in Appendix F. In two of the tests (Specimens 2758 and 2760) lighting conditions and the specimen surface condition prevented accurate crack length measurements in the early phases of the tests. In a third test (Specimen 2757), a temporary malfunction of the cycle counting mechanism caused an interruption of the continuous crack length versus cycles curve (Figure F1).

The raw data (i.e., crack length and cycles) and calculated results (i.e., da/dN and ΔK) are given in Appendix G. Four of the tests (Specimens 2758, 2760, 2762, and 2763) have asterisks shown beside some of the longer crack lengths. These are data where either Equations [1] or [2] were violated. As previously mentioned, such data were not included in formulating the crack growth equations.

TABLE 5
SUMMARY OF TENSILE PROPERTIES

Spec	Temp. (°C)	Neutron Exposure (dpa)	Fast Fluence [E > 0.1 MeV] (10 ²² n/cm ²)	Thermal Fluence (10 ¹⁸ n/cm ²)	Total Fluence (10 ²² n/cm ²)	Strain Rate %/min	Yield Strength		Ultimate Tensile Strength		Uniform Elongation (%)	Total Elongation Chart (%)	Total Elongation Measured (%)	Reduction in Area (%)
							(Mpa)	(ksi)	(Mpa)	(ksi)				
T950	400	0	0	0	0	0.44/4.4*	130	18.9	423	61.4	31	35	36	79
T951	400	0	0	0	0	0.44/4.4	149**	21.6**	415	60.2	31	36	37	64
T923	427	0	0	0	0	0.16	150	21.7	447	64.8	35	40	41	80
T925	427	0	0	0	0	0.16	152	22.1	453	65.7	35	41	41	73
T919	400	5.3	1.35	1.11	2.36	0.44/4.4	593	86.0	640	92.8	2	5	7	44
T920	400	5.1	1.31	1.09	2.30	0.44/4.4	613	88.9	634	91.9	2	5	7	44
T921***	400	3.3	0.90	0.93	1.71	0.44/4.4	555	80.5	599	86.9	3	9	7	44
T922***	400	2.7	0.71	1.15	1.39	0.44/4.4	449	65.1	535	77.5	8	12	11	44

*Strain rate was 0.44%/min for strains ≤2% and 4.4%/min for strains ≥2%.

**Based on Instron chart. The extensometer slipped during the initial portion of the test, thereby invalidating the load-displacement curve. As a result, the yield strength level for Specimen T951 was determined from the Instron chart. Results from other tests demonstrate that yield strength values calculated using the extensometry versus Instron load-displacement records differed by less than 5%.

***Specimens T922 and T921 broke outside the gage length region. The test results are considered valid, however, because failure occurred within the reduced section.

FIGURE 18. Comparison of Postirradiation Yield Strength Levels for PNC SUS 304 Plate with Results Obtained Previously for 304 SS and 304L SS.(20)

FIGURE 19. Comparison of Postirradiation Ultimate Strength Levels for PNC SUS 304 Plate with Results Obtained Previously for 304 SS and 304L SS.(20)

FIGURE 20. Comparison of Postirradiation Total Elongation Values from PNC SUS 304 Plate with Results Obtained Previously for 304 SS and 304L SS.(20)

The results of this study are plotted in Figure 21 for the unirradiated tests, and in Figures 22 and 23 for the irradiated tests. A linear least-squares regression line is fitted through each set of results in Figures 21 through 23, and equations of the form of Equation [4] are also shown. It will be noted, comparing Figures 22 and 23, that the crack growth equations for the two different irradiation levels are quite similar.

The results for the unirradiated and irradiated specimens are compared in Figure 24. Since results for the two different irradiation levels were essentially identical, they are combined in Figure 24 for purposes of comparison. Although there is some overlap in the scatter bands of the two data sets, at a given value of ΔK , FCP rates in the irradiated specimens are generally slightly lower than those in the unirradiated specimens. The fatigue-crack growth rate equation for all of the irradiated specimens (Specimens 2757, 2758, 2759, and 2760) is:

$$\frac{da}{dN} = 3.071 \times 10^{-9} (\Delta K)^{3.251}$$

where da/dN is in mm/cycle and ΔK is in MPa $\sqrt{\text{m}}$.

The results of the present study are also compared in Figure 25 with those for a similar study (Reference 21) where no effect of irradiation was noted. FCP rates on the PNC specimens are somewhat lower than their counterparts from Reference 21, and there are two probable reasons for this: 1) the tests of Reference 21 were run at a somewhat higher temperature (427°C), and FCP rates generally increase with increasing temperature,⁽²²⁾ and 2) the tests of Reference 21 were run at a slightly lower frequency (0.667 Hz), and FCP rates generally increase with decreasing frequency.^(22,23)

A number of studies have been conducted to determine the effect of neutron irradiation upon the FCP behavior of austenitic stainless steels, and these have been summarized in a review article.⁽²⁴⁾ The most generally observed trend is that, when irradiation and test temperatures are in the

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FIGURE 21. Results for Fatigue-Crack Propagation Tests Conducted on Unirradiated SUS 304 Stainless Steel.

HEDL 8505-033.2

FIGURE 22. Results for Fatigue-Crack Propagation Tests Conducted on SUS 304 Irradiated to 2.7 dpa.

HEDL 8505-033.3

FIGURE 23. Results for Fatigue-Crack Propagation Tests Conducted on SUS 304 Irradiated to 5.1 dpa.

HEDL 8505-033.5

FIGURE 24. The Effect of Irradiation Upon the Fatigue-Crack Propagation Behavior of SUS 304 Stainless Steel.

HEDL 8505-033.6

FIGURE 25. Comparison of the Results of the Present Study with Those of an Earlier Study (Reference 21).

range of 400 to 427°C, FCP rates in irradiated material are equal to, or lower than, those in unirradiated material. Hence, the trends observed in the present study are in general agreement with those of previous studies.

Fracture Toughness Tests

Fracture toughness results for unirradiated and irradiated materials are detailed in Table 6 and in Figure 26. Individual load-displacement records are given in Appendix H and photographs of fracture surfaces for irradiated specimens are shown in Appendix I.

In the unirradiated condition, the SUS 304 plate exhibited exceptionally high fracture resistance at both 400 and 427°C. Values of J_C ranged from 1418 ± 33 to 1094 ± 211 kJ/m² and tearing moduli ranged from 956 to 640. The substantial scatter exhibited at 427°C was associated with variations in the crack front symmetry during stable crack extension. The three specimens that fell below the 427°C J_R curve exhibited uneven crack extension (i.e., excessive crack extension occurred on one side of each specimen, Figure 27). This behavior was attributed to a non-uniform microstructure, as described in the next section. By contrast, final crack fronts for the three specimens that lie above the J_R curve were more symmetric (Figure 28). Specimens tested at 400°C displayed relatively uniform crack extension (Figure 29). The fracture toughness response for these specimens was similar to that exhibited by the three specimens tested at 427°C that displayed symmetric stable tearing regions. Localized regions with inferior fracture resistance apparently degraded the overall fracture toughness response for Specimens 2751, 2752 and 2753; however, the fracture properties for these specimens are still very high relative to that for most structural alloys.

Figure 26 reveals that neutron irradiation caused a marked reduction in fracture toughness, but the effects of exposure level between 2.7 and 5.3 dpa could not be distinguished. Based on previous unpublished results, the fracture toughness at 5.3 dpa was expected to be somewhat lower than that at 2.7 dpa. The reason for the absence of a systematic variation of fracture

TABLE 6
SUMMARY OF FRACTURE TOUGHNESS RESULTS

Specimen Number	Neutron Exposure dpa	Thickness		Width		Notch		Crack Length-a ⁹		Crack Length Max. Deviation ^a %
		mm	(inch)	mm	(inch)	mm	(inch)	mm	(inch)	
2740	5.3	25.34	(0.9978)	50.78	(1.9994)	22.21	(0.8743)	32.45	(1.2774)	9
2741	5.3	25.35	(0.9979)	50.81	(2.0004)	22.13	(0.8712)	30.57	(1.2034)	6
2742	5.3	25.34	(0.9975)	50.81	(2.0003)	22.12	(0.8708)	30.44	(1.1984)	4
2743	5.1	25.35	(0.9980)	50.70	(1.9996)	22.25	(0.8761)	31.74	(1.2498)	7
2744	5.1	25.32	(0.9470)	50.83	(2.0010)	22.25	(0.8758)	31.14	(1.2261)	5
2745	3.3	25.38	(0.9992)	50.79	(1.9997)	22.08	(0.8694)	30.40	(1.1970)	4
2746	3.3	25.34	(0.9977)	50.81	(2.0003)	22.26	(0.8763)	30.25	(1.1911)	3
2747	3.3	25.32	(0.9970)	50.80	(2.0001)	22.27	(0.8768)	30.17	(1.1876)	3
2748	2.7	25.33	(0.9972)	50.80	(2.0000)	22.28	(0.8770)	30.64	(1.2064)	3
2749	2.7	25.33	(0.9971)	50.80	(1.9999)	22.28	(0.8773)	30.51	(1.2012)	3
51	2943	--	25.50 (1.0039)	50.82	(2.0007)	22.36	(0.8802)	32.90	(1.2951)	6
	2944	--	25.50 (1.0039)	50.82	(2.0009)	22.37	(0.8806)	33.18	(1.3062)	6
	2945	--	25.50 (1.0039)	50.79	(1.9997)	22.35	(0.8798)	32.29	(1.2713)	6
	2946	--	25.50 (1.0040)	50.82	(2.0008)	22.39	(0.8815)	31.50	(1.2940)	6
	2947	--	25.50 (1.0041)	50.85	(2.0020)	22.41	(0.8823)	33.31	(1.3116)	5
2750	--	25.38	(0.9991)	50.82	(2.0007)	22.56	(0.8880)	32.54	(1.2811)	4
2751	--	25.39	(0.9995)	50.79	(1.9995)	22.29	(0.8777)	32.72	(1.2883)	5
2752	--	25.39	(0.9998)	50.80	(1.9999)	22.27	(0.8769)	32.77	(1.2904)	5
2753	--	25.38	(0.9991)	50.79	(1.9998)	22.26	(0.8765)	31.78	(1.2513)	4
2754	--	25.38	(0.9991)	50.80	(2.0000)	22.29	(0.8777)	32.19	(1.2672)	4
2755	--	25.38	(0.9994)	50.77	(1.9990)	22.24	(0.8755)	32.32	(1.2725)	5

^aMaximum deviation of a single crack length value from the average crack length

TABLE 6 (Continued)

SUMMARY OF FRACTURE TOUGHNESS RESULTS

Specimen Number	Neutron Exposure dpa	Test Temp. (°C) (°F)	t_p^a min	Loading Rate - P		Area ^b		J		Δa	
				kN/min	(lb/min)	J	(in-lb)	kJ/m ²	(in-lb/in ²)	mm	(inch)
2740	5.3	400 (752)	1.4	12	(2600)	73.3	(649)	345.9	(1975)	1.016	(0.0400)
2741	5.3	400 (752)	1.7	12	(2800)	55.6	(492)	239.7	(1369)	0.417	(0.0164)
2742	5.3	400 (752)	1.6	12	(2700)	91.1	(806)	390.5	(2230)	1.806	(0.0711)
2743	5.1	400 (752)	1.5	12	(2600)	89.3	(790)	406.5	(2321)	2.174	(0.0856)
2744	5.1	400 (752)	1.6	12	(2700)	58.2	(515)	257.4	(1470)	0.488	(0.0192)
2745	3.3	400 (752)	1.6	12	(2700)	61.1	(541)	261.8	(1495)	0.986	(0.0388)
2746	3.3	400 (752)	1.6	12	(2800)	76.0	(673)	323.5	(1847)	1.346	(0.0593)
2747	3.3	400 (752)	1.6	12	(2600)	115.0	(1018)	487.6	(2784)	1.603	(0.0631)
2748	2.7	400 (752)	1.5	12	(2600)	48.1	(426)	208.6	(1191)	0.472	(0.0186)
2749	2.7	400 (752)	1.4	12	(2700)	128.0	(1133)	551.5	(3149)	1.737	(0.0684)
2943	--	400 (752)	0.5	19	(4200)	350.6	(3103)	1677.9	(9581)	1.806	(0.0711)
2944	--	400 (752)	0.4	20	(4600)	376.0	(3328)	1825.3	(10423)	2.261	(0.0890)
2945	--	400 (752)	0.7	12	(2600)	225.0	(1991)	1046.0	(5973)	0.861	(0.0339) ^c
2946	--	400 (752)	0.4	22	(4900)	501.3	(4437)	2395.6	(13679)	3.459	(0.1362)
2947	--	400 (752)	0.4	20	(4600)	427.9	(3787)	2088.7	(11927)	2.776	(0.1093)
2750	--	427 (800)	0.5	18	(4100)	357.9	(3168)	1690.8	(9655)	2.177	(0.0857)
2751	--	427 (800)	0.5	19	(4200)	246.9	(2185)	1178.4	(6729)	1.666	(0.0656)
2752	--	427 (800)	0.4	20	(4500)	371.2	(3285)	1774.6	(10133)	3.490	(0.1374)
2753	--	427 (800)	0.5	20	(4400)	459.2	(4064)	2092.8	(11950)	4.036	(0.1589)
2754	--	427 (800)	0.5	19	(4200)	393.4	(3482)	1828.1	(10439)	2.581	(0.1016)
2755	--	427 (800)	0.4	20	(4500)	491.3	(4348)	2299.8	(13132)	3.868	(0.1523)

^a t_p = time to reach first deviation from linearity^b Area under load-displacement curve^c Crack tip blunting

FIGURE 26. J_R Curves for Unirradiated and Irradiated SUS 304. Note that the stretch zone line for low-strength, high-strain hardening materials, $J = 4 \sigma_f (\Delta a)$, accurately predicted the apparent crack extension in Specimen 2945 (triangle with a vertical slash). This specimen was not included in the J_R -curve least-squares regression.

FIGURE 27 - The Three Specimens That Fell Below the 427°C J_R Curve Exhibited Excessive Crack Extension on One Side of the Specimen

- (a) Specimen 2751
- (b) Specimen 2752
- (c) Specimen 2753

FIGURE 28 - The Three Specimens Tested at 427°C That Fell Above the J_R Curve Displayed Symmetric Stable Tearing Regions.

- (a) Specimen 2755
- (b) Specimen 2750
- (c) Specimen 2754

FIGURE 29 - Specimen Tested at 400°C Exhibited Rather Uniform Crack Extension Regions

- (a) Specimen 2943
- (b) Specimen 2944
- (c) Specimen 2947
- (d) Specimen 2946

toughness with neutron exposure in the PNC material is unclear. It is possible that material variability coupled with irradiation exposure gradients within each canister may have masked the effects of exposure level. Because there was no systematic variation of fracture toughness with irradiation level, postirradiation data for exposures ranging from 2.7 to 5.3 dpa were combined into a single J_R curve. The J_C initiation toughness for the irradiated material was $198 \pm 46 \text{ kJ/m}^2$ and the tearing modulus was 71.

Two of the specimens included in the postirradiation J_R curve did not meet ASTM specifications. Specimen 2743 fell outside the ASTM exclusion limit, and Specimen 2740 exhibited an unusual amount of tunneling (i.e., the maximum deviation of a single crack length measurement from the average crack length a_0 (9%) exceeded the ASTM 7% limit). Excluding these two specimens from the J_R -curve regression decreased the postirradiation J_C value by 15%, but it increased the tearing resistance by 20%;

$$J_{ic} = 169 \pm 51 \text{ kJ/m}^2$$

$$(963 \pm 291 \text{ in.-lb/in.}^2)$$

$$dJ_R/da = 175 \pm 45 \text{ Mpa}$$

$$25 \pm 7 \text{ ksi}$$

$$T = 88$$

Irradiation is seen to cause a seven-fold decrease in J_C initiation toughness and a two-fold decrease in dJ_R/da . The irradiation-induced reduction in J_R -curve slope coupled with the two-fold increase in flow strength resulted in an order of magnitude reduction in tearing modulus. Although the fracture resistance is significantly reduced by irradiation to 2 to 5 dpa, it is still relatively high, when compared to that for most structural alloys. Moreover, the postirradiation toughness is expected to be sufficient to preclude non-ductile failure for structures subjected to moderate neutron irradiation levels.

The variability in fracture toughness behavior for the irradiated material, like that for the unirradiated alloy, was associated with differences

in crack front symmetry. The five irradiated specimens falling below the J_R curve displayed uneven amounts of crack extension across the thickness, whereas the five specimens with superior fracture resistance exhibited more symmetric stable tearing regions (see Appendix I).

Microstructure and Fracture Mechanisms

Metallographic and fractographic examination of the unirradiated material revealed that the inferior fracture resistance and non-symmetric crack extension displayed by Specimens 2751, 2752 and 2753 were associated with an uneven distribution of second phase particles. A high density of large inclusions aligned in the primary working direction (Figures 30a and 31a) was located in regions that exhibited large amounts of crack extension. Outside these regions, inclusions were rather sparse and randomly distributed (Figures 30b and 31b). Delta ferrite stringers were observed throughout the matrix, but this second phase did not have a significant influence on the overall fracture response.

Operative fracture mechanisms included elongated tear ridges (Figure 32) and microvoid coalescence (Figure 33). The elongated tear ridges were oriented in the primary working direction and were generally confined to the regions that exhibited unusually large amounts of crack extension. They resulted from a localized failure of the second phase inclusions aligned in the primary rolling direction. Early in the plastic straining process, the inclusions failed and created elongated voids ahead of the advancing crack front. These voids were then subjected to intense plastic deformation which resulted in the formation of elongated tear ridges.

Examination of the fracture surface macromorphology in the excessive crack extension regions revealed a high density of heat-tinted tear ridges extending beyond the overall heat-tinted zone. This demonstrated that the elongated voids nucleated ahead of the advancing crack front. Moreover, the premature formation of tear ridges degraded the local fracture resistance, which accounts for the inferior fracture toughness displayed by Specimens 2751, 2752 and 2753.

FIGURE 30. Unetched Metallographic Profiles of Specimen 2753. (a) Evidence of second phase inclusions aligned in the rolling direction. This sample was located at the 1/4 T position directly beneath the excessive crack extension region. (b) A sparse distribution of randomly distributed inclusions located at the 1/4 T position on the opposite side of Specimen 2753.

FIGURE 31. Typical Microstructures for Specimen 2753. (a) Second phase inclusions and delta ferrite stringers aligned in the primary working direction. This micrograph was taken from the 1/4 T position directly beneath the excessive tearing zone. (b) Typical delta ferrite morphology located at the 1/4 T position directly below the normal tearing region.

FIGURE 32. SEM Fractographs Illustrating Elongated Tear Ridges in (a) Specimen 2752, (b) Specimen 2753.

FIGURE 33. SEM Fractographs Illustrating Equiaxed Microvoid Coalescence
 (a) Near the 1/2 T position of Specimen 2753. Note the steep wall covered with stretch markings in the lower right corner.
 (b) Specimen 2755 which exhibited a symmetric heat-tinted zone.

The variability in fracture toughness response for the irradiated material may also be associated with a non-uniform distribution of inclusions. It was noted that the five irradiated specimens with inferior fracture resistance displayed uneven amounts of crack extension across the thickness. In all likelihood, the excessive crack growth at the 1/4 T position was associated with premature elongated void formation.

A conventional microvoid coalescence mechanism was operative in specimens with symmetric heat-tinted zones and outside the excessive crack extension regions in Specimens 2751, 2752 and 2753. Stereo fractography revealed that regions containing equiaxed dimples were separated by steep ledges containing stretch markings. These features indicate that tremendous amounts of plastic deformation were required during the material separation process, which accounts for the exceptionally high fracture resistance displayed by this heat of SUS 304.

The delta ferrite stringers initiated numerous small secondary dimples, as illustrated at the metallographic-fractographic interface shown in Figure 34. However, the presence of this phase did not adversely affect the overall fracture resistance because these secondary dimples formed during the final stages of the fracture process. The ferrite particles accommodated some plastic deformation, so it was resistant to fracture and decohesion from the matrix. Hence, failure of the delta ferrite phase occurred during the final stages of fracture as the primary microvoids coalesced. Indeed, secondary dimples nucleated by delta ferrite particles were often located along the primary dimple cusps (Figure 34).

FIGURE 34. Metallographic-Fractographic Interface for Specimen 2752. Note that the row of delta ferrite particles in the center of the fractograph nucleated a series of small secondary dimples that were located between two primary dimples.

SUMMARY AND CONCLUSIONS

The effects of fast-neutron irradiation on the tensile, fatigue-crack growth and fracture toughness properties for SUS 304 plate were characterized at 400°C, and the results are summarized below:

1. The degree of irradiation-induced strengthening exhibited by the PNC material was consistent with that exhibited in previous studies of irradiated 304 SS. Irradiation to 3 dpa caused a two-fold increase in yield strength and a three-fold reduction in total elongation. At 5 dpa, the yield strength was increased by a factor of 5 and total elongation was reduced by a factor of 7.
2. Fatigue-crack propagation tests conducted at a cyclic frequency of 1 Hz and a stress ratio (R) of 0.05 showed that there was a slight decrease in fatigue-crack growth rates in the irradiated specimens relative to the behavior of unirradiated specimens. The irradiation levels were approximately 2.7 dpa and 5.1 dpa, and there were no apparent differences in crack growth rates between the two different irradiation levels. Fatigue-crack growth rates in both unirradiated and irradiated materials from the present study are slightly lower than their counterparts from a previous study on similar materials. These differences are believed to be due to minor differences in test temperatures and cyclic frequencies between the two studies.
3. In the unirradiated condition, the SUS 304 plate displayed exceptionally high fracture resistance with J_c values ranging from 1094 to 1418 kJ/m². In addition, the high tearing modulus ($T = 640$ to 956) demonstrated that this material is very resistant to unstable tearing at J levels well above J_c .
4. Neutron irradiation exposures of 3 to 5 dpa caused a seven-fold degradation in J_c (169 kJ/m²) and an order of magnitude reduction in tearing modulus ($T = 88$). No systematic variation in fracture toughness

behavior was observed with increasing irradiation damage. Apparently, material variability masked any correlation between fracture toughness degradation and neutron exposure. Although the fracture toughness was markedly reduced by irradiation exposures of 3 to 5 dpa, the material retained adequate fracture resistance for precluding any possibility of non-ductile fracture.

5. Extensive variability in the fracture resistance of the unirradiated material was attributed to a non-uniform distribution of second phase particles throughout the matrix. Specifically, second phase inclusions aligned in the rolling direction initiated elongated tear ridges ahead of the advancing crack front. The presence of these tear ridges in regions containing a high density of particles degraded the local fracture resistance, thereby accounting for the inferior fracture toughness displayed by some specimens. The same mechanism is believed to be responsible for the pronounced variability in the postirradiation fracture toughness behavior.

REFERENCES

1. ASME Boiler and Pressure Vessel Code, American Society of Mechanical Engineers, 1983.
2. L. A. James, "Estimation of Crack Extension in a Piping Elbow Using Fracture Mechanics Techniques," Journal of Pressure Vessel Technology, Vol. 96, 1974, pp. 273-278.
3. L. A. James, "Fatigue-Crack Propagation Analysis of LMFBR Piping," Coolant Boundary Integrity Considerations in Breeder Reactor Design, Series PVP-PB-027, American Society of Mechanical Engineers, pp. 39-53, 1978.
4. F. J. Loss and R. A. Gray, "Toughness of Irradiated 316 SS Forging and Weld Metal Using the J-Integral," Irradiation Effects on Reactor Structural Materials, February 1 - July 31, 1974, NRL Memorandum Report 2875, Naval Research Laboratory, Washington, D. C. pp. 23-30, August 1974.
5. J. Dufresne, B. Henry and H. Larsson, "Fracture Toughness of Irradiated AISI 304 and 316L Stainless Steels," Effects of Radiation on Structural Materials, ASTM STP 683, American Society for Testing and Materials, Philadelphia, PA, pp. 511-528, 1979.
6. M. F. Kanninen, A. Zahoor, G. Wilkowski, I. Abou-Sayed, C. Marshall, D. Broek, S. Sampath, H. Rhee, and J. Ahmad, Instability Predictions for Circumferentially Cracked Type 304 Stainless Steel Pipes Under Dynamic Loading Volume 1, EPRI NP-2347, Battelle Columbus Laboratories, Columbus, OH, 1982.
7. A. Zahoor and M. F. Kanninen, "A Plastic Fracture Mechanics Prediction of Fracture Instability in a Circumferentially Cracked Pipe in Bending--Part I: J-Integral Analysis," Journal of Pressure Vessel Technology, Vol. 103, 1981, pp. 352-358.
8. G. M. Wilkowski, A. Zahoor and M. F. Kanninen, "A Plastic Fracture Mechanics Prediction of Fracture Instability in a Circumferentially Cracked Pipe in Bending--Part II: Experimental Verification on a Type 304 Stainless Steel Pipe," Journal of Pressure Vessel Technology, Vol. 103, 1981, pp. 359-365.
9. "Standard Terminology Relating to Fracture Testing," Designation: E616-82, 1984 Annual Book of ASTM Standards, Vol. 03.01, pp. 671-684, American Society for Testing and Materials, Philadelphia, 1984.
10. "Standard Test Method for Constant-Load-Amplitude Fatigue Crack Growth Rates Above 10^8 m/cycle," Designation: E647-83, *ibid.*, pp. 711-731.

REFERENCES (Cont'd)

11. L. A. James, "Specimen Size Considerations in Fatigue-Crack Growth Rate Testing," Fatigue Crack Growth Measurement and Data Analysis, ASTM STP 738, pp. 45-57, American Society for Testing and Materials, Philadelphia, 1981.
12. P. Paris and F. Erdogan, "A Critical Analysis of Crack Propagation Laws," Journal of Basic Engineering, Vol. 85, No. 4, 1963, pp. 528-534.
13. ASTM Standard, Plane-Strain Fracture Toughness of Metallic Materials," ASTM E399-83, Volume 03.01, American Society for Testing and Materials, pp. 514-554, 1984.
14. W. J. Mills, L. A. James and J. A. Williams, "A Technique for Measuring Load-Line Displacements of Compact Ductile Fracture Toughness Specimens at Elevated Temperatures," Journal of Testing and Evaluation, Vol. 5, No. 6, 1977, pp. 446-451.
15. ASTM Standard, "J_{ic}, a Measure of Fracture Toughness," ASTM E813-81, Vol. 03.01, American Society for Testing and Materials, pp. 763-781, 1984.
16. W. J. Mills, Effect of Specimen Size on the Fracture Toughness of Type 304 Stainless Steel - Interim Report, HEDL-TME 81-52, Westinghouse Hanford Company, Richland, WA, February 1982.
17. W. J. Mills, "On the Relationship Between Stretch Zone Formation and the J-Integral for High Strain-Hardening Materials," Journal of Testing and Evaluation, Vol. 9, pp. 56-62, 1981.
18. P. C. Paris, H. Tada, A. Zahoor and H. Ernst, "The Theory of Instability of the Tearing Mode for Elastic-Plastic Crack Growth," Elastic-Plastic Fracture, ASTM ASTP 668, American Society for Testing and Materials, Philadelphia, PA, pp. 5-36, 1979.
19. J. C. Chesnutt and R. A. Spurling, "Fracture Topography Microstructure Correlations in the SEM," Metallurgical Transactions, Vol. 8A, 1977, pp. 216-218.
20. L. D. Blackburn, A. L. Ward and J. M. Steichen, "Ductility of Irradiated Type 304 and 316 Stainless Steels," Radiation Effects in Breeder Reactor Structural Materials, M. L. Bleiberg and J. W. Bennett (Eds.), Metallurgical Society of AIME, New York, pp. 317-326, 1977.
21. L. A. James, "The Effect of Fast Neutron Irradiation Upon the Fatigue-Crack Propagation Behavior of Two Austenitic Stainless Steels," Journal of Nuclear Materials, Vol. 59, No. 2, 1976, pp. 183-191.

APPENDIX A

DOSIMETRY RESULTS AND INTERPRETATION

As mentioned previously, dosimeters were included in each canister in order to estimate neutron flux. Results for the $^{54}\text{Fe}(n,p)$ reactions rate for the FMA-1B assembly irradiated in FFTF Cycle 4 are shown in Figure A-1. The results shown are based on spectral sets at canisters "L" and "N", and selected gradient sets, and are plotted as activity (on an arbitrary scale) versus axial position. An unexpected drop in $^{54}\text{Fe}(n,p)$ reaction rate is noted at canister locations "J" and "K". There were no unusual concentrations of fuel, absorbers, or other materials in adjacent assemblies that could have produced such a localized drop in reaction rate.

Therefore, to further resolve this matter, dosimetry results from the FMA-1A assembly,* along with results from the FFTF characterization program (conducted before FFTF Cycle 1), were also utilized to better define the shape of the reaction rate curve for FMA-1B. The reaction rate curve for FMA-1A, again plotted as activity on an arbitrary scale versus axial position, is shown in Figure A-2, and the shape of the curve is closer to the expected shape. FMA-1A had a slightly different configuration from that of FMA-1B in that two of the 3-in. canisters ("J" and "K") were replaced with three 2-in. canisters ("J", "JK", and "K") in order to accommodate a different size of specimen. The difference in canister design placed the dosimeters in "J", "JK", and "K" at a different radial distance than the rest of the dosimeters in the assembly. Therefore, Figure A-2 shows both the original activity data for these three dosimeters, as well as the activities corrected for the radial offset. This also gives some indication of the radial flux gradients through the subassembly.

The radial fluence gradient through the subassembly can also be seen in Figure A-3. This information was developed during the FFTF characterization

*FMA-1A was irradiated in Cycle 2 in FFTF position 2704 which is adjacent to the position 2705 utilized by FMA-1B in Cycle 4.

FIGURE A-1. Axial Variation of ^{54}Fe (n,p) Reaction for FMA-1B.

FIGURE A-2. Axial Variation of $^{54}\text{Fe}(n,p)$ Reaction for FMA-1A.

HEDL 8505-208.1

FIGURE A-3. Radial Variation of Neutron Flux.

program that was conducted prior to Cycle 1 operation. This curve was used to obtain the dosimetry values in Figure A-2 that were corrected for radial offset, and also indicates the variation in exposure expected for fracture toughness specimens irradiated within the same canister. Note also that the magnitude of the difference between measured and predicted reaction rates for canisters "K" and "J" in FMA-1B (see Figure A-1) are within the bounds of the radial gradient as shown in Figure A-3.

Therefore, in view of the excellent agreement between the reaction rate profiles shown in Figures A-1 and A-2 with physics predictions, and the lack of any unusual concentrations of anything would cause a local perturbation, the only reasonable interpretation is that the dosimeters in canisters "J" and "K" of FMA-1B inadvertantly changed position during handling prior to irradiation. The device used to contain the dosimeters, TEDs, and tensile specimens within the canisters might have allowed inadvertant movement of dosimeters (thereby producing a radial off-set) far enough to produce the readings shown in Figure A-1.

REFERENCES (Cont'd)

22. L. A. James, "Fatigue-Crack Propagation in Austenitic Stainless Steels," Atomic Energy Review, Vol. 14, No. 1, 1976, pp. 37-86.
23. L. A. James, "Frequency Effects in the Elevated Temperature Crack Growth Behavior of Austenitic Stainless Steels-A Design Approach," Journal of Pressure Vessel Technology, Vol. 101, No. 2, 1979, pp. 171-176 (see also *ibid*, Vol. 106, No. 4, 1984, pp. 311-312).
24. L. A. James, "Effects of Irradiation and Thermal Aging Upon Fatigue-Crack Growth Behavior of Reactor Pressure Boundary Materials," Time and Load Dependent Degradation of Pressure Boundary Materials, IWG-RRPC-79/2, pp. 129-149, International Atomic Energy Agency, Vienna, Austria, 1979.

APPENDIX B

PRECRACKING SCHEDULE

All fracture toughness specimens were precracked at room temperature at a cyclic frequency of 10 Hz. Irradiated specimens were precracked after they were irradiated. The load-crack length history for each specimen is given in the following table.

PRECRACKING SCHEDULE

<u>SPECIMEN NUMBER</u>	<u>MAXIMUM LOAD (lb)</u>	<u>MINIMUM LOAD (lb)</u>	<u>CYCLES</u>	<u>CRACK LENGTH (Stamped Side) (inch)</u>	<u>CRACK LENGTH (Unstamped Side) (inch)</u>	<u>CRACK LENGTH (Average) (inch)</u>
<u>2740</u>				.8743	.8743	.8743
	3200	160	150,000	1.0139	.9711	.9925
	2550	128	65,000	1.1020	1.0608	1.0814
	2000	100	62,000	1.1483	1.1223	1.1353
	1650	83	68,000	1.1843	1.1563	1.1703
<u>2741</u>				.8712	.8712	.8712
	3200	160	100,000	.9702	.9887	.9795
	2550	128	100,000	1.0212	1.1162	1.0912
	2000	100	50,000	1.0937	1.1502	1.1220
	1650	83	70,000	1.1216	1.1832	1.1524
<u>2742</u>				.8708	.8708	.8708
	3200	160	85,000	1.0008	1.0203	1.0106
	2550	128	70,000	1.1018	1.1374	1.1196
	2000	100	19,000	1.1232	1.1547	1.1390
	1650	83	40,000	1.1548	1.1871	1.1709
<u>2743</u>				.8761	.8761	.8761
	3200	160	150,000	.9894	.9861	.9878
	2550	128	67,500	1.0773	1.0888	1.0831
	2000	100	60,000	1.1224	1.1495	1.1359
	1650	83	5,000	1.2361	1.1786	1.2074

PRECRACKING SCHEDULE

<u>SPECIMEN NUMBER</u>	<u>MAXIMUM LOAD (lb)</u>	<u>MINIMUM LOAD (lb)</u>	<u>CYCLES</u>	<u>CRACK LENGTH (Stamped Side) (inch)</u>	<u>CRACK LENGTH (Unstamped Side) (inch)</u>	<u>CRACK LENGTH (Average) (inch)</u>
<u>2744</u>				.8758	.8758	.8758
	3200	160	140,000	.9794	.9758	.9781
	2550	128	90,000	1.0835	1.0908	1.0872
	2000	100	70,000	1.1304	1.1315	1.1310
	1650	83	85,000	1.1792	1.1737	1.1765
<u>2745</u>				.8694	.8694	.8694
	3200	160	90,000	.9729	.9959	.9844
	2550	128	65,000	1.0924	1.0869	1.0897
	2000	100	60,000	1.1221	1.1582	1.1402
	1650	83	25,000	1.1489	1.1814	1.1652
<u>2746</u>				.8763	.8763	.8763
	3200	160	85,200	.9803	.9933	.9868
	2550	128	75,000	1.1060	1.0751	1.0906
	2000	100	50,000	1.1383	1.1223	1.1303
	1650	83	60,000	1.1793	1.1643	1.1718
<u>2747</u>				.8768	.8768	.8768
	3200	160	80,000	.9903	1.0013	.9958
	2550	128	55,000	1.0793	1.0733	1.0763
	2000	100	56,230	1.1268	1.1258	1.1263
	1650	83	80,000	1.1780	1.1793	1.1787

PRECRACKING SCHEDULE

<u>SPECIMEN NUMBER</u>	<u>MAXIMUM LOAD (1b)</u>	<u>MINIMUM LOAD (1b)</u>	<u>CYCLES</u>	<u>CRACK LENGTH (Stamped Side) (inch)</u>	<u>CRACK LENGTH (Unstamped Side) (inch)</u>	<u>CRACK LENGTH (Average) (inch)</u>
<u>2748</u>				.8770	.8770	.8770
	3200	160	96,810	.9910	.9830	.9870
	2550	128	80,000	1.0828	1.0611	1.0720
	2000	100	60,000	1.1331	1.1212	1.1272
	1650	83	55,000	1.1835	1.1755	1.1795
<u>2749</u>				.8773	.8773	.8773
	3200	160	74,400	1.0113	.9933	1.0023
	2550	128	60,000	1.0778	1.0783	1.0781
	2000	100	56,610	1.1283	1.1258	1.1271
	1650	83	68,000	1.1773	1.1773	1.1773
<u>2750</u>				.888	.888	.888
	3200	160	120,000	.988	.998	.993
	2550	128	50,000	1.098	1.088	1.093
	2000	100	40,000	1.148	1.148	1.148
	1650	83	40,000	1.198	1.188	1.193
<u>2751</u>				.878	.878	.878
	3200	160	170,000	.988	.988	.988
	2550	128	40,000	1.078	1.078	1.078
	2000	100	40,000	1.128	1.128	1.128
	1650	83	37,000	1.178	1.188	1.183

PRECRACKING SCHEDULE

<u>SPECIMEN NUMBER</u>	<u>MAXIMUM LOAD (lb)</u>	<u>MINIMUM LOAD (lb)</u>	<u>CYCLES</u>	<u>CRACK LENGTH (Stamped Side) (inch)</u>	<u>CRACK LENGTH (Unstamped Side) (inch)</u>	<u>CRACK LENGTH (Average) (inch)</u>
<u>2752</u>				.877	.877	.877
	3200	160	160,000	1.007	.947	.977
	2550	128	60,000	1.117	1.077	1.097
	2000	100	25,000	1.147	1.117	1.132
	1650	83	45,000	1.187	1.157	1.172
<u>2753</u>				.877	.877	.877
	3200	160	90,000	1.007	.997	1.002
	2550	128	30,000	1.077	1.077	1.077
	2000	100	47,000	1.127	1.127	1.127
	1650	83	40,000	1.177	1.177	1.177
<u>2754</u>				.878	.878	.878
	3200	160	100,000	1.018	1.018	1.018
	2550	128	25,000	1.098	1.078	1.088
	2000	100	47,000	1.128	1.128	1.128
	1650	83	30,000	1.178	1.178	1.178
<u>2755</u>				.876	.876	.876
	3200	160	120,000	.976	.986	.981
	2550	128	45,000	1.076	1.086	1.081
	2000	100	40,000	1.126	1.126	1.126
	1650	83	35,000	1.176	1.176	1.176

PRECRACKING SCHEDULE

<u>SPECIMEN NUMBER</u>	<u>MAXIMUM LOAD (lb)</u>	<u>MINIMUM LOAD (lb)</u>	<u>CYCLES</u>	<u>CRACK LENGTH (Stamped Side) (inch)</u>	<u>CRACK LENGTH (Unstamped Side) (inch)</u>	<u>CRACK LENGTH (Average) (inch)</u>
<u>2943</u>				.880	.880	.880
	3200	160	80,000	.980	.980	.980
	2550	128	53,000	1.090	1.070	1.080
	2000	100	50,000	1.145	1.120	1.133
	1650	83	70,000	1.200	1.170	1.185
<u>2944</u>				.881	.881	.881
	3200	160	70,000	.976	.991	.984
	2550	128	43,000	1.071	1.091	1.081
	2000	100	44,000	1.121	1.151	1.136
	1650	83	50,000	1.181	1.211	1.196
<u>2945</u>				.880	.880	.880
	3200	160	80,000	.980	.980	.980
	2550	128	65,000	1.080	1.080	1.080
	2000	100	40,000	1.130	1.140	1.135
	1650	83	68,000	1.170	1.190	1.180
<u>2946</u>				.882	.882	.882
	3200	160	75,000	.977	.982	.980
	2550	128	53,000	1.072	1.097	1.0845
	2000	100	45,000	1.122	1.157	1.140
	1650	83	40,000	1.172	1.202	1.187

APPENDIX C

SINGLE-SPECIMEN UNLOADING-COMPLIANCE J_C TESTING

An attempt was made to use the single-specimen unloading-compliance (UC) method to determine J_C for the irradiated material. Test procedures and a compilation of UC results are given below.

During single-specimen J_C tests, specimens were periodically unloaded approximately 10 to 15% of maximum load to monitor changes in compliance. Typical load-displacement curves are shown in Appendix H. The analog load-displacement output was digitized, fed into an on-line real-time minicomputer and stored on magnetic tape for future retrieval and analysis.

At each unloading, the computer calculated the values of J and crack extension, Δa. The unloading compliance was computed from a least-squares regression line fitted through the lower half of the unloading curve. The instantaneous crack length and corresponding crack extension was then determined from the unloading compliance value by the modified Saxena-Hudak equation:

$$\frac{a}{W} = 0.9796 - 3.1350 U - 4.4477 U^2 + 16.0749 U^3 \quad [C-1]$$

where:

$$U = \frac{1}{\sqrt{BEC + 1}}$$

E = Elastic modulus

C = Load-line compliance

Equation [C-1] takes into account the difference in compliance-crack length calibration at the notch surfaces (n-n'; see Figure C-1), where load-line displacements are frequently monitored, and at the outside surfaces (m-m'),

used in high temperature displacement measurements. Compliance values at the two positions were determined by Ashbaugh^(C1) using finite element techniques. The difference in compliance values was incorporated into the Saxena-Hudak equation^(C2) to establish the compliance-crack length relationship given in Equation [C-1].

The irradiated specimens exhibited substantial rotation around the stress reversal point in the remaining ligament. This phenomenon reduced the moment arm of the applied load and altered the relative position of the displacement monitoring point. To account for these effects, a first-order rotation correction, introduced by Donald and Schmidt,^(C3) was applied to the unloading compliance data. The rotation correction for the load and displacement is given below:

$$\frac{V_C}{P_C} = \frac{V_m}{P_m} \left[\frac{1}{(1 - X/Z)(1 - Y/Z)} \right] \quad [C-2]$$

where:

V_m = Measured load-line displacement

V_C = Corrected load-line displacement

P_m = Measured load

P_C = Corrected load

$$X = \frac{V_m H + V_m^2/2}{Z}$$

$$Y = \frac{V_m D + V_m^2/2}{Z}$$

Z = Distance from load line to stress reversal point (= $a + 0.5b$)

D = Vertical distance between the crack plane and displacement measuring point

H = Vertical distance between the crack plane and load point

Unloading compliance results, computed with and without the rotation correction, are reported in Table C-1.

The extensive specimen rotation caused a tendency to overestimate crack extension particularly at the low J values, and this resulted in overly pessimistic J_C levels (Figures C-2 and C-3). At large Δa values, crack front tunneling effects, which caused an underestimation of UC Δa values,^(C4,C5) partially offset the rotational effects. Therefore, errors between measured and predicted Δa values tend to diminish at large crack extension values. Nevertheless, the overestimation of Δa at low crack extensions, prior to the development of significant crack front tunneling, resulted in very low J_C values for most UC tests. This behavior was not unexpected; it was observed in other lots of stainless steel when extensive specimen rotation occurred, as noted in the test specification for fracture mechanics testing of the PNC SUS 304 plate.

The rotational effects noted above are magnified by the high-temperature LVDT extensometry system because it is rigidly attached to the specimen. This caused the flexible link connecting the LVDT core to the upper fixture (Figure 10) to become somewhat rounded. Comparison of load-line displacements obtained using LVDT and conventional clip gage extensometers demonstrated that rounding of the flexible link had very little effect on the total area under the load-displacement curve. However, it did affect the slope of the partial unloading curve. Moreover, as the link became significantly bent, the core did not move properly inside the LVDT during the partial unloadings. This effect caused discontinuities in the J_R curve (e.g., the apparent reduction in crack length between data points 1 and 2, and points 5 and 6 in Figures C-2 and C-3).

As a result of these problems associated with extensive specimen rotation, emphasis was placed on using the conventional multiple-specimen J_R curve technique to determine postirradiation J_C fracture toughness. The unloading compliance results are presented in Table C-1 for completeness.

REFERENCES

- C1 N. E. Ashbaugh, "Material Evaluation: Part I - Mechanical Property Testing and Materials Evaluation and Modeling," Report AFML-TR-79-4127, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, September 1979.
- C2 A. Saxena and S. J. Hudak, Jr., "Review and Extension of Compliance Information for Common Crack Growth Specimens," International Journal of Fracture, Vol. 14, No. 5, October 1978.
- C3 K. Donald and D. Schmidt, "Rotational Effects on Compact Tension Specimens," presented at the ASTM E24.01.09 Task Group Meeting on Elastic-Plastic Fracture, Norfolk, Virginia, March 1977.
- C4 J. A. Joyce and J. P. Gudas, "Computer Interactive J_{IC} Testing of Naval Alloys," Elastic-Plastic Fracture, ASTM-STP 688, J. D. Landes, J. A. Begley and G. A. Clark, Eds., American Society for Testing and Materials, pp. 451-468, 1979.
- C5 G. A. Clark, "Single Specimen Tests for J_{IC} Determination - Revisited," Report 80-103-JINTF-P1, Westinghouse R&D Center, Pittsburgh, PA, April 1980.

FIGURE C-1 - Compact Specimen

FIGURE C-2 - Unloading compliance J_R curve for Specimen 2744. Crack extension values were computed without using the rotation correction given in Equation C-2. The measured final crack extension value is denoted by an "X". Extensive specimen rotation caused an overestimation of predicted crack extension, which resulted in an overly pessimistic J_C level. The multiple-specimen J_R curve for irradiated SUS 304 plate is also shown on this figure for comparison purposes.

FIGURE C-3 - Unloading compliance J_R curve for Specimen 2744. Crack extension values were computed using the rotation correction given in Equation C-2. The measured final crack extension value is denoted with an "X". Note that the rotation correction reduced J_{Ic} by approximately 30%. The multiple-specimen J_R curve for irradiated SUS 304 plate is also shown on this figure for comparison purposes.

TABLE C-1
SUMMARY OF UNLOADING COMPLIANCE RESULTS

SPECIMEN No = 2740

MATERIAL = 304 SS (PNC)

TEMPERATURE = 400C

THICKNESS = .9978 in

WIDTH = 1.9994 in

YIELD STRENGTH = 86,000 psi

GAGE HEIGHT = .5500 in

ULTIMATE STRENGTH = 92,800 psi

LOAD HEIGHT = .5500 in

FLOW STRENGTH = 89,400 psi

CRACK LENGTH = 1.2774 in

CRACK EXTEN. = .0400 in

ELASTIC MOD. = 24.40×10^6 psi

UNLOAD No	COMPLIANCE (10^{-6} in/lb)	AREA (in-lb)	LOAD (lb)	DISPL. (in)	^a J (psi-in)	^b CRACK EXTENSION (in)	^{b,c} CRACK EXT (RDT) (in)
1	3.53158	16.5	3125	.0102	50.2	0.0000	0.0000
2	3.55491	121.2	7200	.0296	368.7	.0020	.0046
3	3.54658	180.5	8000	.0375	549.1	.0013	.0049
4	3.63786	321.2	8610	.0544	977.2	.0092	.0151
5	3.92950	446.4	8700	.0689	1,358.1	.0325	.0402
6	3.91302	494.3	8660	.0741	1,503.8	.0313	.0397
7	4.06631	550.5	8410	.0810	1,674.8	.0427	.0519
8	4.10189	598.0	8310	.0864	1,819.3	.0452	.0551
9	4.13821	649.3	8260	.0925	1,975.4	.0478	.0585

INITIAL CRACK LENGTH (Calculated without rotation correction) = 1.2938

INITIAL CRACK LENGTH (Calculated using rotation correction) = 1.2952

a - MODIFIED MERKLE-CORTEN CORRECTION

b - MODIFIED SAXENA-HUDAK EQUATION

c - CORRECTED FOR SPECIMEN ROTATION

SPECIMEN No = 2741

MATERIAL = 304 SS (PNC)

TEMPERATURE = 400C

THICKNESS = .9979 in

WIDTH = 2.0004 in

GAGE HEIGHT = .5500 in

LOAD HEIGHT = .5500 in

CRACK LENGTH = 1.2034 in

CRACK EXTEN. = .0164 in

ELASTIC MOD. = 24.40×10^6 psi

YIELD STRENGTH = 86,000 psi

ULTIMATE STRENGTH = 92,800 psi

FLOW STRENGTH = 89,400 psi

UNLOAD No	COMPLIANCE (10^{-6} in/lb)	AREA (in-lb)	LOAD (lb)	DISPL. (in)	^a J (psi-in)	^b CRACK EXTENSION (in)	^{b,c} CRACK EXT (RDT) (in)
1	2.88281	12.7	3110	.0086	35.3	0.0000	0.0000
2	2.91786	180.2	9750	.0330	501.1	.0041	.0077
3	2.91333	267.6	10650	.0415	744.2	.0035	.0085
4	2.99756	352.7	10875	.0494	980.9	.0131	.0192
5	3.03932	423.9	11120	.0558	1,178.9	.0176	.0247
6		492.4	11165	.0619	1,369.4		

INITIAL CRACK LENGTH (Calculated without rotation correction) = 1.2287

INITIAL CRACK LENGTH (Calculated using rotation correction) = 1.2300

a - MODIFIED MERKLE-CORTEN CORRECTION

b - MODIFIED SAXENA-HUDAK EQUATION

c - CORRECTED FOR SPECIMEN ROTATION

SPECIMEN No = 2742

MATERIAL = 304 SS (PNC)

TEMPERATURE = 400C

THICKNESS = .9975 in

WIDTH = 2.0003 in

GAGE HEIGHT = .5500 in

LOAD HEIGHT = .5500 in

CRACK LENGTH = 1.1984 in

CRACK EXTEN. = .0711 in

ELASTIC MOD. = 24.40×10^6 psi

YIELD STRENGTH = 86,000 psi

ULTIMATE STRENGTH = 92,800 psi

FLOW STRENGTH = 89,400 psi

UNLOAD No	COMPLIANCE (10^{-6} in/lb)	AREA (in-lb)	LOAD (lb)	DISPL. (in)	^a J (psi-in)	^b CRACK EXTENSION (in)	^{b,c} CRACK EXT (RDT) (in)
1	2.72785	22.7	4200	.0107	62.8	0.0000	0.0000
2	2.76970	89.1	7600	.0220	246.5	.0052	.0069
3	2.78856	180.1	9670	.0323	498.3	.0075	.0108
4	2.76698	284.1	10600	.0425	786.0	.0049	.0098
5	2.80898	377.5	10800	.0512	1,044.5	.0100	.0163
6	2.91222	464.7	10800	.0590	1,285.7	.0222	.0296
7	2.90632	552.3	10600	.0674	1,528.1	.0215	.0303
8	3.00020	613.3	10320	.0729	1,696.9	.0322	.0417
9	3.08432	668.3	10000	.0786	1,849.1	.0413	.0516
10	3.15263	713.6	9810	.0830	1,974.4	.0484	.0594
11	3.19394	766.9	9660	.0883	2,121.9	.0527	.0644
12	3.23991	805.9	9520	.0922	2,229.8	.0573	.0696

INITIAL CRACK LENGTH (Calculated without rotation correction) = 1.2097

INITIAL CRACK LENGTH (Calculated using rotation correction) = 1.2113

a - MODIFIED MERKLE-CORTEN CORRECTION

b - MODIFIED SAXENA-HUDAK EQUATION

c - CORRECTED FOR SPECIMEN ROTATION

SPECIMEN No = 2743

MATERIAL = 304 SS (PNC)

TEMPERATURE = 400C

THICKNESS = .9980 in

WIDTH = 1.9996 in

GAGE HEIGHT = .5500 in

LOAD HEIGHT = .5500 in

CRACK LENGTH = 1.2498 in

CRACK EXTEN. = .0856 in

ELASTIC MOD. = 24.40×10^6 psi

YIELD STRENGTH = 88,900 psi

ULTIMATE STRENGTH = 91,900 psi

FLOW STRENGTH = 90,400 psi

UNLOAD No	COMPLIANCE (10^{-6} in/lb)	AREA (in-lb)	LOAD (lb)	DISPL. (in)	^a J (psi-in)	^b CRACK EXTENSION (in)	^{b,c} CRACK EXT (RDT) (in)
1	2.99833	13.8	3120	.0082	40.6	0.0000	0.0000
2	3.15433	197.7	8950	.0336	581.0	.0167	.0202
3	3.24709	308.4	9500	.0488	906.4	.0260	.0317
4	3.32129	420.2	9450	.0604	1,235.0	.0333	.0406
5	3.40837	504.8	9300	.0694	1,483.6	.0415	.0501
6	3.47986	567.3	8970	.0760	1,667.3	.0480	.0575
7	3.55195	612.6	8800	.0808	1,800.4	.0544	.0645
8	3.64516	661.4	8600	.0866	1,943.8	.0624	.0733
9	3.68786	709.1	8410	.0922	2,084.0	.0660	.0776
10	3.72888	748.5	8320	.0997	2,199.8	.0694	.0821
11	3.76438	789.6	8210	.1016	2,320.6	.0722	.0852

INITIAL CRACK LENGTH (Calculated without rotation correction) = 1.2414

INITIAL CRACK LENGTH (Calculated using rotation correction) = 1.2426

a - MODIFIED MERKLE-CORTEN CORRECTION

b - MODIFIED SAXENA-HUDAK EQUATION

c - CORRECTED FOR SPECIMEN ROTATION

SPECIMEN No = 2744

MATERIAL = 304 SS (PNC)

TEMPERATURE = 400C

THICKNESS = .9970 in

WIDTH = 2.0010 in

GAGE HEIGHT = .5500 in

LOAD HEIGHT = .5500 in

CRACK LENGTH = 1.2261 in

CRACK EXTEN. = .0192 in

ELASTIC MOD. = 24.40×10^6 psi

YIELD STRENGTH = 88,900 psi

ULTIMATE STRENGTH = 91,900 psi

FLOW STRENGTH = 90,400 psi

UNLOAD No	COMPLIANCE (10^{-6} in/lb)	AREA (in-lb)	LOAD (lb)	DISPL. (in)	^a J (psi-in)	^b CRACK EXTENSION (in)	^{b,c} CRACK EXT (RDT) (in)
1	2.82020	22.8	4130	.0107	65.1	0.0000	0.0000
2	2.79688	90.4	7500	.0222	258.1	-.0028	-.0011
3	2.86665	176.6	9280	.0323	504.2	.0055	.0087
4	2.90555	258.5	10070	.0408	738.1	.0101	.0145
5	2.96925	333.4	10350	.0481	951.9	.0173	.0229
6	2.95860	418.3	10400	.0558	1,194.3	.0161	.0229
7	3.02860	476.1	10360	.0617	1,359.4	.0239	.0315
8	3.05569	514.7	10310	.0653	1,469.6	.0268	.0349

INITIAL CRACK LENGTH (Calculated without rotation correction) = 1.2214

INITIAL CRACK LENGTH (Calculated using rotation correction) = 1.2229

a - MODIFIED MERKLE-CORTEN CORRECTION

b - MODIFIED SAXENA-HUDAK EQUATION

c - CORRECTED FOR SPECIMEN ROTATION

SPECIMEN No = 2745

MATERIAL = 304 SS (PNC)

TEMPERATURE = 400C

THICKNESS = .9972 in

WIDTH = 1.9997 in

GAGE HEIGHT = .5500 in

LOAD HEIGHT = .5500 in

CRACK LENGTH = 1.1970 in

CRACK EXTEN. = .0388 in

ELASTIC MOD. = 24.40×10^6 psi

YIELD STRENGTH = 80,500 psi

ULTIMATE STRENGTH = 86,900 psi

FLOW STRENGTH = 83,700 psi

UNLOAD No	COMPLIANCE (10^{-6} in/lb)	AREA (in-lb)	LOAD (lb)	DISPL. (in)	^a J (psi-in)	^b CRACK EXTENSION (in)	^{b,c} CRACK EXT (RDT) (in)
1	2.66073	22.0	4140	.0105	60.8	0.0000	0.0000
2	2.64772	93.9	7880	.0226	259.7	-.0017	.0002
3	2.71595	177.0	9750	.0317	489.4	.0071	.0104
4	2.74568	281.2	10760	.0419	777.6	.0108	.0157
5	2.80974	362.2	10940	.0493	1,001.6	.0187	.0247
6	2.82991	427.3	10930	.0552	1,181.6	.0211	.0280
7	2.88024	474.5	10780	.0593	1,312.1	.0271	.0346
8	2.94779	540.8	10250	.0655	1,495.4	.0349	.0433

INITIAL CRACK LENGTH (Calculated without rotation correction) = 1.2007

INITIAL CRACK LENGTH (Calculated using rotation correction) = 1.2023

a - MODIFIED MERKLE-CORTEN CORRECTION

b - MODIFIED SAXENA-HUDAK EQUATION

c - CORRECTED FOR SPECIMEN ROTATION

SPECIMEN No = 2746

MATERIAL = 304 SS (PNC)

TEMPERATURE = 400C

THICKNESS = .9977 in

WIDTH = 2.0003 in

GAGE HEIGHT = .5500 in

LOAD HEIGHT = .5500 in

CRACK LENGTH = 1.1911 in

CRACK EXTEN. = .0593 in

ELASTIC MOD. = 24.40×10^6 psi

YIELD STRENGTH = 80,500 psi

ULTIMATE STRENGTH = 86,900 psi

FLOW STRENGTH = 83,700 psi

UNLOAD No	COMPLIANCE (10^{-6} in/lb)	AREA (in-lb)	LOAD (lb)	DISPL. (in)	^a J	^b CRACK EXTENSION	^{b,c} CRACK EXT (RDT)
					(psi-in)	(in)	(in)
1	2.85550	7.0	2380	.0065	19.2	0.0000	0.0000
2	3.00808	394.5	10310	.0553	1,082.4	.0174	.0248
3	3.33684	525.5	10130	.0682	1,441.8	.0511	.0602
4	3.40434	590.0	9650	.0747	1,618.8	.0575	.0674
5	3.54431	673.1	9410	.0832	1,846.8	.0701	.0812

INITIAL CRACK LENGTH (Calculated without rotation correction) = 1.2254

INITIAL CRACK LENGTH (Calculated using rotation correction) = 1.2264

a - MODIFIED MERKLE-CORTEN CORRECTION

b - MODIFIED SAXENA-HUDAK EQUATION

c - CORRECTED FOR SPECIMEN ROTATION

SPECIMEN No = 2747
 MATERIAL = 304 SS (PNC)
 TEMPERATURE = 400C

THICKNESS = .9970 in

WIDTH = 2.0001 in

GAGE HEIGHT = .5500 in

LOAD HEIGHT = .5500 in

CRACK LENGTH = 1.1876 in

CRACK EXTEN. = .0631 in

ELASTIC MOD. = 24.40×10^6 psi

YIELD STRENGTH = 80,500 psi

ULTIMATE STRENGTH = 86,900 psi

FLOW STRENGTH = 83,700 psi

UNLOAD No	COMPLIANCE (10^{-6} in/lb)	AREA (in-lb)	LOAD (lb)	DISPL. (in)	^a J (psi-in)	^b CRACK EXTENSION (in)	^{b,c} CRACK EXT (RDT) (in)
1	2.51450	20.5	4100	.0102	56.1	0.0000	0.0000
2	2.51276	101.6	7950	.0236	277.9	-.0002	.0019
3	2.47445	182.5	9200	.0328	499.2	-.0057	-.0021
4	2.52008	272.3	9750	.0422	744.9	.0008	.0059
5	2.64880	375.2	9990	.0528	1,026.4	.0183	.0250
6	2.71112	463.4	10060	.0616	1,267.7	.0263	.0345
7	2.81917	554.6	10010	.0704	1,517.2	.0397	.0491
8	2.81360	645.5	9900	.0800	1,765.8	.0390	.0501
9	2.84079	743.7	9740	.0896	2,034.5	.0423	.0549
10	2.90812	829.6	9600	.0982	2,269.5	.0502	.0642
11	2.95263	903.4	9400	.1060	2,471.3	.0553	.0705
12	3.03952	966.4	9160	.1122	2,643.7	.0649	.0810
13	2.95502	1017.8	9100	.1180	2,784.3	.0555	.0729

INITIAL CRACK LENGTH (Calculated without rotation correction) = 1.1810
 INITIAL CRACK LENGTH (Calculated using rotation correction) = 1.1826

a - MODIFIED MERKLE-CORTEN CORRECTION
 b - MODIFIED SAXENA-HUDAK EQUATION
 c - CORRECTED FOR SPECIMEN ROTATION

SPECIMEN No = 2748

MATERIAL = 304 SS(PNC)

TEMPERATURE = 400C

THICKNESS = .9972 in

WIDTH = 2.0000 in

GAGE HEIGHT = .5500 in

LOAD HEIGHT = .5500 in

CRACK LENGTH = 1.2064 in

CRACK EXTEN. = .0186 in

ELASTIC MOD. = 24.40×10^6 psi

YIELD STRENGTH = 65,100 psi

ULTIMATE STRENGTH = 77,500 psi

FLOW STRENGTH = 71,300 psi

UNLOAD No	COMPLIANCE (10^{-6} in/lb)	AREA (in-lb)	LOAD (lb)	DISPL. (in)	^a J (psi-in)	^b CRACK EXTENSION (in)	^{b,c} CRACK EXT (RDT) (in)
1	2.69910	12.5	3160	.0080	34.9	0.0000	0.0000
2	2.78524	151.0	8450	.0300	421.9	.0108	.0141
3	2.84179	245.4	9220	.0407	685.6	.0176	.0225
4	2.80376	323.3	9450	.0491	903.2	.0130	.0193
5	2.79983	377.2	9525	.0546	1,053.8	.0126	.0197
6	2.87183	426.4	9515	.0598	1,191.3	.0212	.0291

INITIAL CRACK LENGTH (Calculated without rotation correction) = 1.2058

INITIAL CRACK LENGTH (Calculated using rotation correction) = 1.2070

a - MODIFIED MERKLE-CORTEN CORRECTION

b - MODIFIED SAXENA-HUDAK EQUATION

c - CORRECTED FOR SPECIMEN ROTATION

SPECIMEN No = 2749

MATERIAL = 304 SS (PNC)

TEMPERATURE = 400C

THICKNESS = .9971 in

WIDTH = 1.9999 in

GAGE HEIGHT = .5500 in

LOAD HEIGHT = .5500 in

CRACK LENGTH = 1.2012 in

CRACK EXTEN. = .0684 in

ELASTIC MOD. = 24.40×10^6 psi

YIELD STRENGTH = 65,000 psi

ULTIMATE STRENGTH = 77,500 psi

FLOW STRENGTH = 71,250 psi

UNLOAD No	COMPLIANCE (10^{-6} in/lb)	AREA (in-lb)	LOAD (lb)	DISPL. (in)	^a J (psi-in)	^b CRACK EXTENSION (in)	^{b,c} CRACK EXT (ROT) (in)
1	2.73616	22.2	4150	.0106	61.7	0.0000	0.0000
2	2.73175	91.3	7090	.0226	253.6	-.0006	.0013
3	2.82403	169.1	8120	.0328	469.8	.0108	.0141
4	2.86995	249.8	8530	.0424	693.9	.0163	.0211
5	2.72801	340.9	8760	.0528	947.0	-.0010	.0056
6	2.73496	430.8	8870	.0630	1,196.8	-.0002	.0081
7	2.73743	528.4	8880	.0740	1,467.9	.0002	.0103
8	2.76133	629.9	8880	.0854	1,749.9	.0031	.0151
9	2.85921	740.2	8760	.0976	2,056.3	.0150	.0289
10	2.86476	840.0	8730	.1090	2,333.5	.0156	.0315
11	2.93467	948.2	8700	.1210	2,634.1	.0237	.0415
12	3.01841	1059.8	8550	.1340	2,944.1	.0331	.0530
13	2.98202	1133.4	8480	.1424	3,148.6	.0291	.0506

INITIAL CRACK LENGTH (Calculated without rotation correction) = 1.2104

INITIAL CRACK LENGTH (Calculated using rotation correction) = 1.2120

a - MODIFIED MERKLE-CORTEN CORRECTION

b - MODIFIED SAXENA-HUDAK EQUATION

c - CORRECTED FOR SPECIMEN ROTATION

<u>SPECIMEN NUMBER</u>	<u>PRECRACKING SCHEDULE</u>					
	<u>MAXIMUM LOAD (1b)</u>	<u>MINIMUM LOAD (1b)</u>	<u>CYCLES</u>	<u>CRACK LENGTH (Stamped Side) (inch)</u>	<u>CRACK LENGTH (Unstamped Side) (inch)</u>	<u>CRACK LENGTH (Average) (inch)</u>
<u>2947 *</u>						
	3200	160	80,000	.882	.882	.882
				.987	.982	.985
	2550	128	74,000	1.232	1.212	1.222

*Specimen 2947 did not meet the precracking conditions specified in Section 7.6.2 of ASTM E813. The test results indicated, however, that the high precracking loads had little or no effect on the fracture toughness response for this specimen.

APPENDIX D

TENSILE TEST RESULTS

NOMENCLATURE

Spec diao	Initial Specimen Diameter
Spec diaf	Final Specimen Diameter
Spec lengtho	Initial Specimen Length
Spec lengthf	Final Specimen Length
Ext	Extensometer
Chart Sensitivity	Chart calibration factor for extensometer output.
Cal Factor	Extensometer Calibration Factor
Delta ep	Very small correction factor which forces plastic strain on initial part of Instron chart to coincide with that obtained from the extensometer chart.
Tdr	Time Drive
Load Exchange	Value of load when switch from extensometer chart to Instron chart.
Strain Exchange	Distance (in inches) on Instron chart from origin to Load Exchange.
Li	Distance in inches along the displacement (or time) axis from the origin to a point on the extensometer or Instron curve.
Fi	Applied load at Li.
Psi	Stress (in psi)
Mpa	Stress (in MPa)
Ep	Plastic Strain
Psit	True stress (in psi)
Mpat	True stress (in MPa)
Ept	True plastic strain
Ksi	Stress (in ksi)
Epuni	Uniform plastic strain
Eptot	Total plastic strain determined from load-displacement curve.
Eptotm	Total plastic strain determined from pre- and post-test specimen measurements.
RA	Reduction in Area.

Date: 4/4/85
Test Date: 3/29/85

Program: PNC
Specimen No. T-919
Material: 304SS
Heat or I.D. No.
Condition: IPRAD
Anomalies During Test: NONE
Reference:

Extensometer and Time Drive

Test temp= 752 F	Delta ep= .0061
Spec clao= .1252 in.	Tdr gage length= 1.1250 in.
Spec clat= .0703	Crosshead speed= .0050 in./min.
Spec lengtho= 1.8720 in.	Chart speed= 1.00 in./min.
Spec lengthf= 2.0	Tdr full scale= 2000 lbs.
Ext gage length= .4998 in.	Load exchange= 1,134.0 lbs.
Char sensitivity= .10 u./in.	Strain exchange= 6.650 in.
Cal factor= .006361 in./u.	
Ext full scale= 1000 lbs.	

L1	F1	Ps1	Mpa	Ep	Ps1t	Mpat	Ept
1.740	650.0	55,234	380.8	.0000	55,235	380.8	.0000
3.410	1,032.0	83,826	578.0	.0013	83,932	578.7	.0013
4.500	1,077.0	87,482	603.2	.0025	87,703	604.7	.0025
5.540	1,100.0	89,350	616.0	.0038	89,689	618.4	.0038
6.570	1,112.0	90,325	622.8	.0051	90,784	625.9	.0051
7.580	1,120.0	90,974	627.2	.0063	91,552	631.2	.0063
8.600	1,125.0	91,381	630.0	.0076	92,078	634.9	.0076
9.610	1,130.0	91,787	632.8	.0089	92,604	638.5	.0089
10.610	1,134.0	92,112	635.1	.0102	93,048	641.5	.0101
7.650	1,138.0	92,437	637.3	.0145	93,780	646.6	.0144
8.150	1,142.0	92,761	639.6	.0167	94,308	650.2	.0165
9.150	1,136.0	92,274	636.2	.0212	94,234	649.7	.0210
10.150	1,104.0	89,675	618.3	.0263	92,035	634.6	.0260
11.150	1,054.0	85,613	590.3	.0318	88,332	609.0	.0313
12.150	974.0	79,115	545.5	.0378	82,105	566.1	.0371
13.150	754.0	61,245	422.3	.0466	64,100	442.0	.0456
13.850	644.0	52,310	360.7	.0519	55,026	379.4	.0506

Date: 4/4/85
Test Date: 3/29/85

Program: PNC
Specimen No. T-919
Material: 304SS
Heat or I.D. No.
Condition: IRPAD
Anomalies During Test: NONE
Reference:

	Ep	Ks1	Mpa
	0.000	55.2	380.8
	.001	78.0	537.5
	.002	86.0	592.6
	.003	88.2	607.9
	.004	89.5	617.1
	.005	90.3	622.3
	.006	90.8	626.0
	.007	91.2	628.7
	.008	91.5	630.9
	.009	91.8	633.0
	.010	92.1	634.8
*	.017	92.8	639.6
	.020	92.4	637.1
	.030	86.9	599.3
	.040	74.6	514.7
	.050	55.5	382.9
	.052	52.3	360.7

Prop Elastic Limit= 55.2 Ks1 380.8 Mpa
Yield Strength = 86.0 Ks1 592.6 Mpa
Yield Strength Instron Chart= 88,700 Psi
Ultimate Strength = 92.8 Ks1 639.6 Mpa
Fracture Strength = 52.3 Ks1 360.7 Mpa
Epuni= .017
Epto.= .052
Epto.n= .068
RA= .439

Date: 4/4/85
Test Date: 4/1/85

Program: PNC
Specimen No. T-920
Material: 304SS
Heat or I.D. No.
Condition: IRRAD
Anomalies During Test: NONE
Reference:

Extensometer and Time Drive

Test temp= 752 F	Delta ep= .0053
Spec clao= .1251 in.	Tdr gage length= 1.1250 in.
Spec claf= .0703	Crosshead speed= .0050 in./min.
Spec lengtho= 1.8710 in.	Chart speed= 1.00 in./min.
Spec lengthf= 2.00	Tdr full scale= 2000 lbs.
Ext gage length= .4998 in.	Load exchange= 1,128.0 lbs.
Char. sensitivity= .10 v./in.	Strain exchange= 7.200 in.
Cal factor= .006361 in./v.	
Ext full scale= 2000 lbs.	

Li	Fi	Psi	Mpa	Ep	Psit	Mpat	Ept
1.950	760.0	61,831	426.3	-.0000	61,830	426.3	-.0000
3.760	1,080.0	87,866	605.8	.0013	87,978	606.6	.0013
4.800	1,102.0	89,656	618.2	.0025	89,883	619.7	.0025
5.840	1,116.0	90,795	626.0	.0038	91,141	628.4	.0038
6.860	1,120.0	91,120	628.2	.0051	91,585	631.5	.0051
7.870	1,122.0	91,283	629.4	.0064	91,865	633.4	.0064
8.870	1,124.0	91,445	630.5	.0076	92,145	635.3	.0076
9.880	1,126.0	91,608	631.6	.0089	92,426	637.3	.0089
10.880	1,127.0	91,689	632.2	.0102	92,625	638.6	.0101
11.880	1,128.0	91,771	632.7	.0115	92,823	640.0	.0114
8.200	1,130.0	91,934	633.9	.0159	93,393	643.9	.0157
9.200	1,124.0	91,445	630.5	.0204	93,314	643.4	.0202
10.200	1,094.0	89,005	613.7	.0255	91,274	629.3	.0252
11.200	1,044.0	84,937	585.6	.0310	87,566	603.7	.0305
12.200	958.0	77,940	537.4	.0371	80,835	557.3	.0365
13.200	844.0	68,665	473.4	.0439	71,680	494.2	.0430
13.800	744.0	60,530	417.3	.0486	63,471	437.6	.0475

Date: 4/4/85
Test Date: 4/1/85

Program: PNC
Specimen No. T-920
Material: 304SS
Heat or I.D. No.
Condition: IRRAD
Anomalies During Test: NONE
Reference:

Ep	Ksi	Mpa
0.000	61.8	426.3
.001	82.2	566.8
.002	88.9	612.9
.003	90.1	621.0
.004	90.8	626.3
.005	91.1	628.1
.006	91.2	629.0
.007	91.4	629.9
.008	91.5	630.8
.009	91.6	631.6
.010	91.7	632.1
* .016	91.9	633.9
.020	91.5	630.8
.030	85.6	590.5
.040	74.0	510.4
.049	60.5	417.3

Prop. Elastic Limit=	61.8 Ksi	426.3 Mpa
Yield Strength =	88.9 Ksi	612.9 Mpa
Yield Strength Instron Chart=		88,191 Psi
Ultimate Strength =	91.9 Ksi	633.9 Mpa
Fracture Strength =	60.5 Ksi	417.3 Mpa
Epuni=	.016	
Eptoc=	.049	
Eptocr=	.069	
RA=	.438	

Date: 4/4/85
Test Date: 4/1/85

Program: PNC
Specimen No. T-921
Material: 304SS
Heat or I.D. No.
Condition: IPPAD
Anomalies During Test: BROKE OUTSIDE GAGE
Reference:

Extensometer and Time Drive

Test temp= 752 F	Delta ep= .0271
Spec clao= .1252 in.	Tdr gage length= 1.1250 in.
Spec claf= .0703	Crosshead speed= .0050 in./min.
Spec lengtho= 1.8725 in.	Chart speed= 1.00 in./min.
Spec lengthf= 2.0	Tdr full scale= 2000 lbs.
Ext gage length= .4998 in.	
Char sensitivity= .10 v./in.	
Cal factor= .006361 in./v.	Load exchange= 1,040.0 lbs.
Ext full scale= 2000 lbs.	Strain exchange= 7.400 in.

L1	F1	Ps1	Mpa	Ep	Ps1t	Mpat	Ept
2.900	670.0	54,422	375.2	.0000	54,423	375.2	.0000
4.920	974.0	79,115	545.5	.0013	79,215	546.2	.0013
6.050	1,004.0	81,552	562.3	.0026	81,761	563.7	.0026
7.110	1,020.0	82,852	571.2	.0038	83,170	573.4	.0038
8.130	1,026.0	83,339	574.6	.0051	83,766	577.5	.0051
9.150	1,032.0	83,826	578.0	.0064	84,362	581.7	.0064
10.170	1,036.0	84,151	580.2	.0077	84,797	584.7	.0076
11.170	1,040.0	84,476	582.4	.0089	85,230	587.6	.0089
8.400	1,050.0	85,289	588.0	.0132	86,410	595.8	.0131
9.400	1,062.0	86,263	594.8	.0173	87,759	605.1	.0172
10.400	1,068.0	86,751	598.1	.0217	88,629	611.1	.0214
11.400	1,070.0	86,913	599.2	.0261	89,177	614.9	.0257
12.400	1,066.0	86,588	597.0	.0306	89,236	615.3	.0301
13.400	1,040.0	84,476	582.4	.0356	87,483	603.2	.0350
14.400	990.0	80,415	554.4	.0678	85,866	592.0	.0656
15.400	922.0	74,891	516.4	.0737	80,412	554.4	.0711
16.400	820.0	66,606	459.2	.0804	71,959	496.1	.0773
17.400	650.0	52,798	364.0	.0885	57,470	396.2	.0848

Date: 4/4/85
Test Date: 4/1/85

Program: PNC
Specimen No. T-921
Material: 304SS
Heat or I.D. No.
Condition: IRRAD
Anomalies During Test: BROKE OUTSIDE GAGE
Reference:

Ep	Ks1	Mpa
0.000	54.4	375.2
.001	74.0	510.3
.002	80.5	555.0
.003	82.0	565.3
.004	82.9	571.6
.005	83.3	574.3
.006	83.7	576.9
.007	84.0	579.0
.008	84.2	580.8
.009	84.5	582.5
.010	84.7	583.9
.020	86.6	596.8
* .026	86.9	599.2
.030	86.6	597.3
.040	83.9	578.6
.050	82.7	569.9
.060	81.4	561.2
.070	78.4	540.2
.080	67.1	462.4
.088	52.8	364.0

Prop. Elastic Limit= 54.4 Ks1 375.2 Mpa
Yield Strength = 80.5 Ks1 555.0 Mpa
Yield Strength Instron Chart= 78,628 Psi
Ultimate Strength = 86.9 Ks1 599.2 Mpa
Fracture Strength = 52.8 Ks1 364.0 Mpa
Epuni= .026
Epto.= .088
Eptob= .068
RA= .439

Date: 4/3/85
Test Date: 4/2/85

Program: PNC
Specimen No. T-922
Material: 304SS
Heat or I.D. No.
Condition: IPPAD
Anomalies During Test: Broke outside gage
Reference:

Extensometer and Time Drive

Test temp= 752 F	Delta ep= .0003
Spec clao= .1253 in.	Tdr gage length= 1.1250 in.
Spec clat= .0703	Crosshead speed= .0050 in./min.
Spec lengtho= 1.8720 in.	Chart speed= 1.00 in./min.
Spec lengthf= 2.078	Tdr full scale= 2000 lbs.
Ext gage length= .4998 in.	
Char sensitivity= .10 v./in.	
Cal factor= .005361 in./v.	Load exchange= 848.0 lbs.
Ext full scale= 2000 lbs.	Strain exchange= 6.500 in.

L1	F1	Ps1	Mpa	Ep	Ps1t	Mpat	Ept
2.150	640.0	51,902	357.9	-.0000	51,902	357.8	-.0000
3.440	766.0	63,743	439.5	.0013	63,823	440.0	.0013
4.500	814.0	66,013	455.1	.0025	66,181	456.3	.0025
5.530	826.0	66,987	461.9	.0038	67,242	463.6	.0038
6.550	836.0	67,798	467.4	.0051	68,142	469.8	.0051
7.570	840.0	68,122	469.7	.0064	68,556	472.7	.0064
8.580	848.0	68,771	474.2	.0076	69,296	477.8	.0076
9.500	880.0	71,366	492.1	.0158	72,492	499.8	.0157
10.500	958.0	72,826	502.1	.0243	74,592	514.3	.0240
12.500	916.0	74,285	512.2	.0327	76,716	528.9	.0322
14.500	926.0	75,096	517.8	.0414	78,203	539.2	.0405
16.500	938.0	76,070	524.5	.0500	79,872	550.7	.0488
18.500	944.0	76,556	527.8	.0587	81,052	558.8	.0571
20.500	950.0	77,043	531.2	.0675	82,242	567.0	.0653
22.500	955.0	77,448	534.0	.0763	83,354	574.7	.0735
23.000	956.0	77,529	534.5	.0785	83,612	576.5	.0755
24.000	954.0	77,367	533.4	.0829	83,784	577.7	.0797
26.000	926.0	75,096	517.8	.0925	82,042	565.7	.0885
28.000	820.0	66,500	458.5	.1038	73,406	506.1	.0988
30.000	726.0	58,877	405.9	.1149	65,644	452.6	.1088
31.000	656.0	53,200	366.8	.1210	59,638	411.2	.1142
31.200	620.0	50,281	346.7	.1227	56,452	389.2	.1158

Date: 4/3/85
Test Date: 4/2/85

Program: PHC
Specimen No. T-922
Material: 304SS
Heat or I.D. No.
Condition: IRRAD
Anomalies During Test: Broke outside gage
Reference:

Ep	Ks1	Mpa
0.000	51.9	357.9
.001	61.4	423.1
.002	65.1	448.6
.003	66.4	457.6
.004	67.1	462.7
.005	67.7	467.1
.006	68.0	469.0
.007	68.4	471.9
.008	68.9	475.0
.009	69.2	477.1
.010	69.5	479.3
.020	72.1	497.1
.030	73.8	508.9
.040	75.0	516.9
.050	76.1	524.5
.060	76.6	528.3
.070	77.2	532.0
* .078	77.5	534.5
.080	77.5	534.2
.090	75.7	521.9
.100	69.4	478.6
.123	50.3	346.7

Prop. Elastic Limit= 51.9 Ks1 357.9 Mpa
Yield Strength = 65.1 Ks1 448.6 Mpa
Yield Strength Instron Chart= 63,662 Psi
Ultimate Strength = 77.5 Ks1 534.5 Mpa
Fracture Strength = 50.3 Ks1 346.7 Mpa
Epuni= .078
Epto.= .123
Epto n= .110
RA= .439

Date: 7/9/84
Test Date: 7/2/84

Program:
Specimen No. T-923
Material: PNC 304SS
Heat or I.D. No.
Condition:
Anomalies During Test: NONE
Reference:

Extensometer and Time Drive

Test temp= 800 F	Delta ep= .0029
Spec diao= .1247 in.	Tdr gage length= 1.1250 in.
Spec diaf= .0552 in.	Crosshead speed= .0020 in./min.
Spec lengtho= 1.8720 in.	Chart speed= .20 in./min.
Spec lengthf= 2.3280 in.	Tdr full scale= 1000 lbs.
Ext gage length= .5011 in.	
Chart sensitivity= .10 v./in.	
Cal factor= .004920 in./v.	Load exchange= 315.0 lbs.
Ext full scale= 500 lbs.	Strain exchange= 2.500 in.

L1	P1	Ps1	Mpa	Ep	Ps1t	Mpat	Ept
1.670	155.0	12,691	87.5	-.0000	12,691	87.5	-.0000
3.120	247.0	20,224	139.4	.0010	20,244	139.6	.0010
4.190	264.0	21,616	149.0	.0020	21,659	149.3	.0020
5.240	275.0	22,517	155.2	.0029	22,583	155.7	.0029
6.280	282.0	23,090	159.2	.0039	23,181	159.8	.0039
7.310	289.0	23,663	163.2	.0049	23,779	164.0	.0049
8.340	295.0	24,155	166.5	.0059	24,297	167.5	.0059
9.370	300.0	24,564	169.4	.0069	24,733	170.5	.0069
10.390	305.0	24,973	172.2	.0079	25,169	173.5	.0078
11.420	310.0	25,383	175.0	.0088	25,607	176.6	.0088
12.440	315.0	25,792	177.8	.0098	26,045	179.6	.0098
3.000	335.0	27,430	189.1	.0137	27,805	191.7	.0136
4.000	366.0	29,968	206.6	.0217	30,617	211.1	.0214
5.000	393.0	32,179	221.9	.0298	33,137	228.5	.0293
6.000	419.0	34,308	236.5	.0379	35,608	245.5	.0372
7.000	444.0	36,355	250.7	.0461	38,030	262.2	.0450
8.000	466.0	38,156	263.1	.0543	40,229	277.4	.0529
9.000	488.0	39,957	275.5	.0626	42,457	292.7	.0607
10.000	508.0	41,595	286.8	.0709	44,543	307.1	.0685
14.000	576.0	47,163	325.2	.1045	52,089	359.1	.0994
18.000	633.0	51,830	357.4	.1384	59,001	406.8	.1296
22.000	680.0	55,678	383.9	.1725	65,285	450.1	.1592
26.000	725.0	59,363	409.3	.2068	71,639	493.9	.1880
30.000	758.0	62,065	427.9	.2414	77,047	531.2	.2162
34.000	773.0	63,293	436.4	.2765	80,794	557.1	.2441
38.000	790.0	64,685	446.0	.3116	84,839	584.9	.2712
42.350	792.0	64,849	447.1	.3502	87,557	603.7	.3002
44.000	760.0	62,229	429.1	.3658	84,990	586.0	.3117
45.000	709.0	58,053	400.3	.3761	79,889	550.8	.3193
46.000	623.0	51,011	351.7	.3875	70,780	488.0	.3275
46.500	559.0	45,771	315.6	.3938	63,737	439.9	.3321
46.770	490.0	40,121	276.6	.3982	56,099	386.8	.3352

Date: 7/9/84
Test Date: 7/2/84

Program:
Specimen No. T-923
Material: PNC 304SS
Heat or I.D. No.
Condition:
Anomalies During Test: NONE
Reference:

Ep	Ksi	Mpa
0.000	12.7	87.5
.001	20.2	139.6
.002	21.7	149.3
.003	22.6	155.5
.004	23.1	159.5
.005	23.7	163.5
.006	24.2	166.9
.007	24.6	169.7
.008	25.0	172.6
.009	25.4	175.5
.010	25.9	178.4
.020	29.4	203.0
.030	32.2	222.3
.040	34.8	240.2
.050	37.2	256.6
.060	39.4	271.6
.070	41.4	285.6
.080	43.1	297.2
.090	44.8	308.7
.100	46.4	320.1
.150	53.1	366.4
.200	58.6	404.3
.250	62.4	430.0
.300	64.2	442.8
.350	64.8	447.1
* .350	64.8	447.1
.398	40.1	276.6

Prop. Elastic Limit= 12.7 Ksi 87.5 Mpa
Yield Strength = 21.7 Ksi 149.3 Mpa
Yield Strength Instron Chart= 22,926 Psi
Ultimate Strength = 64.8 Ksi 447.1 Mpa
Fracture Strength = 40.1 Ksi 276.6 Mpa
Epuni= .350
Eptot= .398
Eptotm= .405
RA= .804

Date: 7/9 84
Test Date: 6/29/84

Program:
Specimen No. T-9.25
Material: PNC 304SS
Heat or I.D. No.
Condition:
Anomalies During Test: NONE
Reference:

Extensometer and Time Drive

Test temp= 800 F	Delta ep= .0020
Spec diao= .1244 in.	Tdr gage length= 1.1250 in.
Spec diaf= .0652 in.	Crosshead speed= .0020 in./min.
Spec lengtho= 1.8725 in.	Chart speed= .20 in./min.
Spec lengthf= 2.3300 in.	Tdr full scale= 1000 lbs.
Ext gage length= .5011 in.	
Chart sensitivity= .10 v./in.	
Cal factor= .004920 in./v.	Load exchange= 324.0 lbs.
Ext full scale= 500 lbs.	Strain exchange= 2.450 in.

L1	P1	Ps1	Mpa	Ep	Ps1t	Mpat	Ept
1.800	183.0	15,056	103.8	-.0000	15,056	103.8	-.0000
3.120	251.0	20,651	142.4	.0010	20,671	142.5	.0010
4.190	267.5	22,009	151.7	.0019	22,051	152.0	.0019
5.260	280.0	23,037	158.8	.0029	23,105	159.3	.0029
6.300	286.0	23,531	162.2	.0039	23,623	162.9	.0039
7.330	294.0	24,189	166.8	.0049	24,308	167.6	.0049
8.360	300.0	24,683	170.2	.0059	24,828	171.2	.0059
9.390	305.0	25,094	173.0	.0069	25,266	174.2	.0069
10.400	310.0	25,505	175.9	.0078	25,705	177.2	.0078
11.430	315.0	25,917	178.7	.0088	26,146	180.3	.0088
12.450	320.0	26,328	181.5	.0098	26,586	183.3	.0098
13.480	324.0	26,657	183.8	.0108	26,945	185.8	.0107
3.000	343.0	28,220	194.6	.0151	28,647	197.5	.0150
4.000	372.0	30,606	211.0	.0232	31,316	215.9	.0229
5.000	402.0	33,075	228.0	.0312	34,106	235.2	.0307
6.000	428.0	35,214	242.8	.0393	36,598	252.3	.0386
7.000	451.0	37,106	255.8	.0475	38,869	268.0	.0464
8.000	473.0	38,916	268.3	.0558	41,086	283.3	.0543
9.000	495.0	40,726	280.8	.0640	43,333	298.8	.0620
10.000	514.0	42,289	291.6	.0723	45,349	312.7	.0698
14.000	582.0	47,884	330.2	.1059	52,955	365.1	.1007
18.000	639.0	52,574	362.5	.1398	59,923	413.2	.1309
22.000	690.0	56,770	391.4	.1738	66,639	459.5	.1603
26.000	728.0	59,896	413.0	.2083	72,372	499.0	.1892
30.000	756.0	62,200	428.9	.2430	77,316	533.1	.2175
34.000	780.0	64,175	442.5	.2779	82,007	565.4	.2452
38.000	793.0	65,244	449.8	.3130	85,669	590.7	.2722
41.950	798.0	65,656	452.7	.3480	88,504	610.2	.2986
44.000	778.0	64,010	441.3	.3668	87,490	603.2	.3125
46.000	669.0	55,042	379.5	.3878	76,387	526.7	.3277
47.000	555.0	45,663	314.8	.4000	63,929	440.8	.3365
47.600	490.0	40,315	278.0	.4073	56,734	391.2	.3416

Date: 7.9.84
Test Date: 6/29/84

Program:
Specimen No. T-925
Material: PNC 304SS
Heat or I.D. No.
Condition:
Anomalies During Test: NONE
Reference:

Ep	Ksi	Mpa
0.000	15.1	103.8
.001	20.7	142.7
.002	22.1	152.1
.003	23.1	159.1
.004	23.6	162.6
.005	24.2	167.1
.006	24.7	170.5
.007	25.1	173.4
.008	25.6	176.3
.009	26.0	179.2
.010	26.4	182.0
.020	29.7	204.5
.030	32.7	225.5
.040	35.4	243.9
.050	37.7	259.6
.060	39.8	274.7
.070	41.9	288.5
.080	43.6	300.4
.090	45.2	311.9
.100	46.9	323.4
.150	53.8	371.2
.200	59.1	407.8
.250	62.6	431.6
.300	64.8	447.1
* .348	65.7	452.7
.350	65.5	451.5
.400	45.7	315.0
.407	40.3	278.0

Prop. Elastic Limit= 15.1 Ksi 103.8 Mpa
Yield Strength = 22.1 Ksi 152.1 Mpa
Yield Strength Instron Chart= 23,037 Psi
Ultimate Strength = 65.7 Ksi 452.7 Mpa
Fracture Strength = 40.3 Ksi 278.0 Mpa
Epuni= .348
Eptot= .407
Eptotm= .407
RA= .725

Date: 4/15/85
Test Date: 4/8/85

Program: PNC
Specimen No. T-950
Material: 304SS
Heat or I.D. No.
Condition:
Anomalies During Test:
Reference:

Extensometer and Time Drive

Test temp= 752 F
Spec diao= .1252 in.
Spec diaf= .0578 in.
Spec lengtho= 1.8750 in.
Spec lengthf= 2.2850 in.
Ext gage length= .5011 in.
Chart sensitivity= .10 v./in.
Cal factor= .004898 in./v.
Ext full scale= 1000 lbs.

Delta ep= -.0011
Tdr gage length= 1.1250 in.
Crosshead speed= .0050 in./min.
Chart speed= 1.00 in./min.
Tdr full scale= 1000 lbs.

Load exchange= 322.0 lbs.
Strain exchange= 5.000 in.

Li	Pi	Psi	Mpa	Ep	Psit	Mpat	Ept
1.900	169.0	13,727	94.6	.0007	13,736	94.7	.0007
3.350	230.0	18,682	128.8	.0019	18,718	129.1	.0019
4.530	260.0	21,119	145.6	.0030	21,182	146.0	.0030
5.620	278.0	22,581	155.7	.0040	22,671	156.3	.0040
6.700	288.0	23,393	161.3	.0050	23,511	162.1	.0050
7.770	297.0	24,124	166.3	.0061	24,270	167.3	.0060
8.830	303.0	24,612	169.7	.0071	24,786	170.9	.0070
9.870	310.0	25,180	173.6	.0081	25,384	175.0	.0080
10.920	317.0	25,749	177.5	.0091	25,983	179.1	.0090
12.000	322.0	26,155	180.3	.0101	26,420	182.2	.0101
10.000	390.0	31,679	218.4	.0308	32,654	225.1	.0303
15.000	458.0	37,202	256.5	.0514	39,116	269.7	.0502
20.000	507.0	41,182	283.9	.0725	44,169	304.5	.0700
25.000	550.0	44,675	308.0	.0938	48,864	336.9	.0896
30.000	589.0	47,843	329.9	.1151	53,349	367.8	.1089
35.000	621.0	50,442	347.8	.1366	57,332	395.3	.1280
40.000	650.0	52,798	364.0	.1581	61,147	421.6	.1468
45.000	674.0	54,747	377.5	.1798	64,591	445.3	.1654
50.000	695.0	56,453	389.2	.2015	67,831	467.7	.1836
55.000	715.0	58,077	400.4	.2233	71,047	489.9	.2016
60.000	729.0	59,215	408.3	.2452	73,735	508.4	.2193
65.000	742.0	60,271	415.6	.2671	76,371	526.6	.2368
70.000	752.0	61,083	421.2	.2891	78,744	542.9	.2540
74.000	756.0	61,408	423.4	.3068	80,249	553.3	.2676
77.000	740.0	60,108	414.4	.3205	79,374	547.3	.2780
79.000	700.0	56,859	392.0	.3303	75,641	521.5	.2854
81.000	630.0	51,173	352.8	.3408	68,614	473.1	.2933
83.000	520.0	42,238	291.2	.3522	57,116	393.8	.3018

Date: 4/15/85
Test Date: 4/8/85

Program: PNC
Specimen No. T-950
Material: 304SS
Heat or I.D. No.
Condition:
Anomalies During Test:
Reference:

Ep	Ksi	Mpa
0.000	13.7	94.6
.001	15.1	104.1
.002	18.9	130.3
.003	21.1	145.8
.004	22.6	155.7
.005	23.4	161.1
.006	24.1	166.1
.007	24.6	169.5
.008	25.1	173.3
.009	25.7	177.2
.010	26.1	180.0
.020	28.8	198.5
.030	31.5	217.0
.040	34.1	235.4
.050	36.8	253.8
.060	38.8	267.6
.070	40.7	280.6
.080	42.4	292.4
.090	44.1	303.7
.100	45.6	314.4
.150	51.9	357.9
.200	56.3	388.4
.250	59.4	409.9
.300	61.3	422.5
* .307	61.4	423.4
.350	44.0	303.3
.352	42.2	291.2

Prop. Elastic Limit=	13.7 Ksi	94.6 Mpa
Yield Strength =	18.9 Ksi	130.3 Mpa
Yield Strength Instron Chart=		19,495 Psi
Ultimate Strength =	61.4 Ksi	423.4 Mpa
Fracture Strength =	42.2 Ksi	291.2 Mpa
Epuni=	.307	
Eptot=	.352	
Eptotm=	.364	
RA=	.787	

Date: 4/12/85
Test Date: 4/10/85

Program: PNC
Specimen No. T-951
Material: 304SS
Heat or I.D. No.
Condition:
Anomalies During Test:
Reference:

Extensometer and Time Drive

Test temp= 752 F	Delta ep= .0013
Spec diao= .1257 in.	Tdr gage length= 1.1250 in.
Spec diaf= .0753 in.	Crosshead speed= .0050 in./min.
Spec lengtho= 1.8740 in.	Chart speed= 1.00 in./min.
Spec lengthf= 2.2890 in.	Tdr full scale= 1000 lbs.
Ext gage length= .4998 in.	
Chart sensitivity= .10 v./in.	
Cal factor= .006361 in./v.	Load exchange= 330.0 lbs.
Ext full scale= 1000 lbs.	Strain exchange= 5.200 in.

Li	Pi	Psi	Mpa	Ep	Psit	Mpat	Ept
.790	220.0	17,728	122.2	-.0000	17,728	122.2	-.0000
1.920	271.0	21,838	150.6	.0013	21,866	150.8	.0013
2.950	288.0	23,208	160.0	.0025	23,266	160.4	.0025
3.980	299.0	24,094	166.1	.0038	24,186	166.8	.0038
5.000	308.0	24,819	171.1	.0051	24,945	172.0	.0051
6.020	313.0	25,222	173.9	.0064	25,383	175.0	.0063
7.030	320.0	25,786	177.8	.0076	25,983	179.1	.0076
8.040	326.0	26,270	181.1	.0089	26,503	182.7	.0089
9.060	330.0	26,592	183.3	.0102	26,863	185.2	.0101
10.200	413.0	33,280	229.5	.0299	34,275	236.3	.0294
15.200	467.0	37,632	259.5	.0505	39,531	272.6	.0492
25.200	554.0	44,643	307.8	.0923	48,762	336.2	.0883
35.200	620.0	49,961	344.5	.1347	56,692	390.9	.1264
45.200	671.0	54,071	372.8	.1776	63,675	439.0	.1635
55.200	707.0	56,972	392.8	.2210	69,561	479.6	.1996
65.200	734.0	59,147	407.8	.2646	74,798	515.7	.2348
75.200	747.0	60,195	415.0	.3087	78,774	543.1	.2690
77.200	735.0	59,228	408.4	.3179	78,057	538.2	.2760
80.200	683.0	55,038	379.5	.3328	73,355	505.8	.2873
82.200	610.0	49,155	338.9	.3439	66,060	455.5	.2956
84.200	480.0	38,679	266.7	.3567	52,478	361.8	.3051

Date: 4/12/85
Test Date: 4/10/85

Program: PNC
Specimen No. T-951
Material: 304SS
Heat or I.D. No.
Condition:
Anomalies During Test:
Reference:

Ep	Ksi	Mpa
0.000	17.7	122.2
.001	21.0	144.6
.002	22.6	156.0
.003	23.5	162.3
.004	24.2	166.9
.005	24.8	170.8
.006	25.1	173.1
.007	25.5	175.9
.008	25.9	178.8
.009	26.3	181.3
.010	26.5	183.0
.020	29.9	206.3
.030	33.3	229.6
.040	35.4	244.2
.050	37.5	258.8
.060	39.2	270.5
.070	40.9	282.0
.080	42.6	293.6
.090	44.3	305.2
.100	45.6	314.5
.150	51.4	354.6
.200	55.6	383.1
.250	58.4	402.8
.300	60.0	413.6
* .309	60.2	415.0
.350	44.2	304.7
.357	38.7	266.7

Prop. Elastic Limit= 17.7 Ksi 122.2 Mpa
Yield Strength =
Yield Strength Instron Chart= 21,596 Psi
Ultimate Strength = 60.2 Ksi 415.0 Mpa
Fracture Strength = 38.7 Ksi 266.7 Mpa
Epuni= .309
Eptot= .357
Eptotm= .369
RA= .641

APPENDIX E

PHOTOGRAPHS OF IRRADIATED TENSILE SPECIMENS

Photographs of the irradiated tensile specimen and fracture surfaces are given on Pages E-2 to E-13. The dimensions of the scale shown in each photograph are in inches.

2
SPECIMEN T919

SPECIMEN T919

E-3

1 2

1 3

SPECIMEN T919

SPECIMEN T920

SPECIMEN T920

E-6

1 2

1 3

SPECIMEN T920

E-7

SPECIMEN T921

SPECIMEN T921

E-9

1

2

1

3

SPECIMEN T921

E-10

20

24

28

4

8

12

16

20

24

28

4

8

12

1

2

1

3

40

48

56

8

16

24

32

40

48

56

8

16

SPECIMEN T922

SPECIMEN T922

E-12

APPENDIX F

CRACK LENGTH VERSUS CYCLES CURVES FOR THE FATIGUE-CRACK GROWTH TESTS

FIGURE F-1 - Plot of Crack Length Versus Cycles for Specimen 2757

FIGURE F-2 - Plot of Crack Length Versus Cycles for Specimen 2758

FIGURE F-3 - Plot of Crack Length Versus Cycles for Specimen 2759

F-5

FIGURE F-4 - Plot of Crack Length Versus Cycles for Specimen 2760

F-6

FIGURE F-5 - Plot of Crack Length Versus Cycles for Specimen 2762

F-7

FIGURE F-6 - Plot of Crack Length Versus Cycles for Specimen 2763

SPECIMEN T922

APPENDIX G

TEST DATA AND DETAILED CALCULATIONS FOR THE FATIGUE-CRACK GROWTH TESTS

NOTE: Data was taken and calculations made using the units employed in the laboratory:

Specimen Dimensions = inches

Temperature = °F

Cyclic Frequency = cycles/minute

Load = pounds

Crack Length = inches

da/dN = inch/cycle

K = psi $\sqrt{\text{inch}}$

Flow Stress = psi

An asterisk next to a crack length indicates that the remaining ligament criterion (e.g., Equation [1] or [2]) was violated.

SPECIMEN NO.2757 (PNC)

Material:Irrad. Type 304

Fluence:5.1 dpa

Notch=.6000 W= 1.9986

R= .050

t= .2476

Pmax= 750

Design: CS

Freq: 60 Waveshape:Triangle

Temp: 752F

Sigma f: 88900

N	a	da/dN	Log (da/dN)	Kmax	DK	Log DK
0	.6707					
24,000	.7003	1.2333E-06	-5.90892	13451	12779	4.10649
44,000	.7227	1.1200E-06	-5.95078	13908	13213	4.12100
64,000	.7420	9.6500E-07	-6.01547	14287	13573	4.13268
0	.7483					
33,000	.7808	9.8485E-07	-6.00663	14897	14152	4.15083
70,200	.8180	1.0000E-06	-6.00000	15595	14815	4.17070
92,200	.8454	1.2455E-06	-5.90467	16281	15467	4.18941
103,000	.8587	1.2315E-06	-5.90957	16736	15899	4.20137
131,000	.8915	1.1714E-06	-5.93128	17274	16410	4.21511
146,000	.9112	1.3133E-06	-5.88163	17919	17023	4.23103
161,000	.9429	2.1133E-06	-5.67503	18587	17657	4.24693
171,000	.9655	2.2600E-06	-5.64589	19337	18370	4.26410
187,000	.9957	1.8875E-06	-5.72411	20114	19108	4.28122
203,000	1.0460	3.1438E-06	-5.50255	21402	20332	4.30818
211,000	1.0670	2.6250E-06	-5.58087	22663	21530	4.33305
218,000	1.0958	4.1143E-06	-5.38571	23621	22440	4.35102
223,000	1.1233	5.5000E-06	-5.25964	24789	23550	4.37198
225,500	1.1386	6.1200E-06	-5.21325	25745	24458	4.38841
230,500	1.1665	5.5800E-06	-5.25337	26775	25437	4.40546
235,500	1.1926	5.2200E-06	-5.28233	28166	26758	4.42745
239,000	1.2290	1.0400E-05	-4.98297	29937	28440	4.45393
242,000	1.2620	1.1000E-05	-4.95861	32137	30530	4.48472
243,000	1.2849	2.2900E-05	-4.64016	34115	32410	4.51067
244,250	1.3213	2.9120E-05	-4.53581	36449	34627	4.53941
245,500	1.3653	3.5200E-05	-4.45346	40070	38066	4.58054

SPECIMEN NO.2758 (PNC)

Material:Irrad. Type 304

Fluence:5.1 dpa

Notch= .6010 W= 1.9991

R= .050

t= .2478

Pmax= 1000

Design: CS

Freq: 60 Waveshape:Triangle

Temp: 752F

Sigma f: 88900

N	a	da/dN	Log (da/dN)	Kmax	DK	Log DK
8,500	.7760	2.9733E-06	-5.52676	20435	19414	4.28811
16,000	.7983	4.1700E-06	-5.37986	21321	20254	4.30652
26,000	.8400	2.0000E-06	-5.69897	22408	21287	4.32812
42,000	.8720	3.3750E-06	-5.47173	23338	22171	4.34578
50,000	.8990	3.0875E-06	-5.51039	24202	22992	4.36157
58,000	.9237	5.0429E-06	-5.29732	25269	24005	4.38031
65,000	.9590	5.7167E-06	-5.24286	26604	25274	4.40268
71,000	.9933	6.8000E-06	-5.16749	27665	26281	4.41965
73,500	1.0103	5.3600E-06	-5.27084	28326	26910	4.42991
76,000	1.0237	5.2000E-06	-5.28400	28923	27477	4.43897
78,500	1.0367	9.0667E-06	-5.04255	29546	28068	4.44822
80,000	1.0503	8.1600E-06	-5.08831	30375	28856	4.46024
82,500	1.0707	1.0100E-05	-4.99568	31688	30104	4.47862
85,500	1.1010	6.6667E-06	-5.17609	33380	31711	4.50121
90,000	1.1310	7.0000E-06	-5.15490	35158	33401	4.52375
94,000	1.1590	1.5333E-05	-4.81436	36861	35018	4.54429
95,500	1.1820	1.2000E-05	-4.92082	38334	36417	4.56131
97,000	1.2000	3.7000E-05	-4.43180	40474	38450	4.58490
98,000	1.2370	1.2556E-05	-4.90116	42527	40401	4.60639
98,900	1.2483	4.8700E-05	-4.31247	45334	43067	4.63415
99,900	1.2970	7.8571E-05	-4.10474	50986	48437	4.68518
100,600	1.3520	6.1500E-05	-4.21112	55316	52551	4.72058
100,800	1.3643	1.0175E-04	-3.99247	59174	56215	4.74986
101,200	1.4050	9.5000E-05	-4.02228	64079	60875	4.78444
101,400	1.4240*					

SPECIMEN NO.2759 (PNC)

Material: Irrad. Type 304
 Notch= .6010 W= 1.9995
 t= .2473
 Design: CS
 Temp: 752F

Fluence: 2.7 dpa
 R= .050
 Pmax= 1000
 Freq: 60 Waveshape: Triangle
 Sigma f: 65100

N	a	da/dN	Log (da/dN)	Kmax	DK	Log DK
0	.6743					
10,000	.7007	2.6400E-06	-5.57840	17992	17092	4.23280
25,000	.7417	2.7333E-06	-5.56331	18788	17849	4.25161
42,000	.7793	2.2118E-06	-5.65526	19769	18781	4.27371
52,000	.8013	2.2000E-06	-5.65758	20555	19528	4.29065
63,000	.8417	3.6727E-06	-5.43501	21424	20353	4.30862
73,000	.8697	2.8000E-06	-5.55284	22436	21314	4.32868
82,000	.9020	3.5889E-06	-5.44504	23388	22219	4.34672
92,000	.9353	3.3300E-06	-5.47756	24495	23270	4.36680
97,000	.9620	5.3400E-06	-5.27246	25582	24303	4.38565
103,000	.9833	3.5500E-06	-5.44977	26508	25183	4.40110
111,000	1.0190	4.4625E-06	-5.35042	27681	26297	4.41991
117,000	1.0820	1.0500E-05	-4.97881	29930	28433	4.45383
122,000	1.1217	7.9400E-06	-5.10018	32617	30986	4.49117
128,000	1.2440	2.0383E-05	-4.69072	37792	35902	4.55512

SPECIMEN NO.2760 (PNC)

Material:Irrad. Type 304
 Notch= .6031 W= 1.9996
 t= .2483

Design: CS
 Temp: 752F

Fluence: 2.7 dpa
 R= .050
 Pmax= 750
 Freq: 60 Waveshape:Triangle
 Sigma f: 65100

N	a	da/dN	Log (da/dN)	Kmax	DK	Log DK
92,160	.7961	6.5426E-07	-6.18425	15795	15006	4.17625
140,000	.8274	1.0680E-06	-5.97143	16421	15600	4.19313
165,000	.8541	2.5000E-06	-5.60206	17306	16441	4.21592
185,000	.9041	2.0625E-06	-5.68561	18347	17429	4.24128
201,000	.9371	2.3533E-06	-5.62832	19279	18315	4.26281
216,000	.9724	2.2850E-06	-5.64111	20489	19464	4.28924
236,000	1.0181	2.8000E-06	-5.55284	21702	20617	4.31423
246,000	1.0461	4.0000E-06	-5.39794	22486	21362	4.32963
250,000	1.0621	4.5000E-06	-5.34679	23125	21968	4.34180
254,000	1.0801	4.0000E-06	-5.39794	23795	22605	4.35421
258,000	1.0961	5.5750E-06	-5.25376	24590	23361	4.36849
262,000	1.1184	4.5667E-06	-5.34040	25381	24112	4.38222
265,000	1.1321	7.8667E-06	-5.10421	26246	24934	4.39679
268,000	1.1557	6.6000E-06	-5.18046	27151	25793	4.41150
270,000	1.1689	4.8000E-06	-5.31876	27992	26593	4.42476
274,000	1.1881	8.0000E-06	-5.09691	29300	27835	4.44460
277,500	1.2161	9.6500E-06	-5.01547	30719	29183	4.46514
279,500	1.2354	1.7000E-05	-4.76955	32464	30840	4.48912
281,500	1.2694	1.2700E-05	-4.89620	34134	32428	4.51092
282,500	1.2821	2.0000E-05	-4.69897	35392	33623	4.52663
283,500	1.3021	2.0000E-05	-4.69897	37041	35189	4.54640
284,500	1.3221	3.0000E-05	-4.52288	39289	37324	4.57199
285,500	1.3521	3.1000E-05	-4.50864	42355	40237	4.60463
286,500	1.3831	3.0600E-05	-4.51428	44956	42709	4.63051
287,000	1.3984*	4.7400E-05	-4.32422	47358	44991	4.65312
287,500	1.4221*					

SPECIMEN NO.2762 (PNC)

Material: Ann. Type 304
 Notch= .5998 W= 1.9982
 t= .2487
 Design: CS
 Temp: 752F

Fluence: 0.0 dpa
 R= .050
 Pmax= 750
 Freq: 60 Waveshape: Triangle
 Sigma f: 40525

N	a	da/dN	Log (da/dN)	Kmax	DK	Log DK
0	.6528					
35,000	.6770	6.9143E-07	-6.16025	13046	12394	4.09320
55,000	.7066	1.4800E-06	-5.82974	13504	12829	4.10820
70,000	.7233	1.1133E-06	-5.95337	13912	13217	4.12113
85,000	.7469	1.5733E-06	-5.80318	14279	13565	4.13242
100,000	.7693	1.4933E-06	-5.82584	14712	13976	4.14538
115,000	.7966	1.8200E-06	-5.73993	15197	14438	4.15949
126,000	.8154	1.7091E-06	-5.76723	15667	14884	4.17271
137,000	.8377	2.0273E-06	-5.69309	16103	15298	4.18462
148,000	.8556	1.6273E-06	-5.78854	16546	15718	4.19640
159,000	.8785	2.0818E-06	-5.68156	17013	16163	4.20851
169,000	.9031	2.4600E-06	-5.60906	17583	16704	4.22282
178,000	.9194	1.8111E-06	-5.74205	18098	17193	4.23534
187,000	.9362	1.8667E-06	-5.72893	18531	17605	4.24563
196,000	.9652	3.2222E-06	-5.49184	19159	18201	4.26010
204,000	.9835	2.2875E-06	-5.64064	19845	18853	4.27537
212,000	1.0181	4.3250E-06	-5.36401	20660	19627	4.29286
218,000	1.0363	3.0333E-06	-5.51808	21532	20455	4.31080
224,000	1.0651	4.8000E-06	-5.31876	22360	21242	4.32720
228,000	1.0936	7.1250E-06	-5.14722	23446	22274	4.34779
232,000	1.1280	8.6000E-06	-5.06550	24745	23508	4.37122
235,400	1.1681	1.1794E-05	-4.92833	26451	25129	4.40017
236,400	1.1833	1.5200E-05	-4.81816	27852	26459	4.42258
237,300	1.2038	2.2778E-05	-4.64249	28825	27384	4.43750
238,000	1.2199	2.3000E-05	-4.63827	29885	28390	4.45317
238,600	1.2382	3.0500E-05	-4.51570	30942	29395	4.46827
239,100	1.2489*	2.1400E-05	-4.66959	31884	30290	4.48130

APPENDIX H

LOAD-DISPLACEMENT RECORDS FOR FRACTURE TOUGHNESS TESTS

The load versus load-line displacement records are given on Pages H-2 to H-22. The construction lines for determining the area under load-displacement curves and the corresponding area calculations are shown on Pages H-12 to H-22.

TEST#3 S/N 2740 304SS (PNC)

17

400°C

1-14-95 UAT

Specimen 2740

2000
1000
100

1000
1000
1000

H-2
LOAD (pounds)
12,000
8000
4000
0

Specimen 2741

Specimen 2742

S-H

Specimen 2743

Specimen 2744

7/ U/UV

1.1 IN. ALUMINUM 6061-T6 1/2" X 1/2" X 1/8"

Specimen 2745

8-H

Specimen 2746

6-H

LOAD / LBS

DISPLACEMENT, IN

Specimen 2747

Specimen 2748

H-11

Specimen 2749

$4000 \times .4 = 1600$
 $960 \div 1600 = 0.6$

TEST 394A ON 2750 TISS (PNC) 1T
 6-15-84 LOT

800°F

H-12

4000 x .4 = 1600
960 / 1600 = .6

TEST #15 212751 3045S (PNC) IT 800F
G-18-PV UNIT

YOUNG'S MOD = 1600
 $900 \div 0.11 = 8180$

1K ST # 396A

SIN 7752 30485 (PNC)

IT

800°F

6-17-FV uST

10,000

LOAD (pounds)

Specimen 2752

LOAD
10000
10000

LOAD
10000
10000

1780
1595
A = 3265

(1074)
A = 1790

1000 x 1000 = 100
 $A = \frac{30485 \times 5 \times 1000}{2} = 155$

H-14

5000

0

0

0.5

1.0

DISPLACEMENT (inch)

מ'תקנ'ס

6 20-1411GT

Specimen 2753

LEAD
LEAD
LEAD

4207
4208
4209

$$4000 \times 4 = 1600$$

$$960 \div 1600 = 0.6$$

TEST # 831A WIN 2154 30V-S (PN) 1T
1-24-54 WBT

200F

Specimen 2754

LOAD
10000
10000

LOAD
10000
10000

1760.33
1719.0
3479.33

(1056)
AE 1712.33

1000 x 1.45 = 1450
AE 528.33
1000 x 1.719 = 1719

LOAD (pounds)

91-H

5000

0

0.5

1.0

DISPLACEMENT (inch)

$4000 \times 4 = 1600$
 $760 - 1600 = 0.6$

TEST # 402A SIN 2755 30Y55 (PNC) IT
 7-25-86 URT

800F

Specimen 2755

LOAD
 10000
 10000

URT
 100
 100 IT

10,000

LOAD (pounds)

$\frac{2530}{10000} = 0.253$
 $\frac{10000}{3937.5} = 0.02539$

(15.15)
 $A = 0.539$

H-17

5000

$\frac{10000 \times 1000}{10000} = 100$
 $\frac{7.67 \times 5}{1} \times 100 = 1517.5$
 $A = 0.539$

0

0.5

1.0

DISPLACEMENT (inch)

752°F

$$60 \div 6012 = 60375$$

4-4-85 UAT

Specimen 2945

FOAD
YOTAT
1004

4407
1000
1001

10,000

LOAD (pounds)

H-20

5000

0

0.5

1.0

DISPLACEMENT (inch)

U² = 1991

$Y_{0.2} \times Y = 160$
 $166 \div 160 = 60.275$

TEST#419A SIN2746 30VSS (DNC) IT 752°F
 4-S-85 uDT

Specimen 2946

LOAD
 1000
 1000
 1000

$2/2.5$
 28.6
 $K = 14.57$

(12.85)
 $K = 2.57$

$1000 \div 12.85$
 $2/2.5$
 $K = 2.57$

H-21

$$4000 \times .400 = 1600$$

$$906 \div 1600 = .60375$$

TEST 421A SIN 2947 30VBS (PUC) 1T 752°F
Y-22-95 u&T

Specimen 2947

6400
1600
1000
4000
1000
1000

LOAD (pounds)

5000

0

0.5

1.0

DISPLACEMENT (inch)

2042.04
1745.00
1745.00
A = 3787.04

(1245)
A = 2012.44

1000 x 1000 = 1000
640 x 1000 = 6400
A = 2

H-22

APPENDIX I

PHOTOGRAPHS OF FRACTURE SURFACES FOR IRRADIATED FRACTURE TOUGHNESS SPECIMENS

The dimensions of the scale shown in each photograph are in inches.

MADE IN

3

U.S.A.

4

15

SPECIMEN 2740

I-2

MADE IN

3

U.S.A.

4

5

SPECIMEN 2741

I-3

MADE IN

3

U.S.A.

4

5

SPECIMEN 2742

I-4

MADE IN

3

U.S.A.

4

5

SPECIMEN 2743

I-5

MADE IN

3

U.S.A.

4

5

SPECIMEN 2744

I-6

MADE IN

3

U.S.A.

4

5

SPECIMEN 2745

I-7

MADE IN

3

U.S.A.

4

5

SPECIMEN 2746

I-8

MADE IN

3

U.S.A.

4

5

SPECIMEN 2747

I-9

MADE IN

3

U.S.A.

4

5

SPECIMEN 2748

I-10

MADE IN

3

U.S.A.

4

5

SPECIMEN 2749

I-11

SPECIMEN NO.2763 (PNC)

Material: Ann. Type 304
 Notch= .6009 W= 1.9992
 t= .2489
 Design: CS
 Temp: 752F

Fluence: 0.0 dpa
 R= .050
 Pmax= 1000
 Freq: 60 Waveshape: Triangle
 Sigma f: 40525

N	a	da/dN	Log (da/dN)	Kmax	DK	Log DK
0	.6656					
		1.8083E-06	-5.74272	17628	16747	4.22393
12,000	.6873	2.1000E-06	-5.67778	18167	17258	4.23700
24,000	.7125	3.1800E-06	-5.49757	18846	17903	4.25294
34,000	.7443	2.8267E-06	-5.54873	19504	18529	4.26784
41,500	.7655	2.6533E-06	-5.57621	20034	19032	4.27948
49,000	.7854	3.0400E-06	-5.51713	20604	19574	4.29167
56,500	.8082	4.1333E-06	-5.38370	21354	20286	4.30721
64,000	.8392	4.6500E-06	-5.33255	22220	21109	4.32447
70,000	.8671	3.4000E-06	-5.46852	22862	21719	4.33683
74,000	.8807	5.5500E-06	-5.25571	23438	22266	4.34764
78,000	.9029	5.8667E-06	-5.23161	24104	22899	4.35982
81,000	.9205	8.3600E-06	-5.07779	24778	23539	4.37179
83,500	.9414	8.6500E-06	-5.06298	25477	24203	4.38387
85,500	.9587	1.0550E-05	-4.97675	26212	24901	4.39622
87,500	.9798	1.1222E-05	-4.94992	27041	25689	4.40975
89,300	1.0000	1.1313E-05	-4.94644	27850	26458	4.42256
90,900	1.0181	1.8067E-05	-4.74312	28858	27416	4.43800
92,400	1.0452	1.6750E-05	-4.77599	29978	28479	4.45453
93,600	1.0653	2.6400E-05	-4.57840	31156	29598	4.47126
94,600	1.0917	1.6875E-05	-4.77276	32230	30618	4.48598
95,400	1.1052	4.1875E-05	-4.37805	33579	31900	4.50379
96,200	1.1387*	3.3000E-05	-4.48149	35018	33267	4.52201
96,600	1.1519*	5.0000E-05	-4.30103	35855	34062	4.53228
96,850	1.1644*					

APPENDIX J

CALIBRATION RECORDS FOR THE DUAL LVDT EXTENSOMETER
SYSTEM FOR TENSILE TESTING

CALIBRATION RECORD FOR DUAL LVDT EXTENSOMETRY SYSTEM
USED FOR TESTING UNIRRADIATED SPECIMENS

<u>Point Number</u>	<u>Displacement (inch)</u>	<u>Voltage Run 1 (V)</u>	<u>Voltage Run 2 (V)</u>
1	0.000	-0.075	-0.073
2	0.001	+0.139	+0.140
3	0.002	0.343	0.346
4	0.003	0.550	0.553
5	0.004	0.754	0.757
6	0.005	0.958	0.962
7	0.006	1.161	1.164
8	0.007	1.366	1.368
9	0.008	1.569	1.572
10	0.009	1.775	1.779
11	0.010	1.980	1.984
12	0.015	3.001	3.005
13	0.020	4.022	4.024
14	0.025	5.040	5.043
15	0.030	6.066	6.068
16	0.035	7.088	7.089
17	0.040	8.108	8.112
18	0.045	9.122	9.123
19	0.050	10.134	10.136

CALIBRATION RECORD FOR DUAL LVDT EXTENSOMETRY
SYSTEM USED FOR POSTIRRADIATION TESTING

<u>Point Number</u>	<u>Displacement (inch)</u>	<u>Voltage Run 1 (V)</u>	<u>Voltage Run 2 (V)</u>
1	0.000	-0.069	-0.073
2	0.001	+0.087	+0.083
3	0.002	0.245	0.239
4	0.003	0.403	0.399
5	0.004	0.564	0.556
6	0.005	0.719	0.710
7	0.006	0.877	0.869
8	0.007	1.036	1.025
9	0.008	1.190	1.187
10	0.009	1.353	1.347
11	0.010	1.509	1.501
12	0.015	2.297	2.289
13	0.020	3.081	3.073
14	0.025	3.860	3.857
15	0.030	4.653	4.649
16	0.035	5.442	5.435
17	0.040	6.226	6.214
18	0.045	7.008	7.003
19	0.050	7.785	7.778